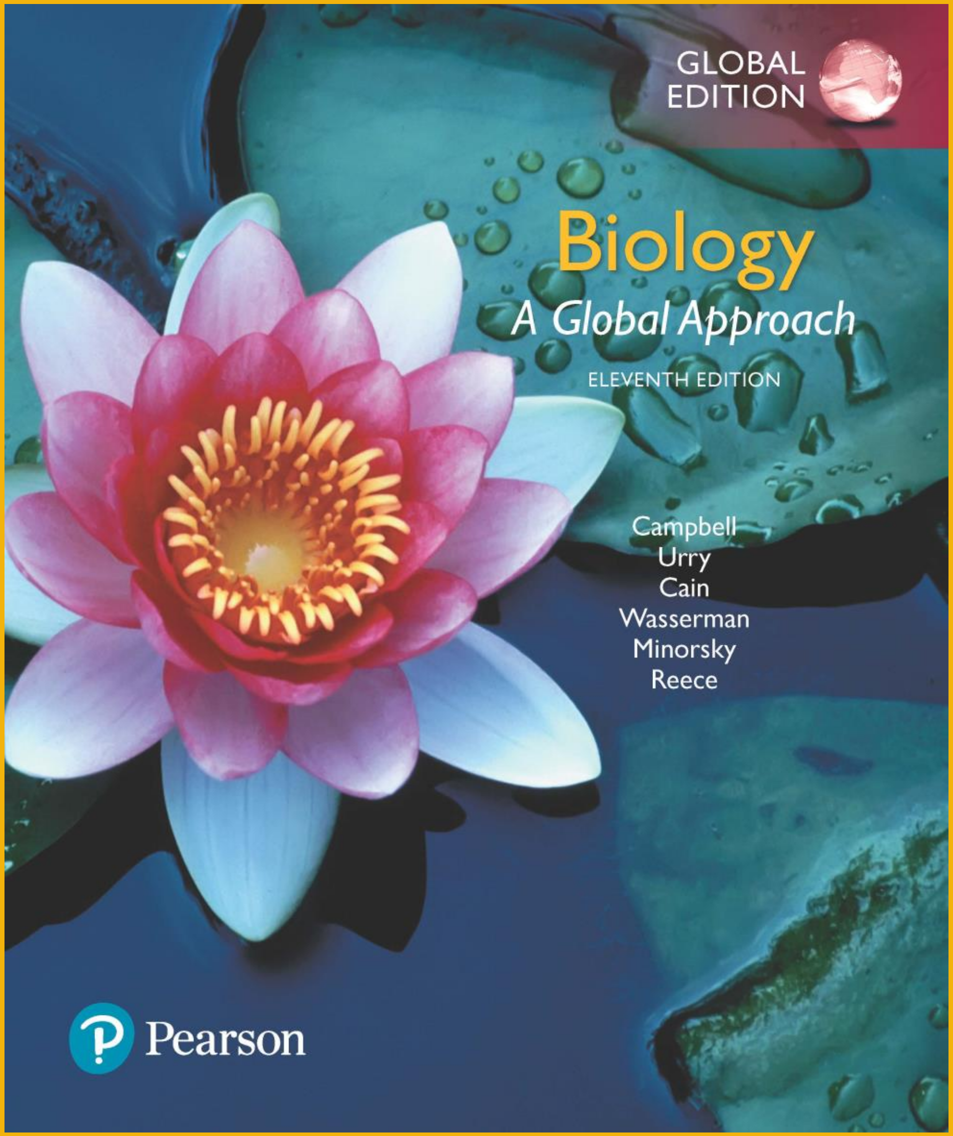



# Chapter 5

# Biological Macromolecules and Lipids

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

# 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 and are complex
- Large biological molecules have unique properties that arise from the orderly arrangement of their atoms

Figure 5.1

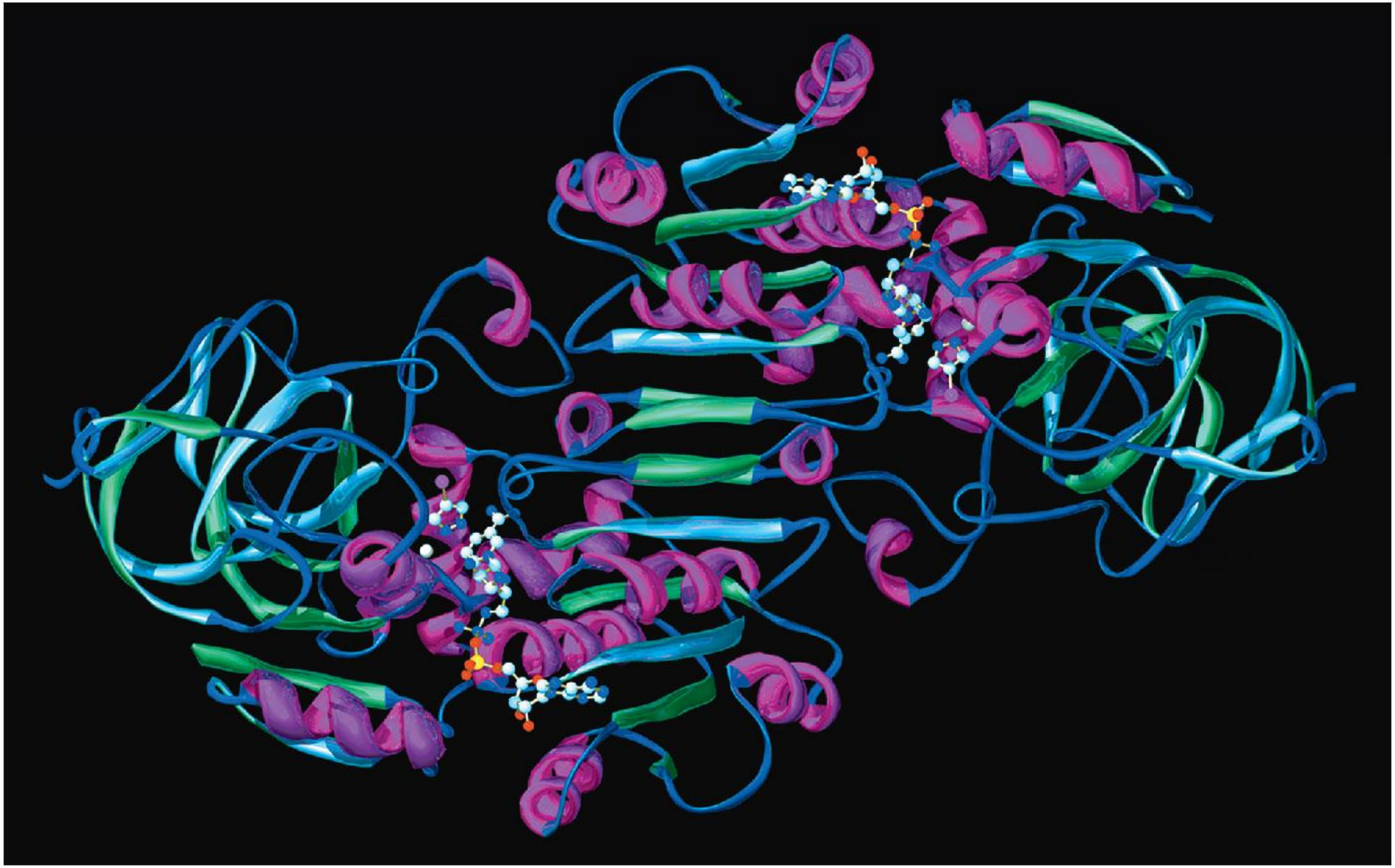


Figure 5.1a

**The scientist in the foreground is using 3-D glasses to help her visualize the structure of the protein displayed on her screen.**

# Concept 5.1: Macromolecules are polymers, built from monomers

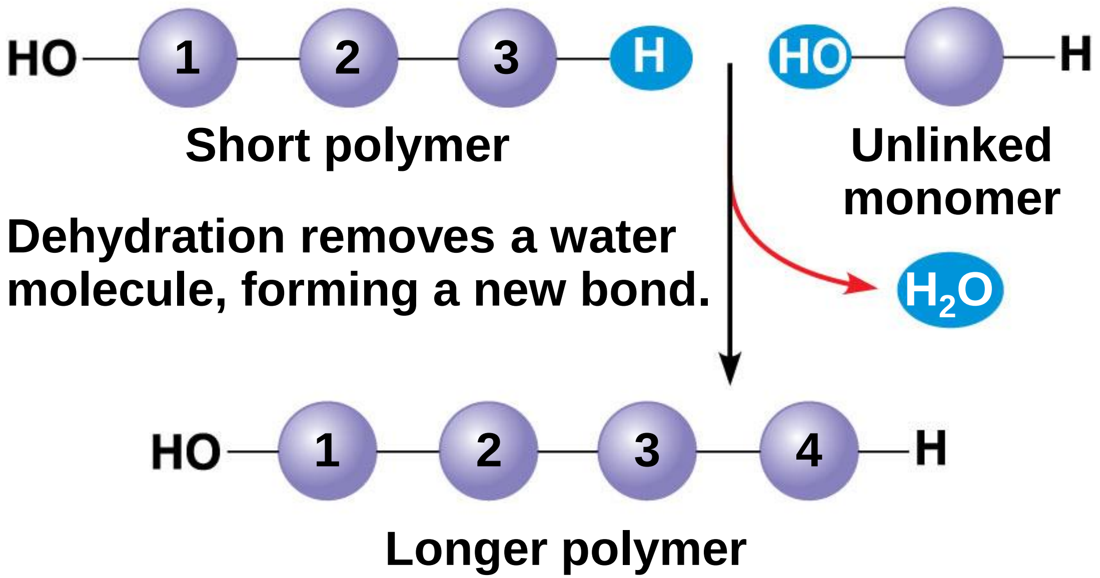
- A **polymer** is a long molecule consisting of many similar building blocks
- The repeating units that serve as building blocks are called **monomers**
- Carbohydrates, proteins, and nucleic acids are polymers

# The Synthesis and Breakdown of Polymers

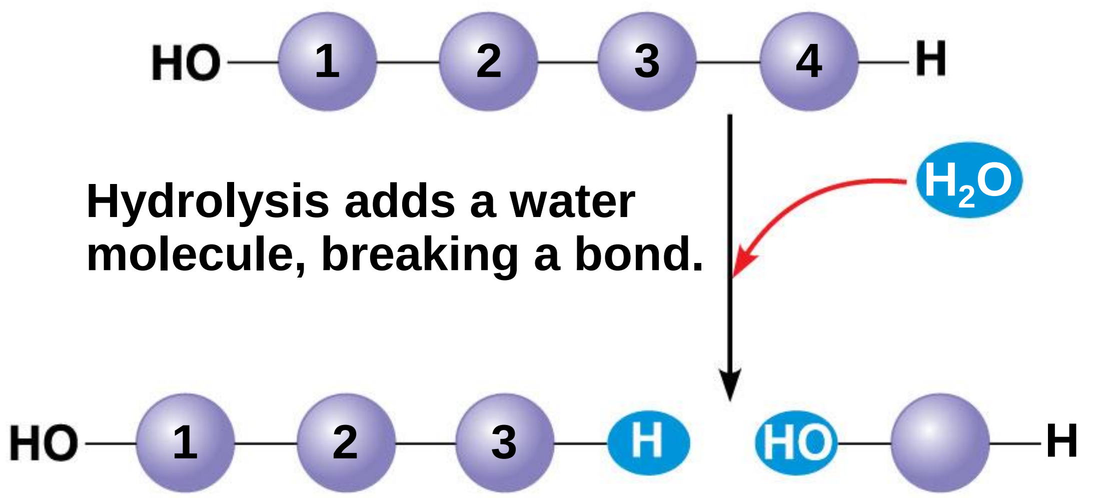
- **Enzymes** are specialized macromolecules that speed up chemical reactions such as those that make or break down polymers
- A **dehydration reaction** occurs when two monomers bond together through the loss of a water molecule
- Polymers are disassembled to monomers by **hydrolysis**, a reaction that is essentially the reverse of the dehydration reaction

Figure 5.2

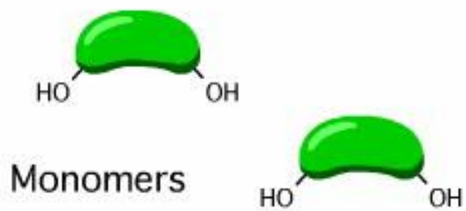
## (a) Dehydration reaction: synthesizing a polymer




## (b) Hydrolysis: breaking down a polymer



# Animation: Polymers



# The Diversity of Polymers

- A cell has thousands of different macromolecules
- Macromolecules vary among cells of an organism, vary more within a species, and vary even more between species
- A huge 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 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 location of the carbonyl group (as aldose or ketose)
  - The number of carbons in the carbon skeleton

Figure 5.3

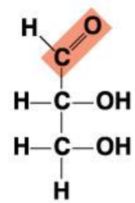
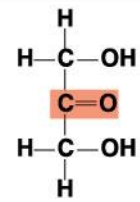
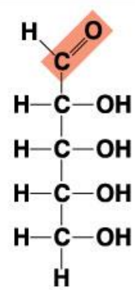
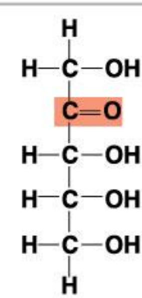
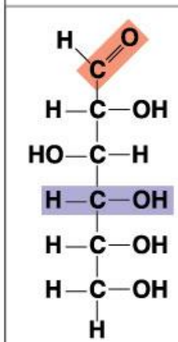
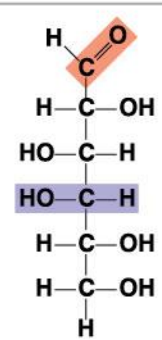
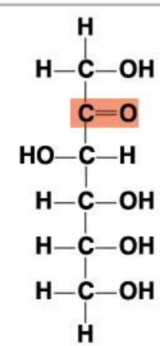
| Aldoses (Aldehyde Sugars) | Ketoses (Ketone Sugars) |
|---|---|
| **Trioses: three-carbon sugars ($C_3H_6O_3$)** | |
|  Glyceraldehyde |  Dihydroxyacetone |
| **Pentoses: five-carbon sugars ($C_5H_{10}O_5$)** | |
|  Ribose |  Ribulose |
| **Hexoses: six-carbon sugars ($C_6H_{12}O_6$)** | |
|  Glucose  Galactose |  Fructose |

Figure 5.3a

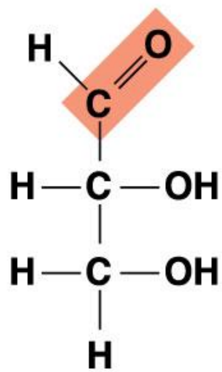
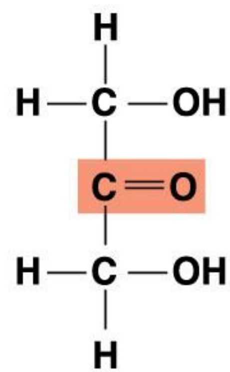
| Aldose (Aldehyde Sugar) | Ketose (Ketone Sugar) |
| --- | --- |
| Trioses: three-carbon sugars ($C_3H_6O_3$) | |
|  |  |
| Glyceraldehyde | Dihydroxyacetone |

Figure 5.3b

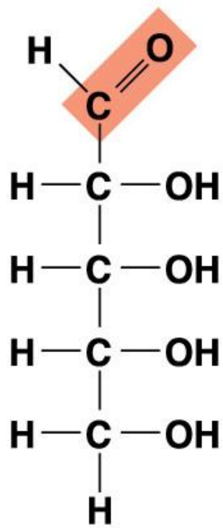
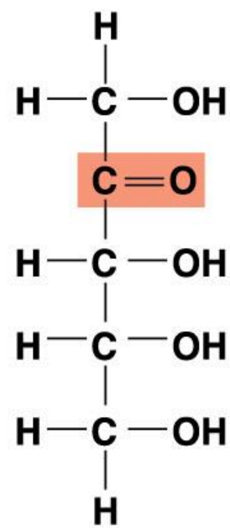
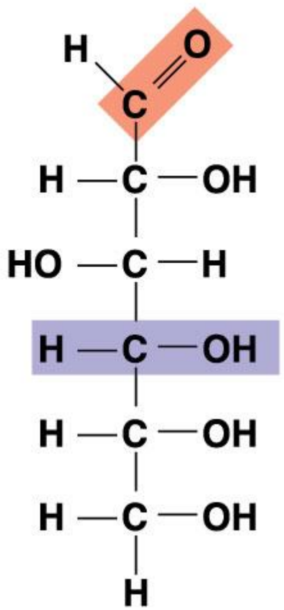
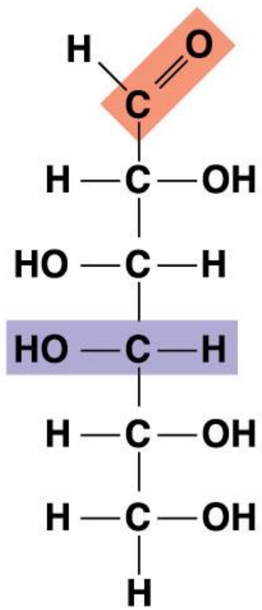
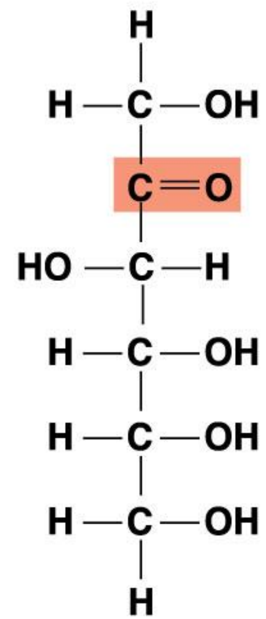
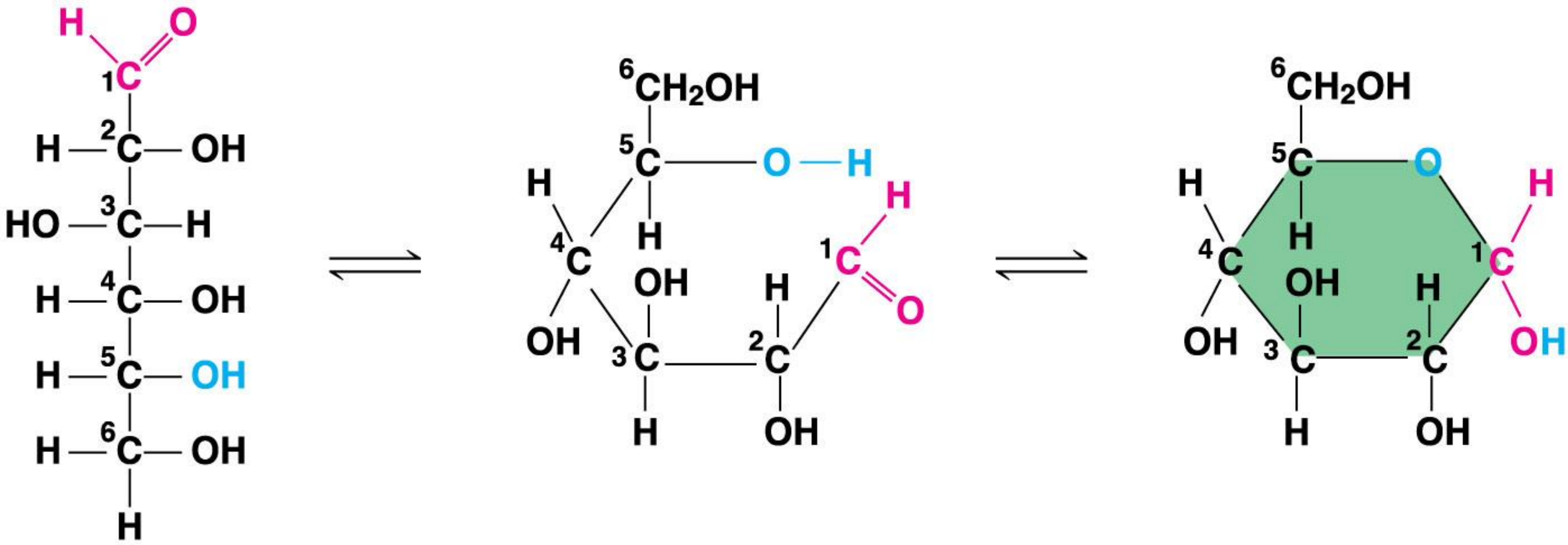
| Aldose (Aldehyde Sugar) | Ketose (Ketone Sugar) |
|---|---|
| Pentoses: five-carbon sugars ($C_5H_{10}O_5$) | |
|  |  |
| Ribose | Ribulose |

Figure 5.3c

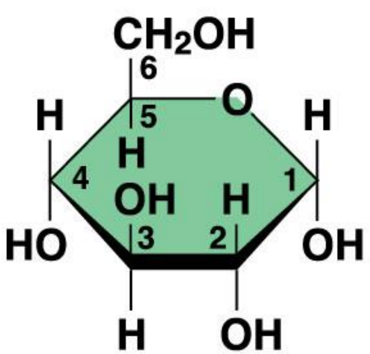
| Aldose (Aldehyde Sugar) | Ketose (Ketone Sugar) |
| --- | --- |
| Hexoses: six-carbon sugars ($C_6H_{12}O_6$) | |
|  Glucose  Galactose |  Fructose |

- 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

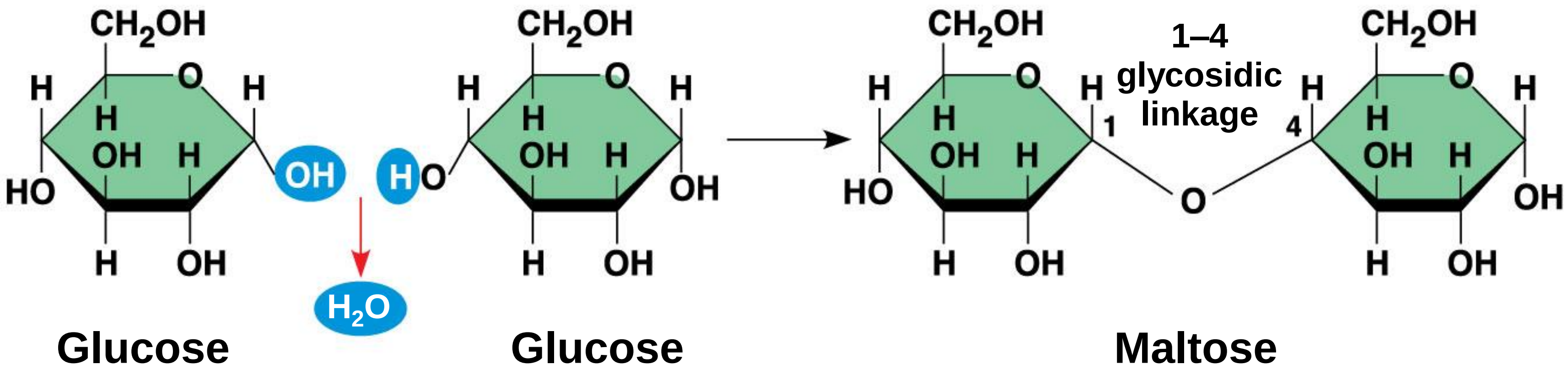


(b) Abbreviated ring structure

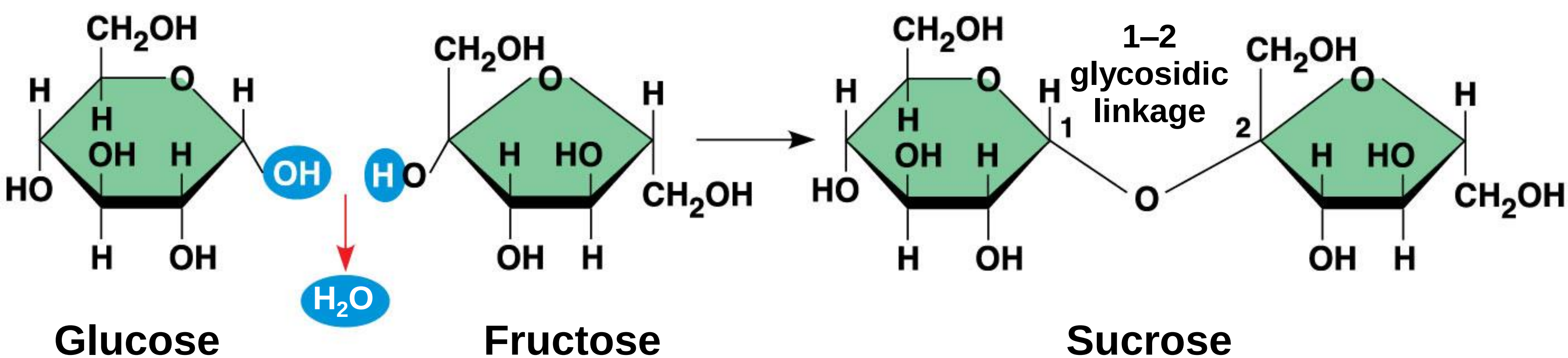
- A **disaccharide** is formed when a dehydration reaction joins two monosaccharides
- This covalent bond is called a **glycosidic linkage**

Figure 5.5

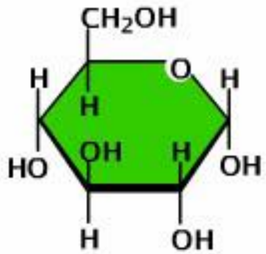
## (a) Dehydration reaction in the synthesis of maltose



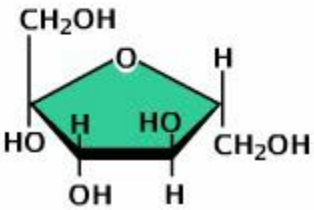

## (b) Dehydration reaction in the synthesis of sucrose



# Animation: Disaccharides



Glucose



Fructose

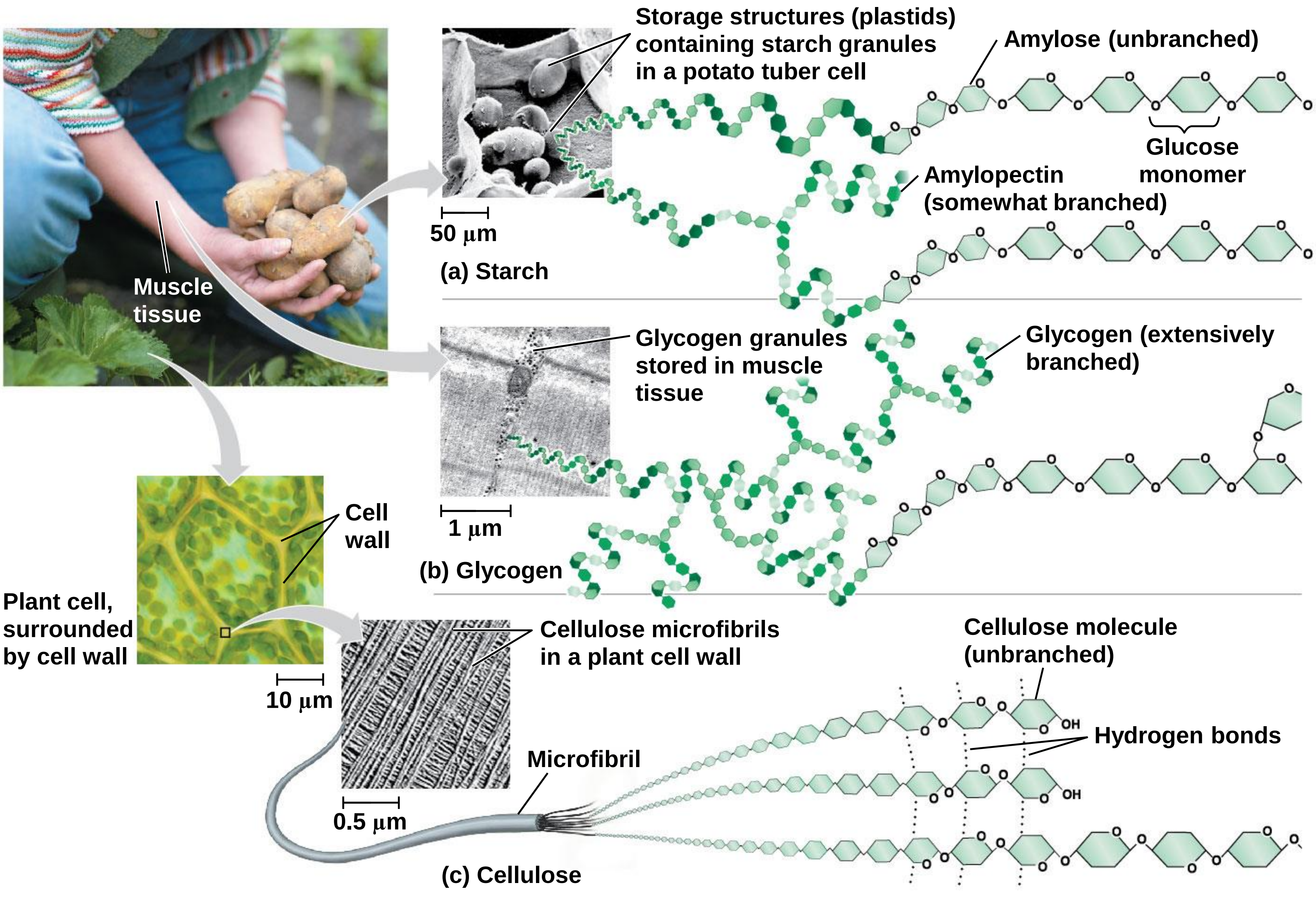
# Polysaccharides

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

# *Storage Polysaccharides*

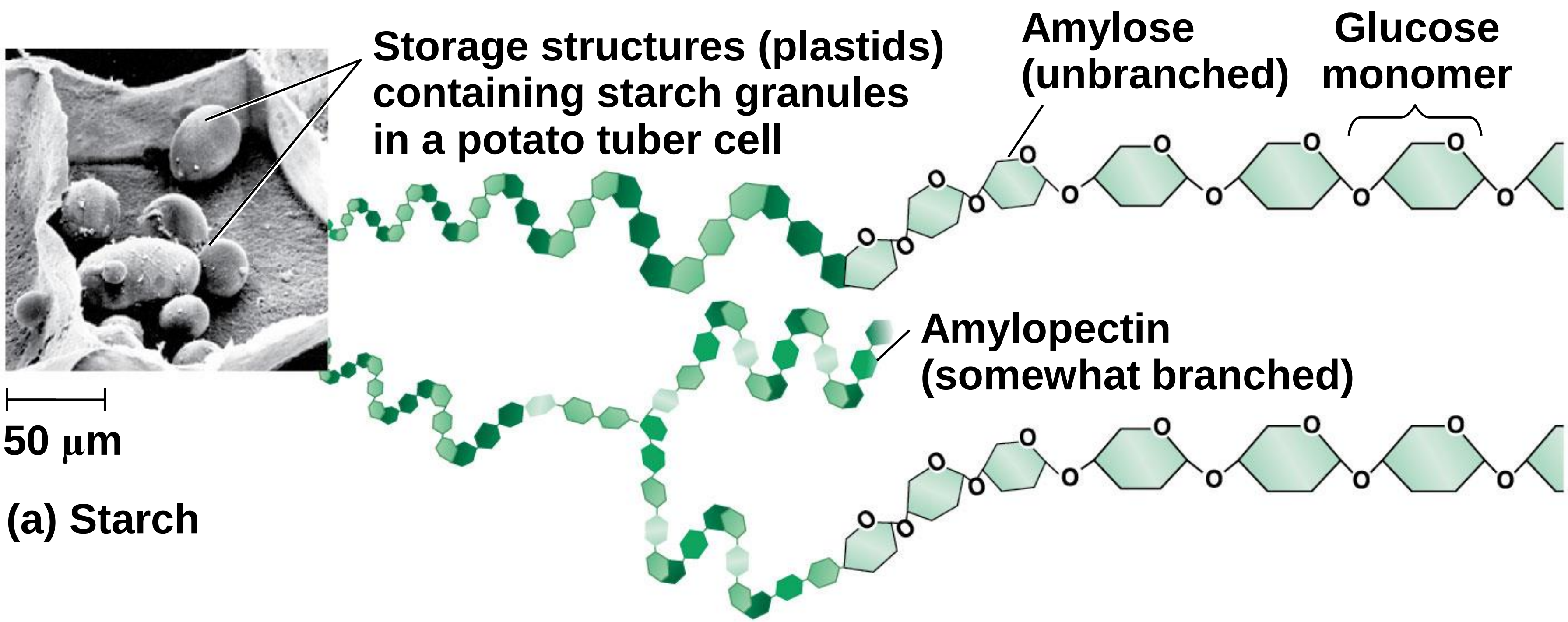
- **Starch**, a storage polysaccharide of plants, consists of glucose monomers
- Plants store surplus starch as granules within chloroplasts and other plastids
- The simplest form of starch is amylose

Figure 5.6



Storage structures (plastids) containing starch granules in a potato tuber cell
Amylose (unbranched)
Glucose monomer
Amylopectin (somewhat branched)
50 µm
(a) Starch
Muscle tissue
Glycogen granules stored 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)
Hydrogen bonds
Microfibril
0.5 µm
(c) Cellulose

Figure 5.6a




(a) Starch

Figure 5.6aa

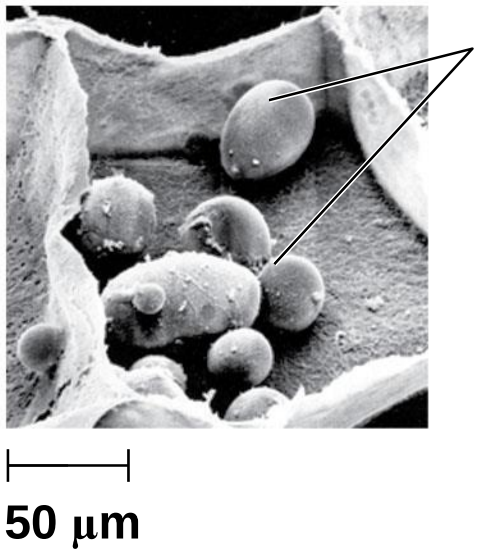
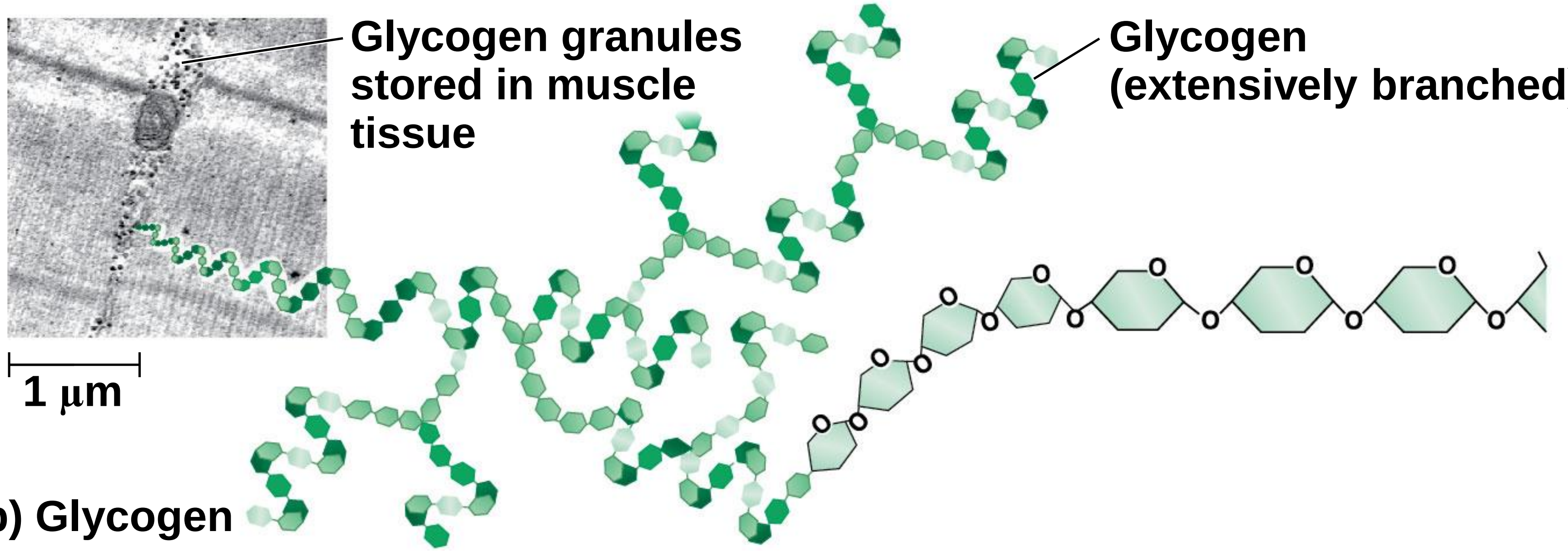

Storage structures (plastids)
containing starch granules
in a potato tuber cell
50 μm

Figure 5.6b




(b) Glycogen

Figure 5.6ba

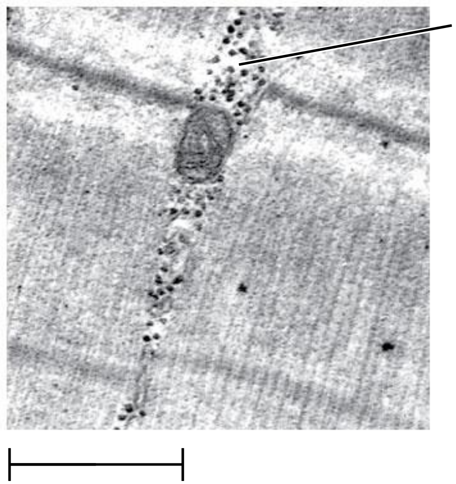
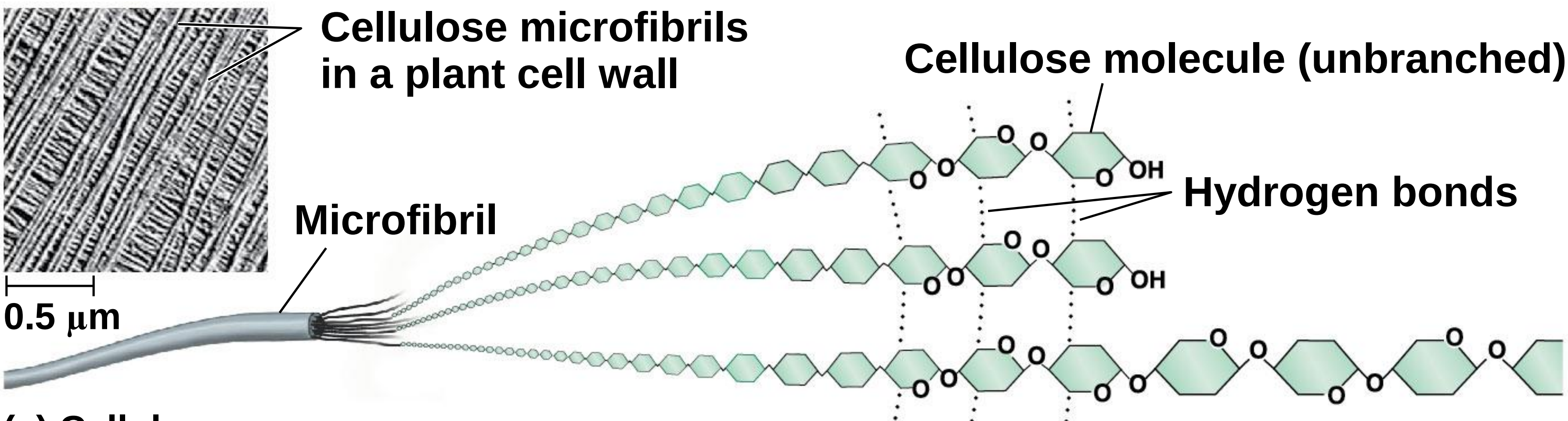


Figure 5.6c




(c) Cellulose

Figure 5.6ca

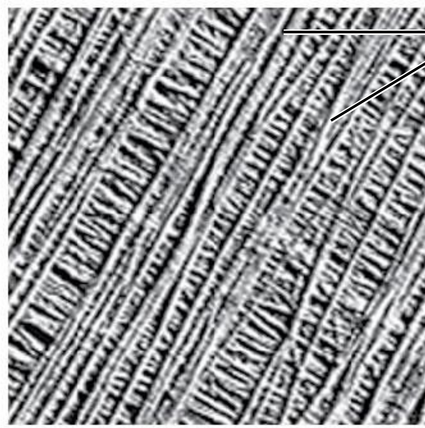
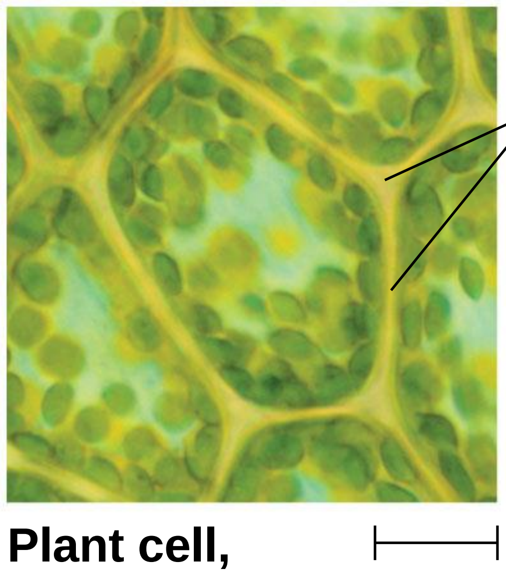
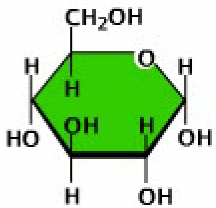


Figure 5.6d




Plant cell, surrounded by cell wall

# Animation: Polysaccharides

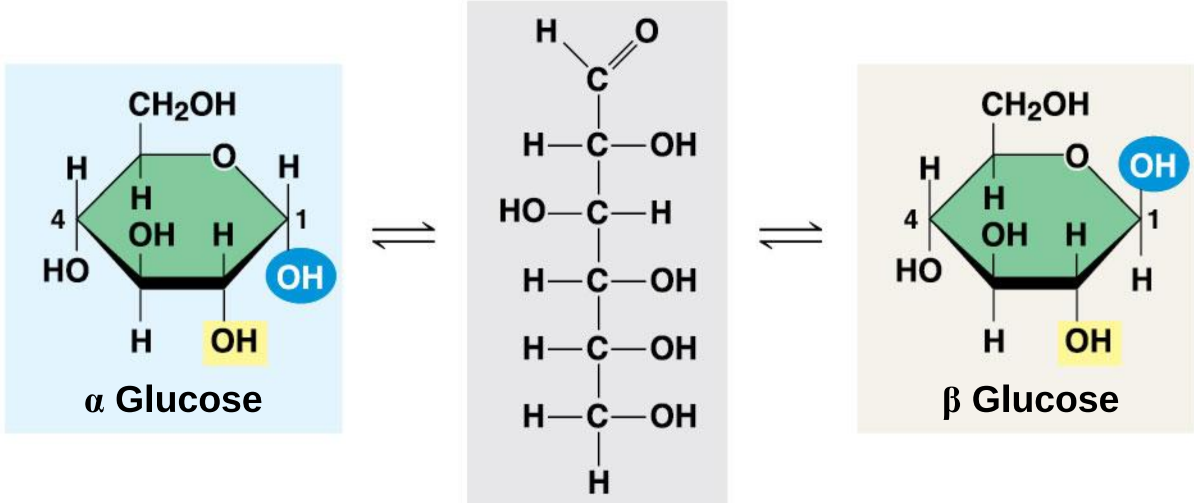


- **Glycogen** is a storage polysaccharide in animals
- Glycogen is stored mainly in liver and muscle cells
- Hydrolysis of glycogen in these cells releases glucose when the demand for sugar increases

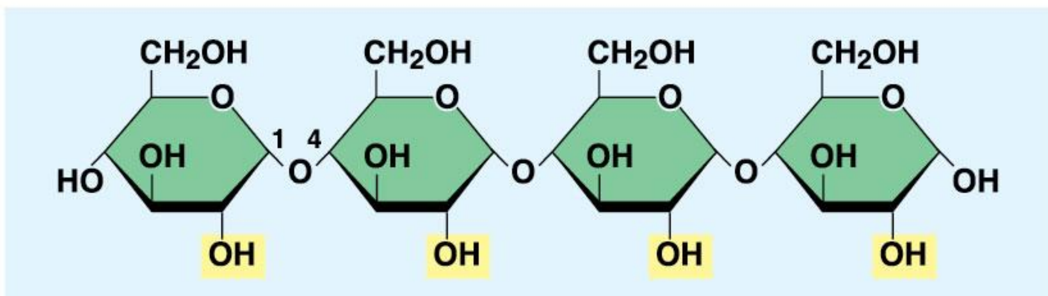
# *Structural Polysaccharides*

- 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 ($\beta$)

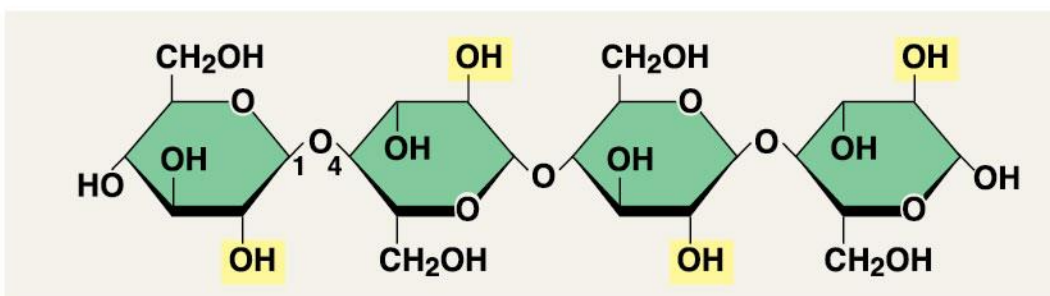
Figure 5.7




(a) α and β glucose ring structures

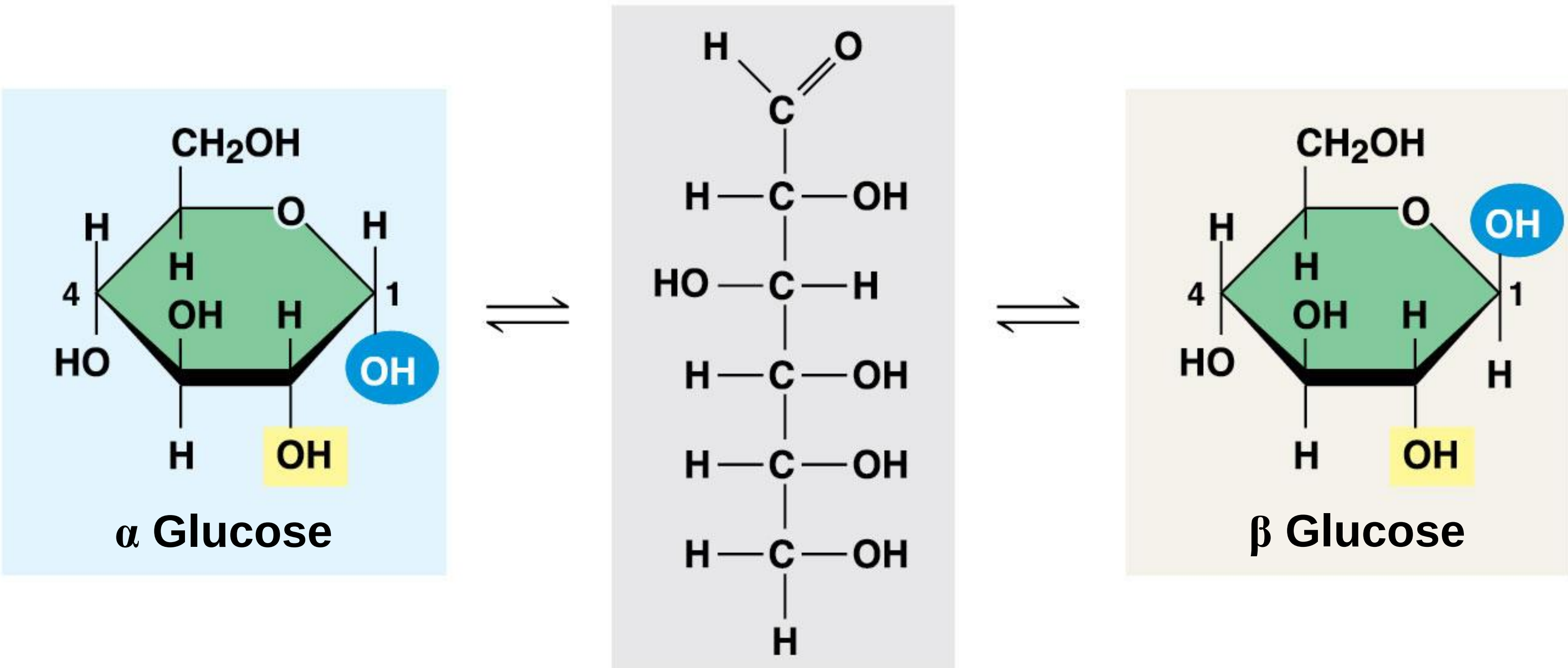


(b) Starch: 1–4 linkage of α glucose monomers

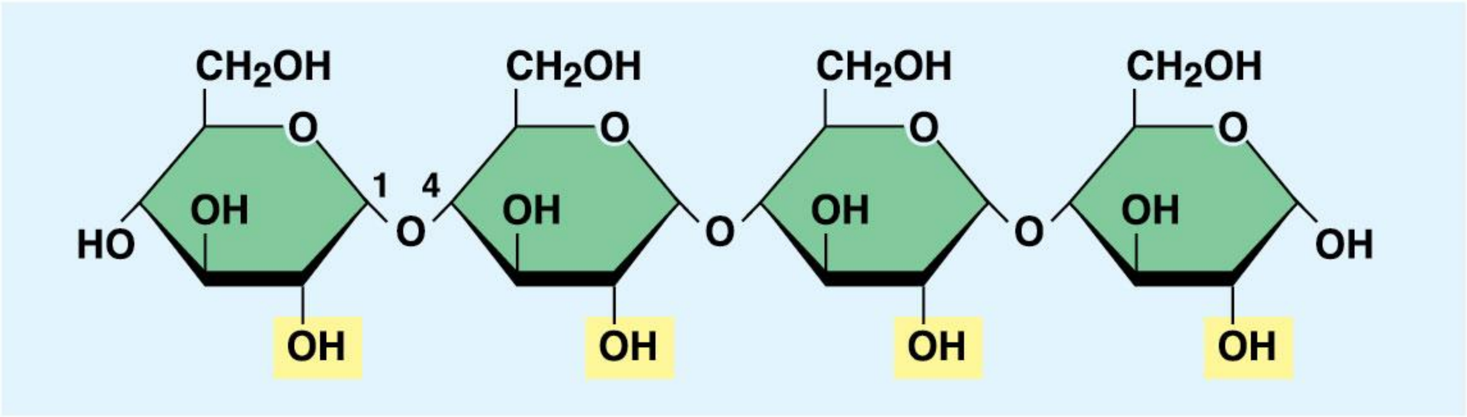


(c) Cellulose: 1–4 linkage of β glucose monomers

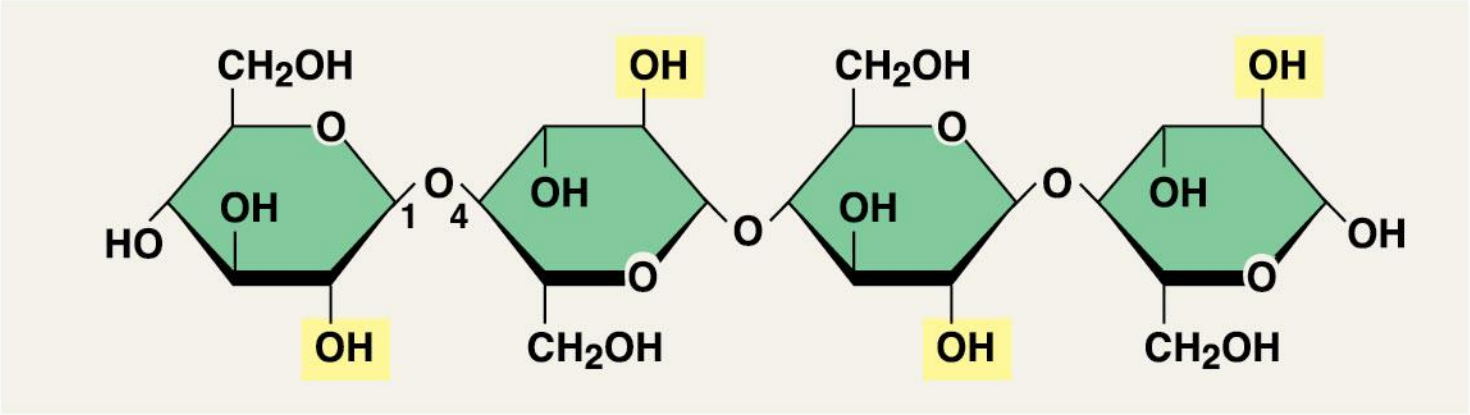
Figure 5.7a




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




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



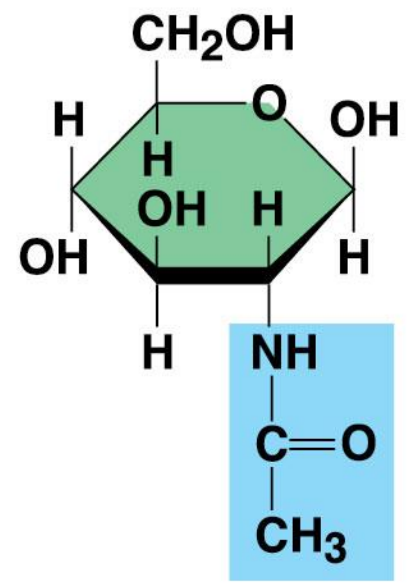

**(c) Cellulose: 1–4 linkage of β glucose monomers**

- Starch (α configuration) is largely helical
- Cellulose molecules (β configuration) are straight and unbranched
- Some hydroxyl groups on the monomers of cellulose can hydrogen-bond with hydroxyls of parallel cellulose molecules

- Enzymes that digest starch by hydrolyzing α linkages can’t hydrolyze β linkages in cellulose
- The 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 5.8




The structure of the chitin monomer

Chitin, embedded in proteins, forms the exoskeleton of arthropods.

Figure 5.8a

**Chitin, embedded in proteins, forms the exoskeleton of arthropods.**

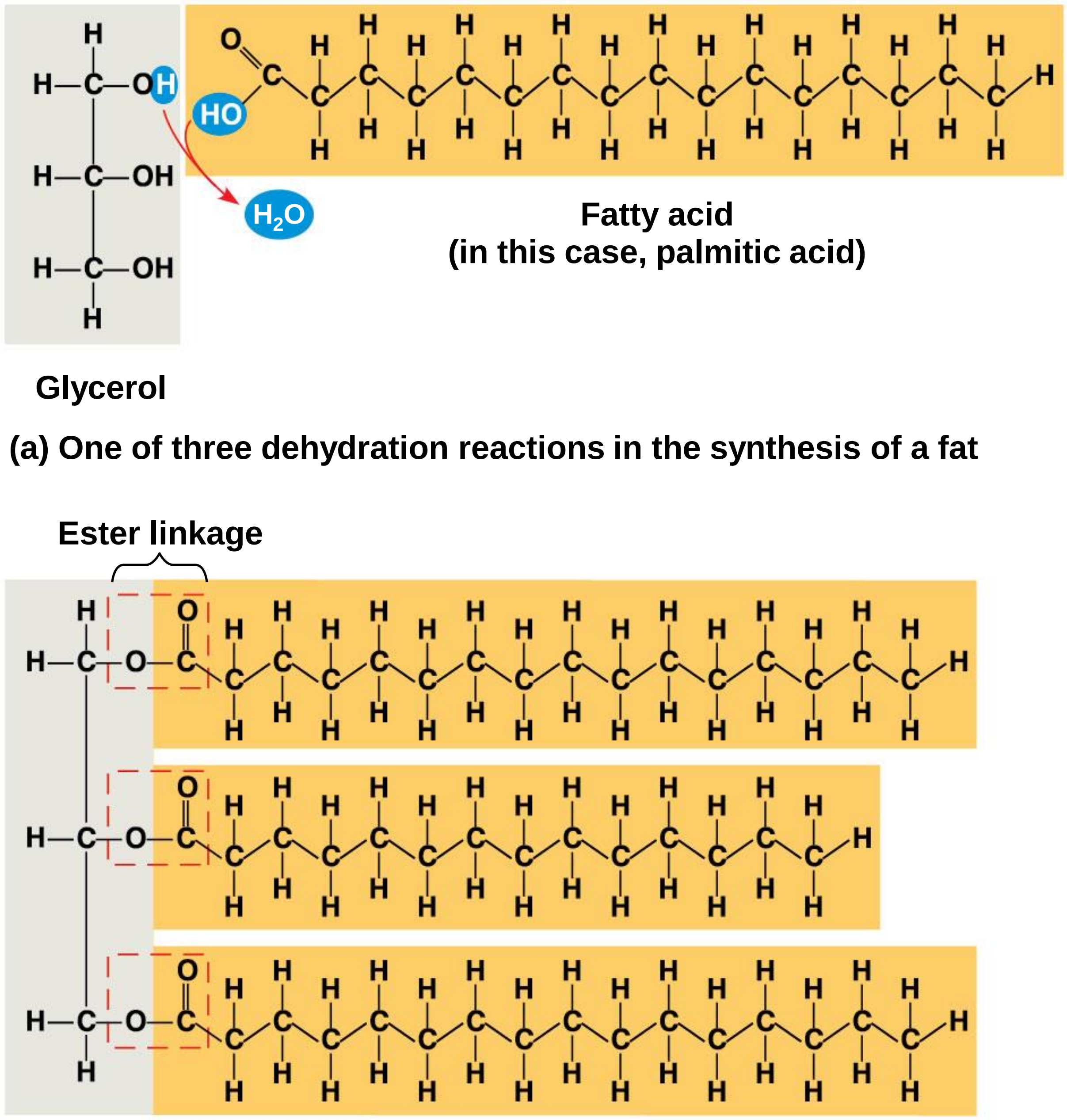
# Concept 5.3: Lipids are a diverse group of hydrophobic molecules

- **Lipids** are the one class of large biological molecules that does not include true polymers
- The unifying feature of lipids is that they mix poorly, if at all, with water
- Lipids consist mostly of hydrocarbon regions
- 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

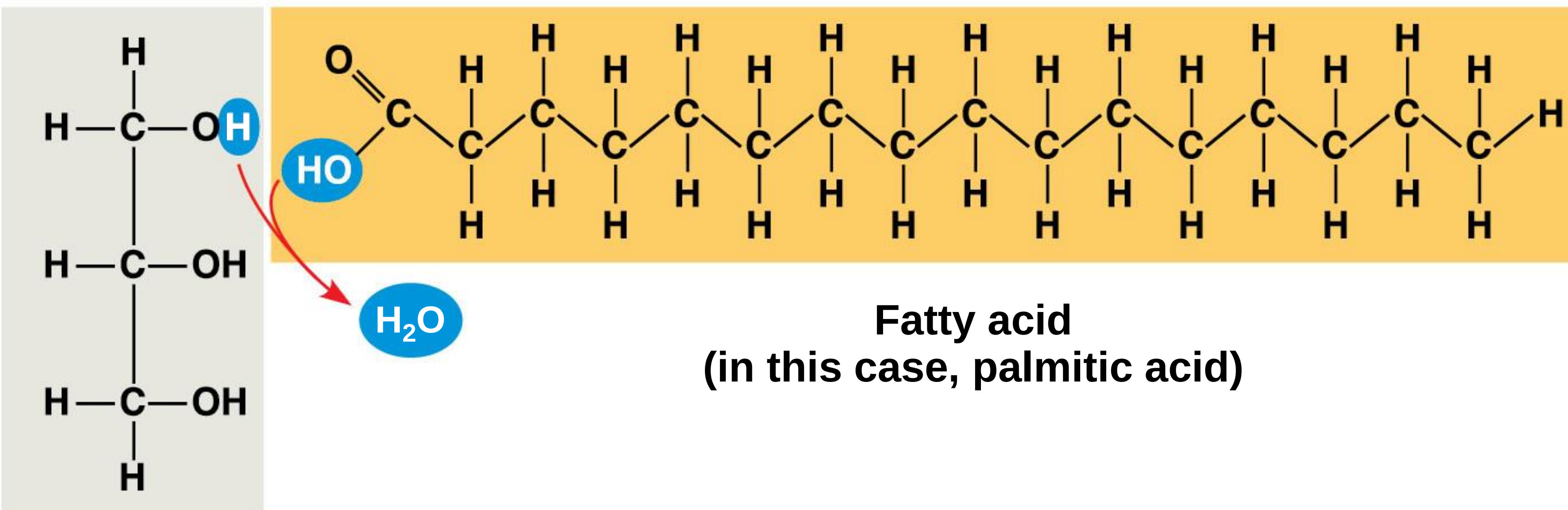
Figure 5.9




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

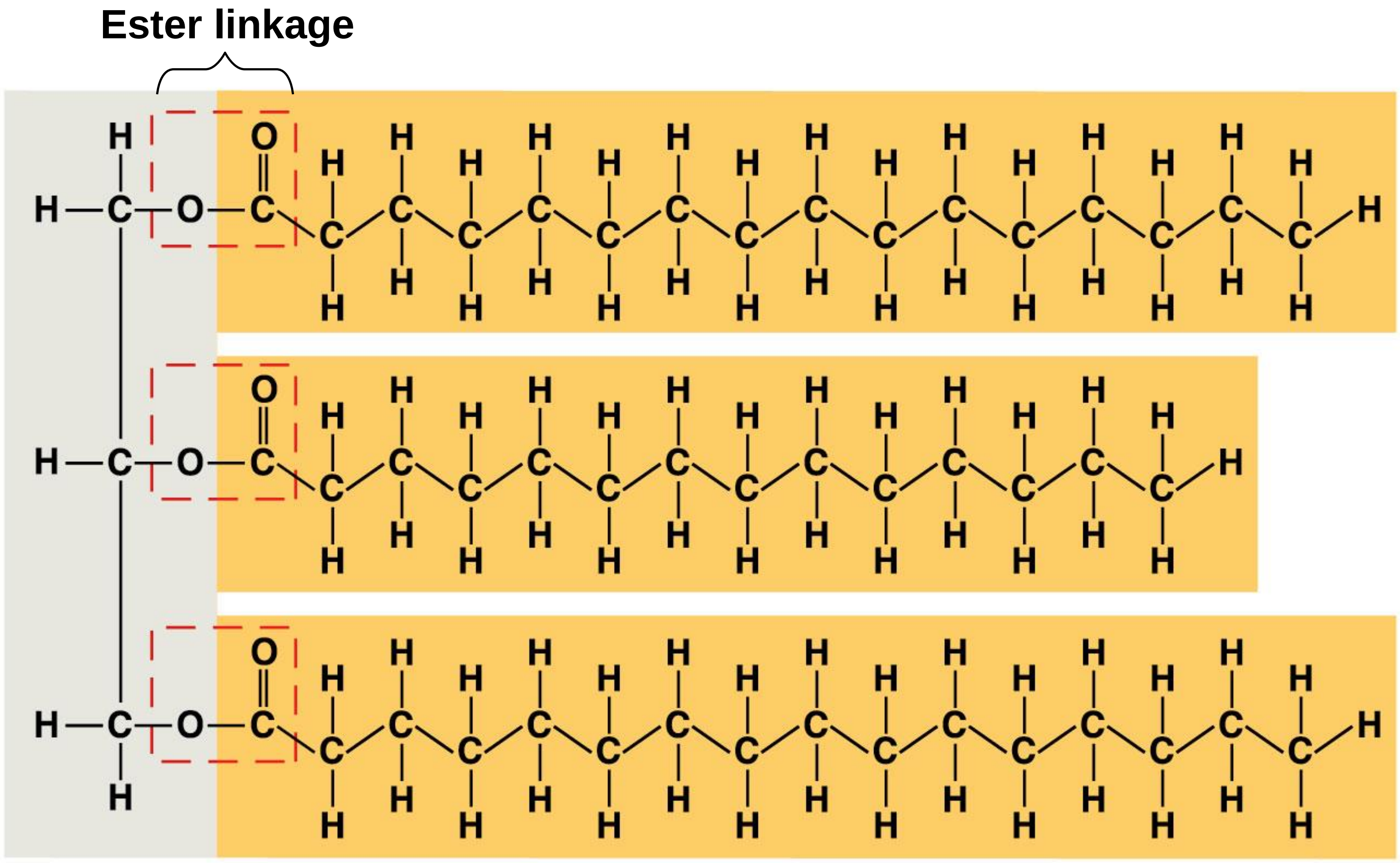
**(b) Fat molecule (triacylglycerol)**

Figure 5.9a



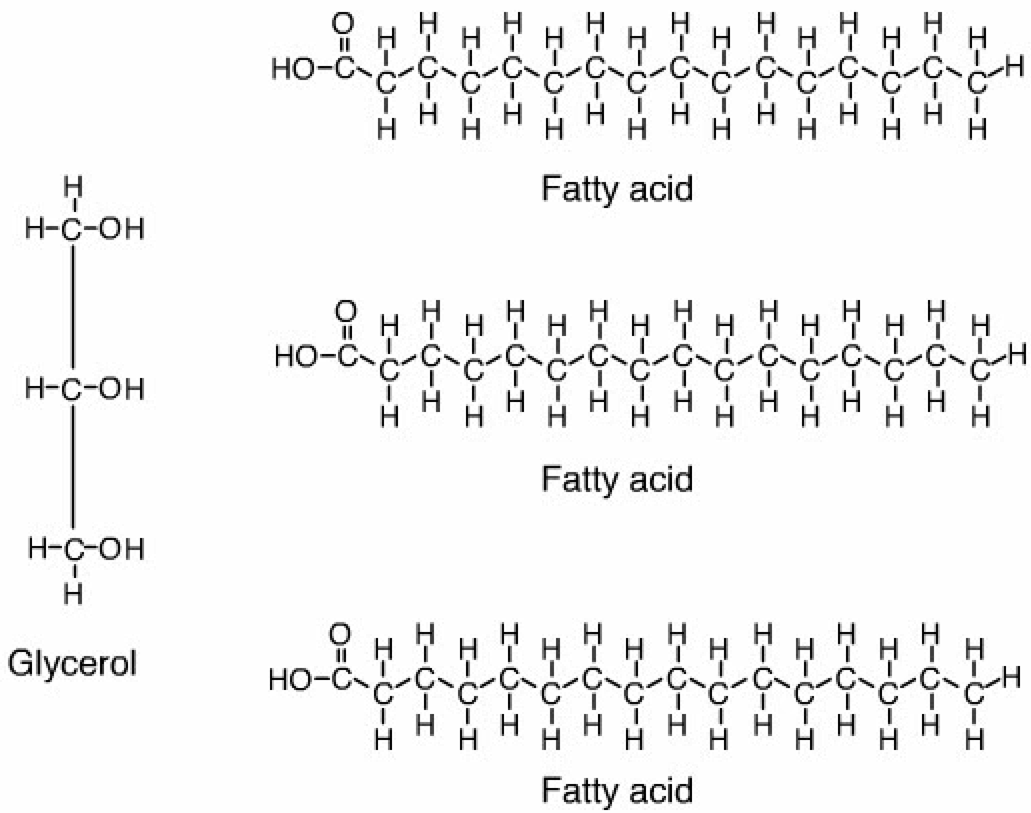

Glycerol

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




(b) Fat molecule (triacylglycerol)

# Animation: Fats

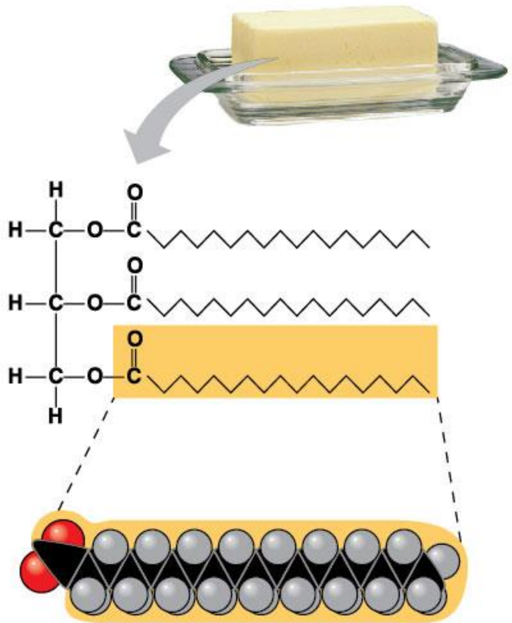


- Fats separate from water because water molecules hydrogen-bond to each other and exclude the fats
- In a fat, three fatty acids are joined to glycerol by an ester linkage, creating a **triacylglycerol**, or triglyceride
- The fatty acids in a fat can be all the same or of two or three different kinds

- 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 5.10

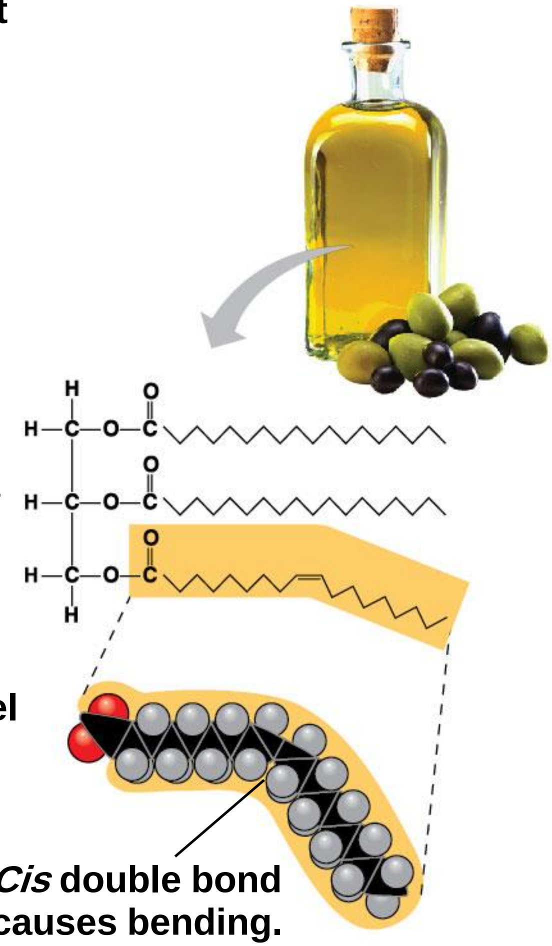
**(a) Saturated fat**



**Structural formula of a saturated fat molecule**

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

**(b) Unsaturated fat**

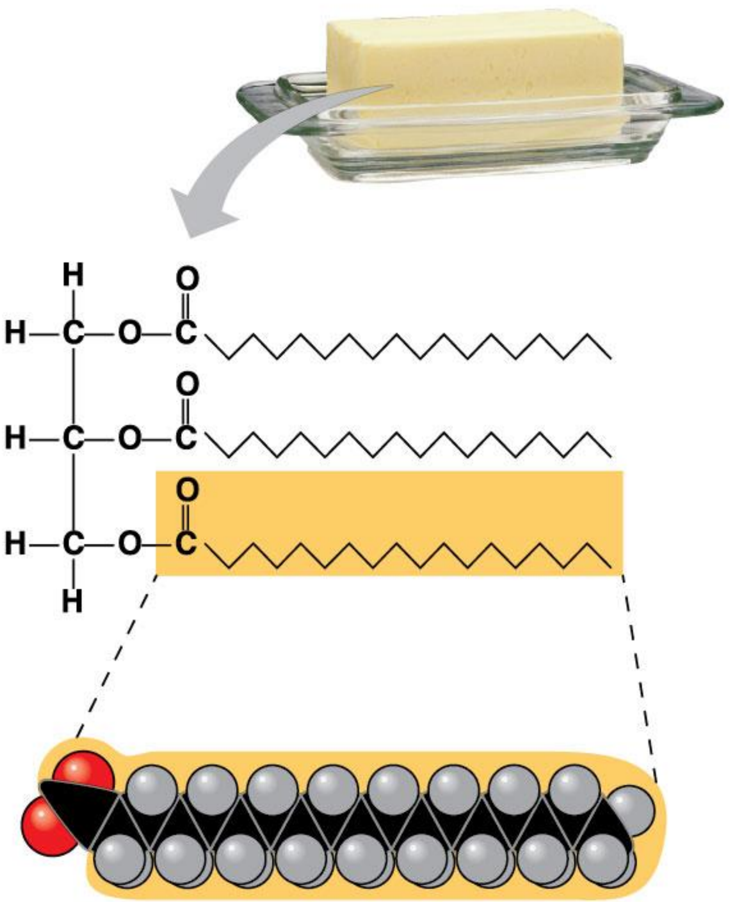



**Structural formula of an unsaturated fat molecule**

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

Figure 5.10a

## (a) Saturated fat




**Structural formula of a saturated fat molecule**

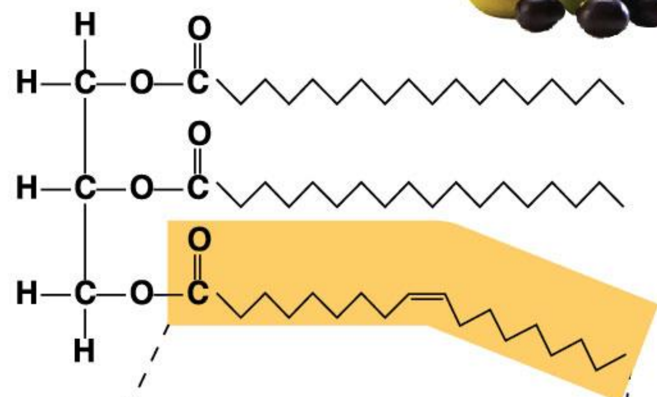
**Space-filling model of stearic acid, a saturated fatty acid**

Figure 5.10aa

Figure 5.10b

# (b) Unsaturated fat

Structural formula of an unsaturated fat molecule



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

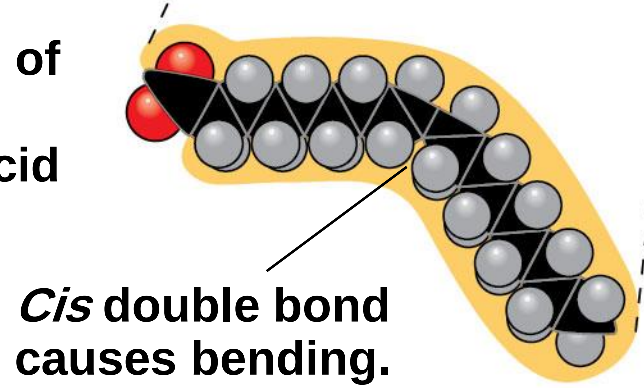


Figure 5.10ba

- 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

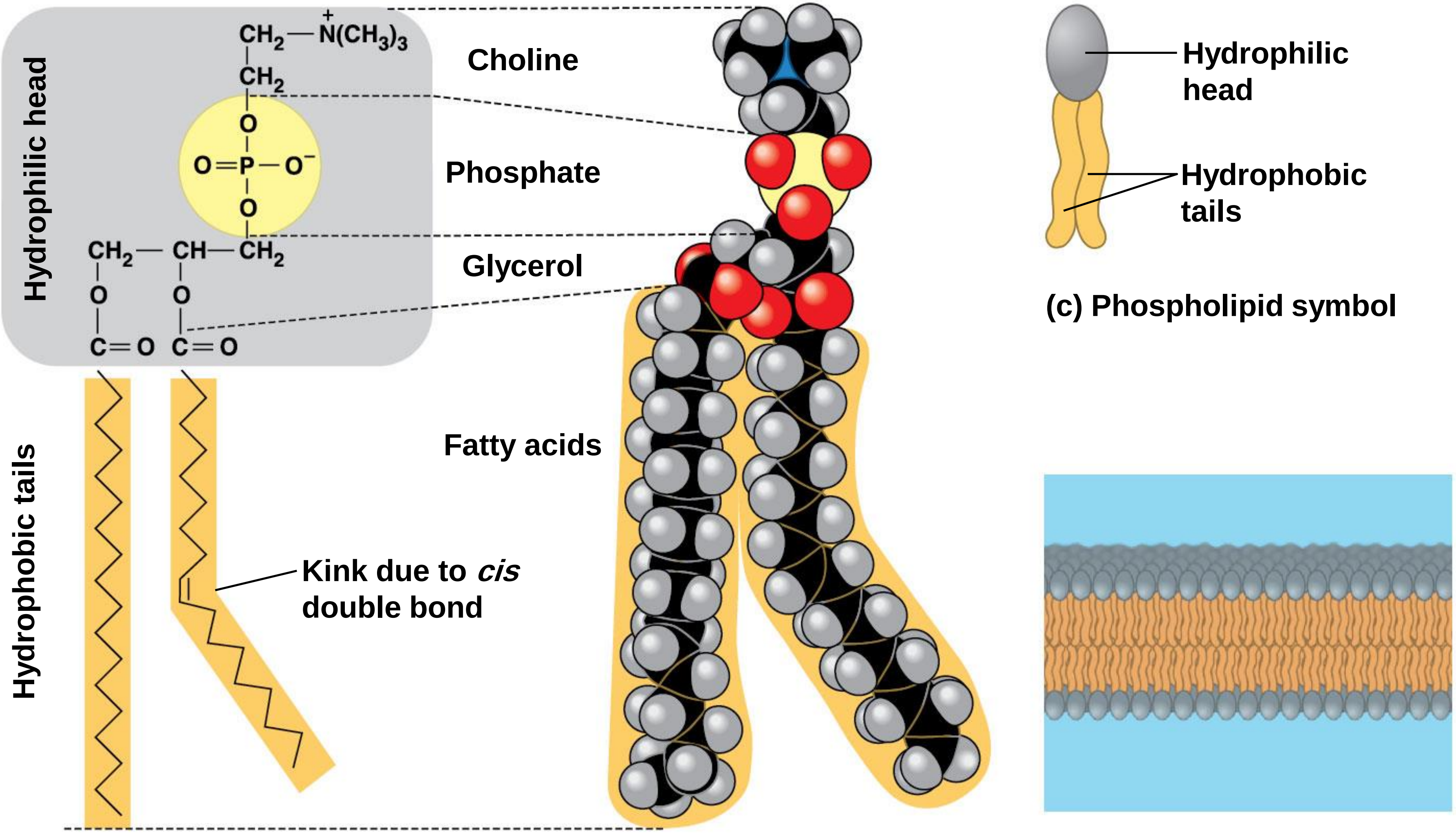
- A diet rich in saturated fats may contribute to cardiovascular disease through plaque deposits
- Hydrogenation is the process of converting unsaturated fats to saturated fats by adding hydrogen
- Hydrogenating vegetable oils also creates unsaturated fats with *trans* double bonds
- These ***trans***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

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

# Phospholipids

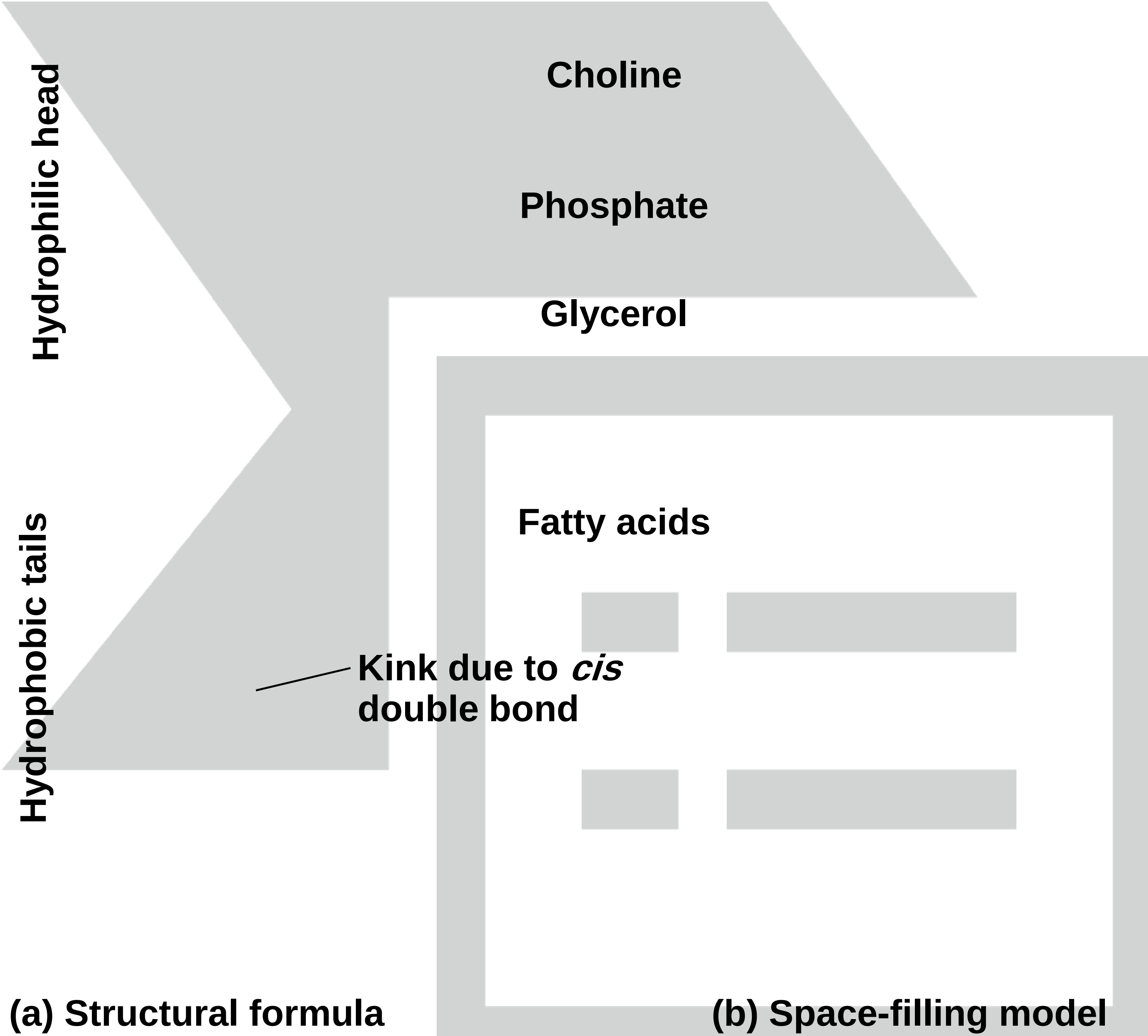
- In a **phospholipid**, two fatty acids and a phosphate group are attached to glycerol
- The two fatty acid tails are hydrophobic, but the phosphate group and its attachments form a hydrophilic head

Figure 5.11




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

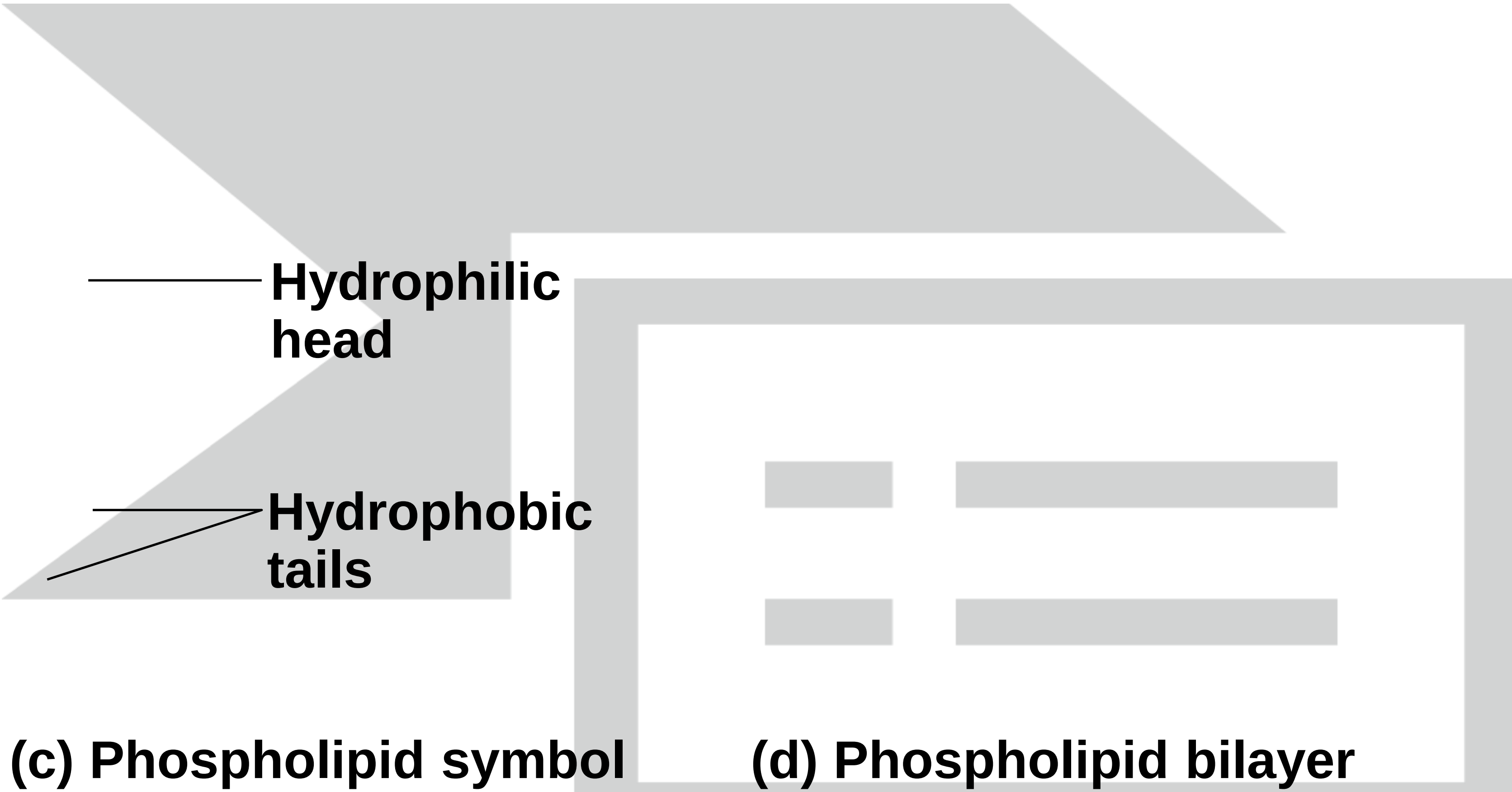
Figure 5.11a




(a) Structural formula

(b) Space-filling model

Figure 5.11b




(c) Phospholipid symbol

(d) Phospholipid bilayer

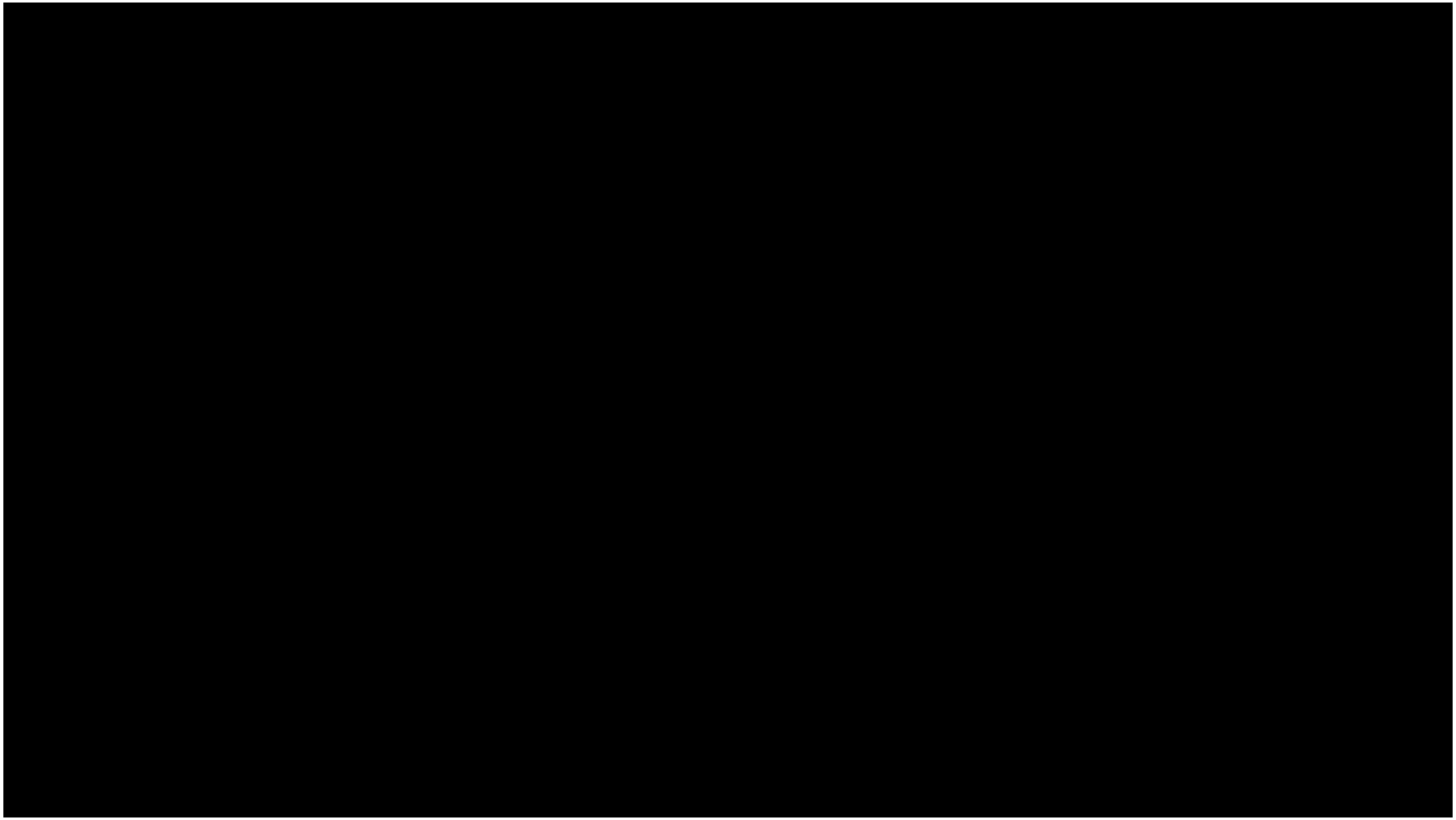
- When phospholipids are added to water, they self-assemble into double-layered sheets called bilayers
- At the surface of a cell, phospholipids are also arranged in a bilayer, with the hydrophobic tails pointing toward the interior
- The phospholipid bilayer forms a boundary between the cell and its external environment

# Steroids

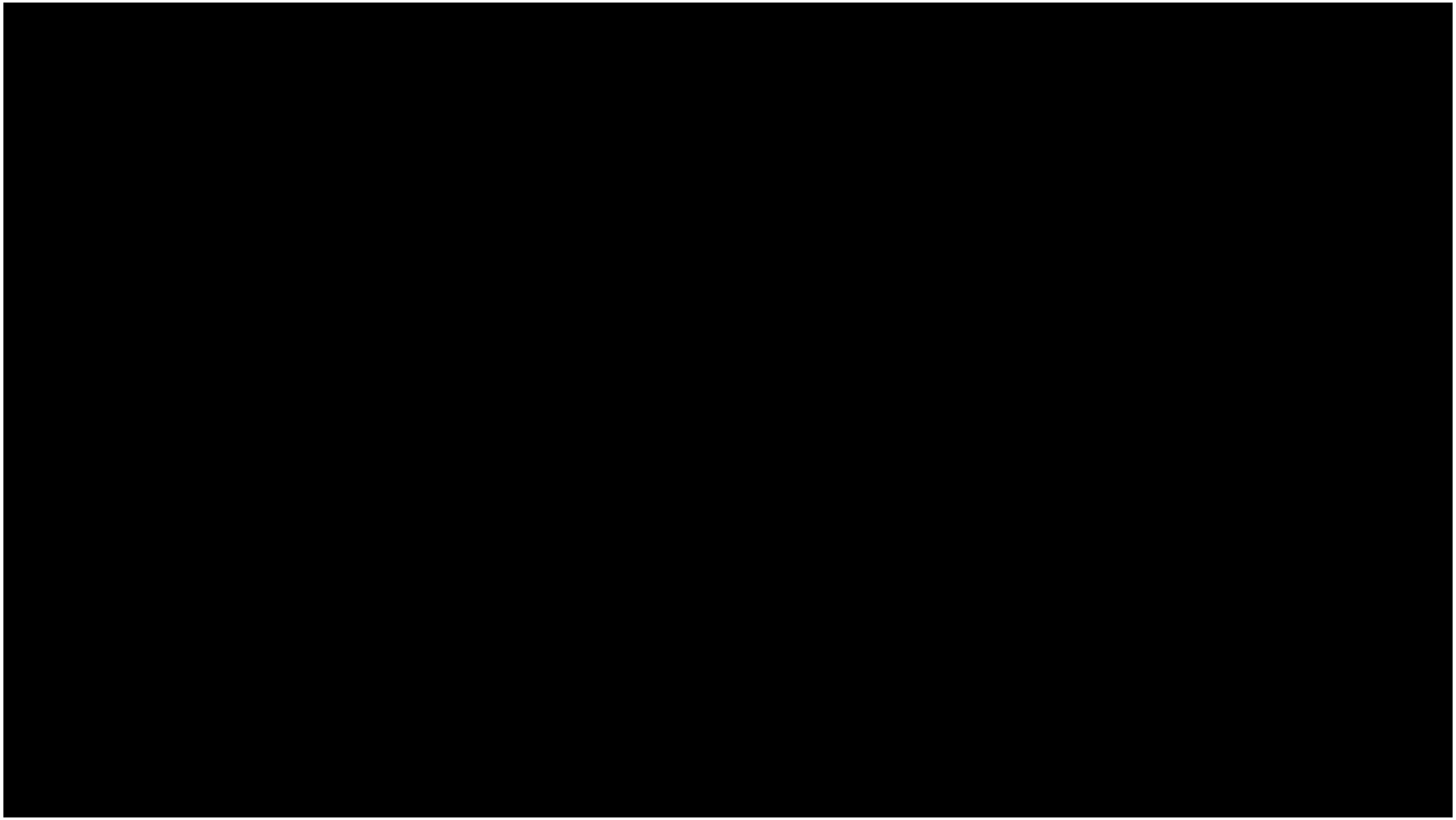
- **Steroids** are lipids characterized by a carbon skeleton consisting of four fused rings
- **Cholesterol**, a type of steroid, is a component in animal cell membranes and a precursor from which other steroids are synthesized
- A high level of cholesterol in the blood may contribute to cardiovascular disease

Figure 5.12

# Video: Space-filling Model of Cholesterol



# Video: Stick Model of Cholesterol



# 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
- Some proteins speed up chemical reactions
- Other protein functions include defense, storage, transport, cellular communication, movement, and structural support

Figure 5.13a

## 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.**

Antibodies
Virus
Bacterium
Transport protein
Ovalbumin
Amino acids for embryo
Cell membrane

## Enzymatic proteins

**Function: Selective acceleration of chemical reactions**

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

Figure 5.13ab

# Defensive proteins

**Function: Protection against disease**

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

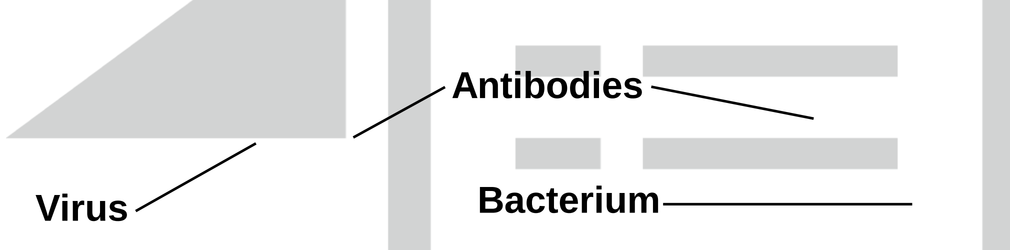


Figure 5.13ac

## 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.**

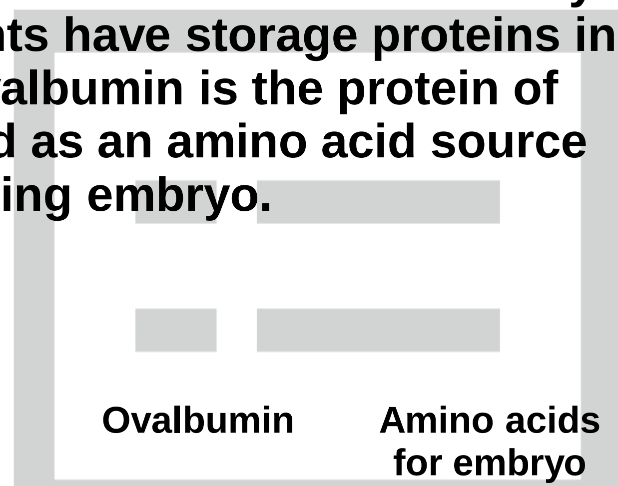


Figure 5.13aca

Figure 5.13ad

# 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.**

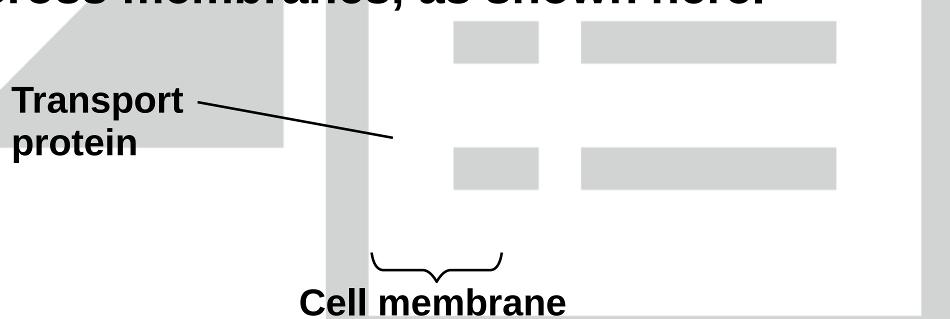


Figure 5.13b

## 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.**

High blood sugar

Insulin secreted

Normal blood sugar

## 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.**

Receptor protein

Signaling molecules

## 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.**

Actin

Myosin

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.**

Collagen

Connective tissue

60 μm

Figure 5.13ba

## 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.**

Figure 5.13bb

## 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.**

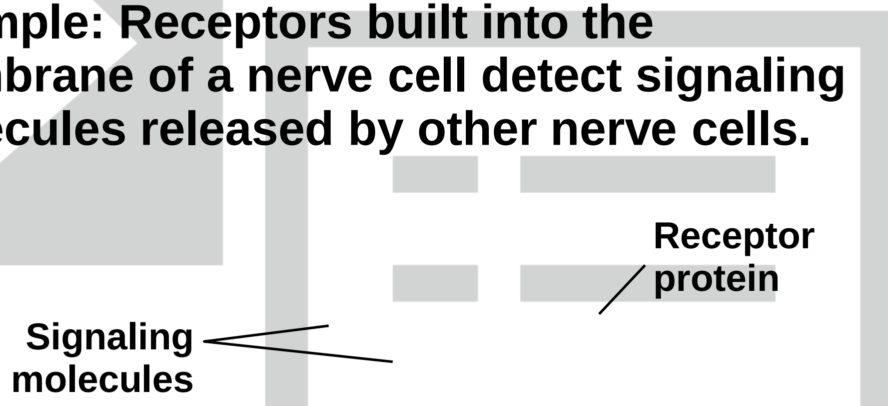
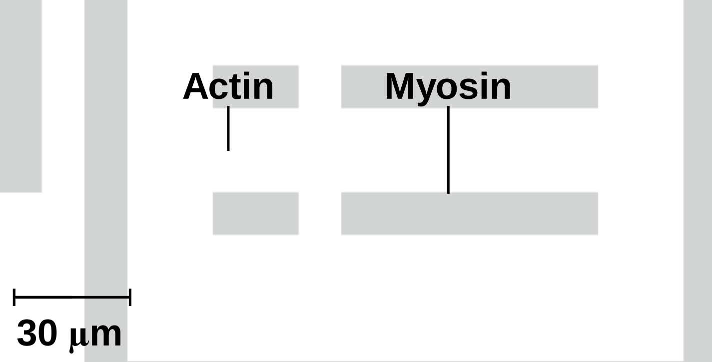


Figure 5.13bc

# 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.**




**Muscle tissue**

Figure 5.13bca

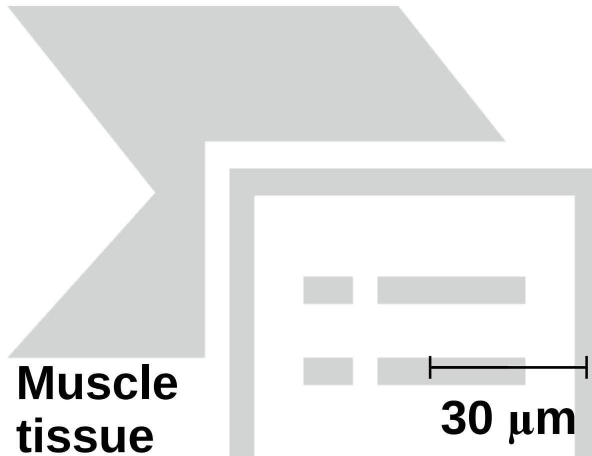


Figure 5.13bd

# Structural proteins

## Function: Support

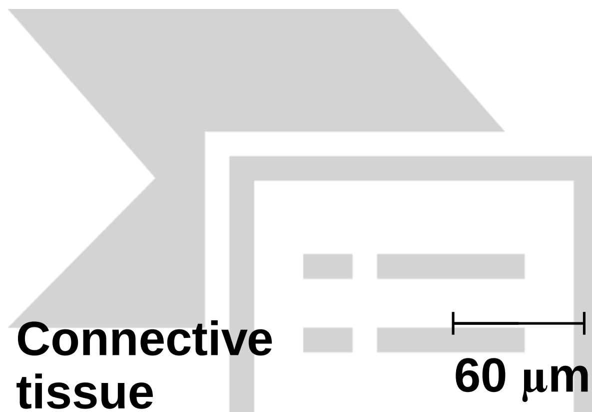
**Examples: Keratin is the protein of hair, horns, feathers, and other skin appendages. Insects and spiders use silk fibers to make their cocoons and webs, respectively. Collagen and elastin proteins provide a fibrous framework in animal connective tissues.**

Collagen

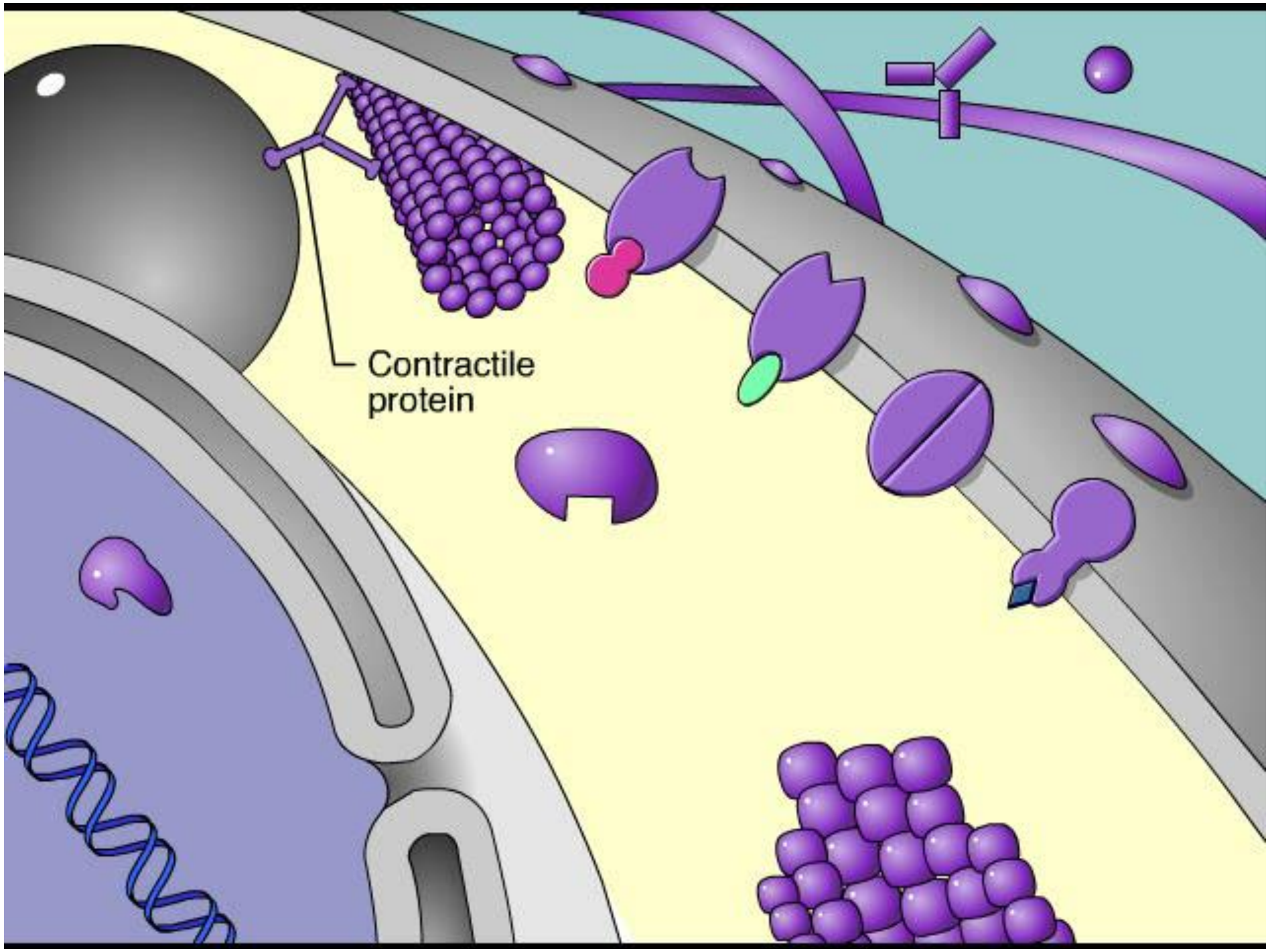
Connective tissue

60 µm

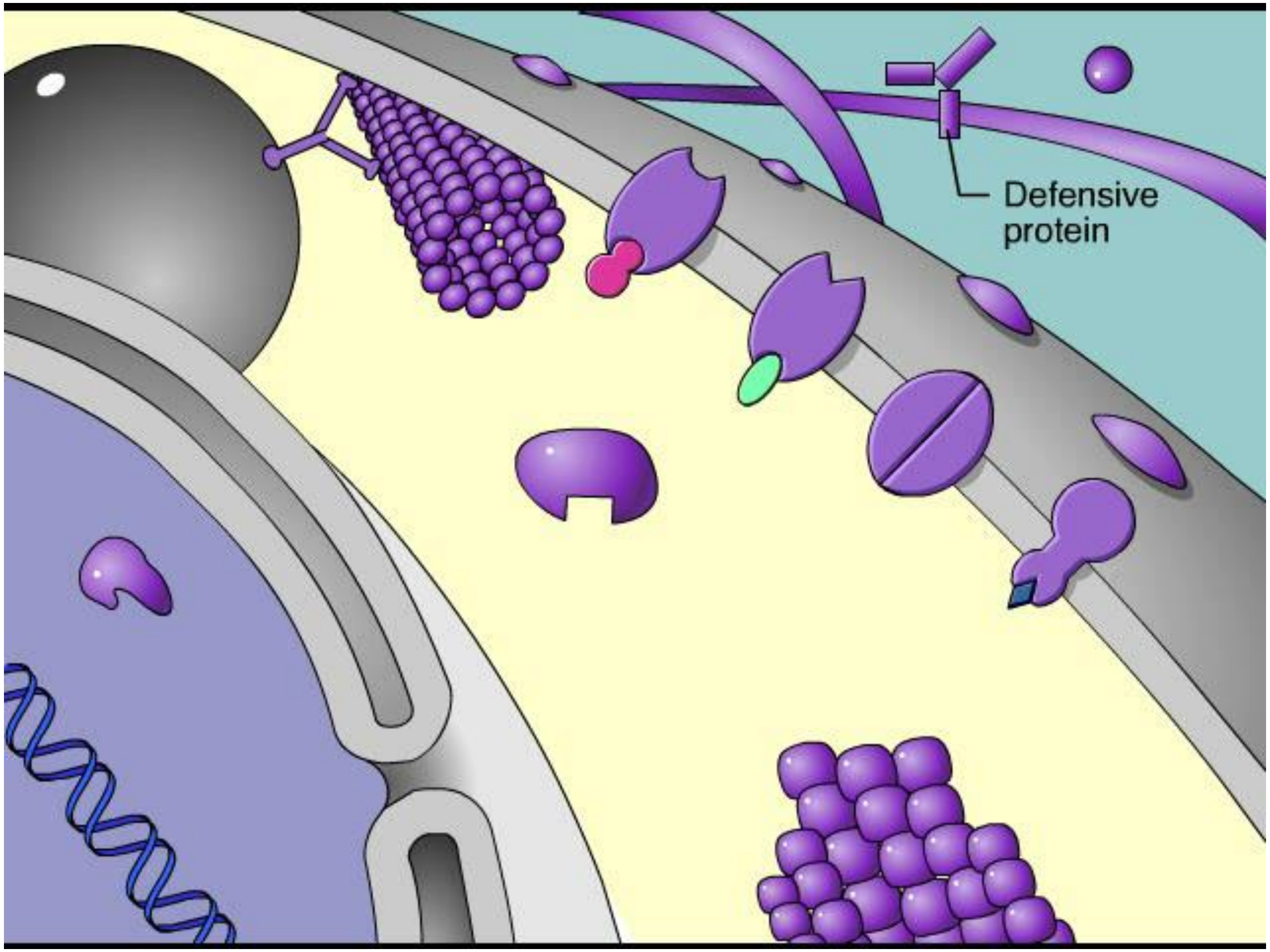
Figure 5.13bda



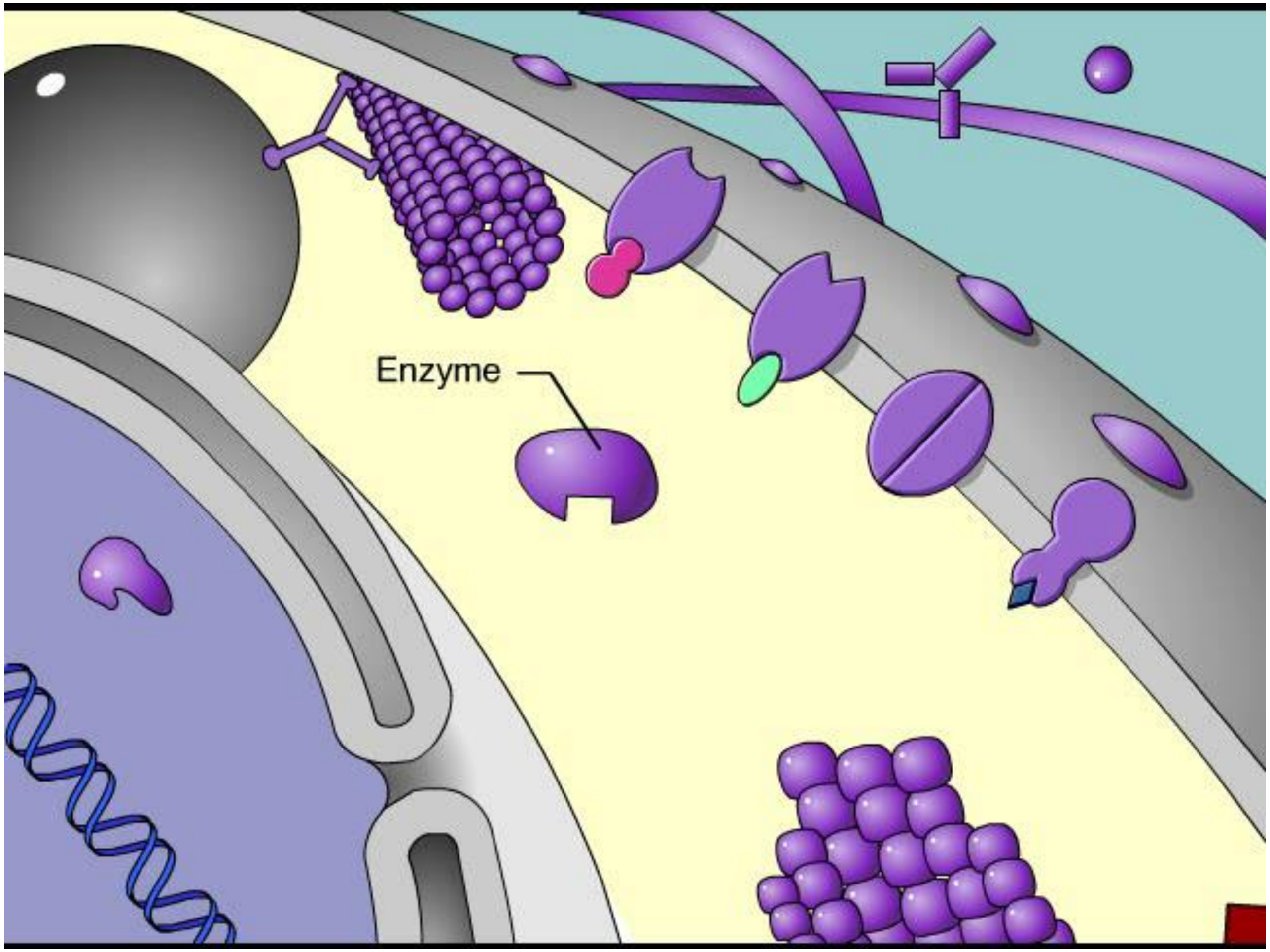
# Animation: Contractile Proteins



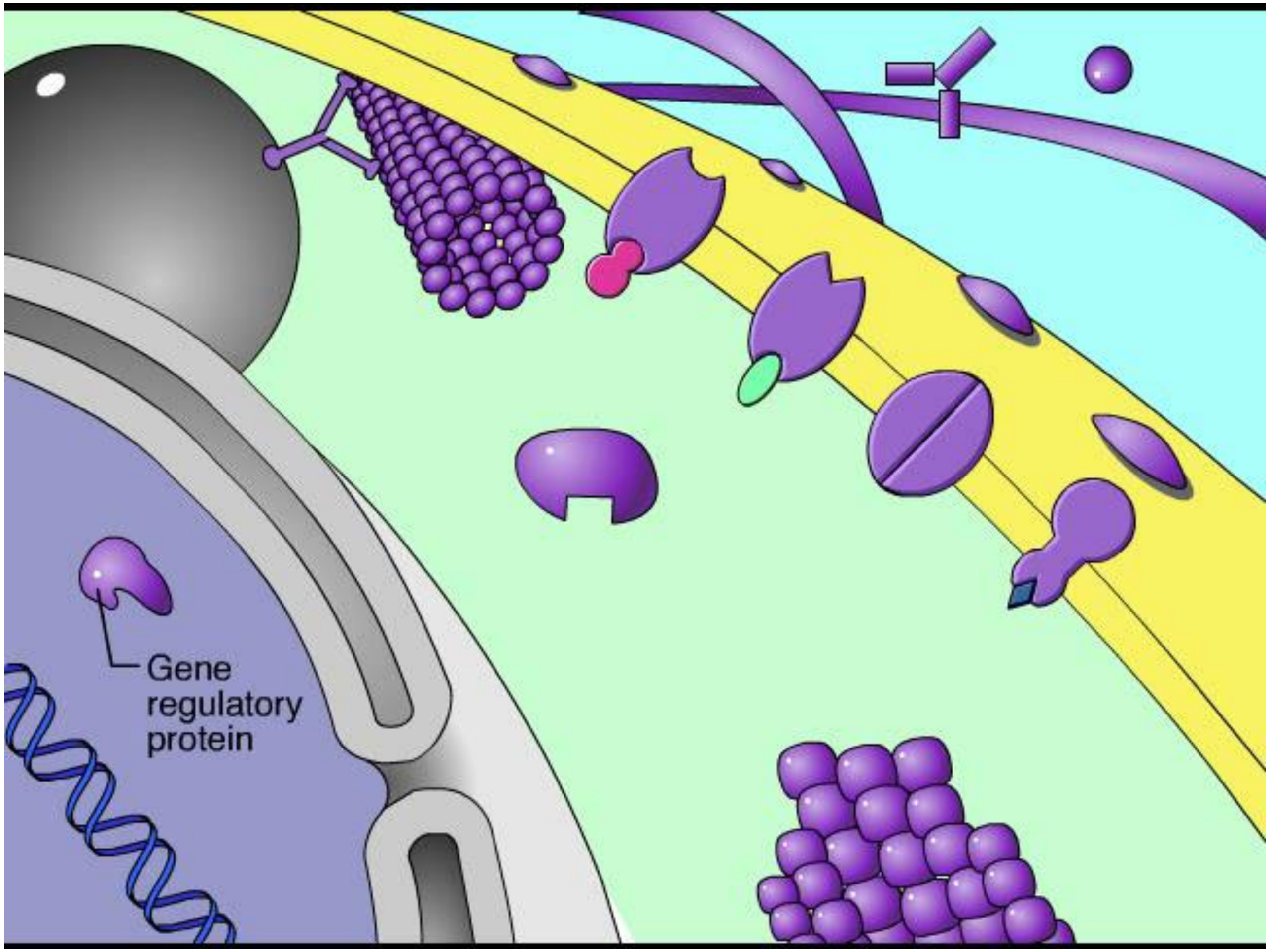
# Animation: Defensive Proteins



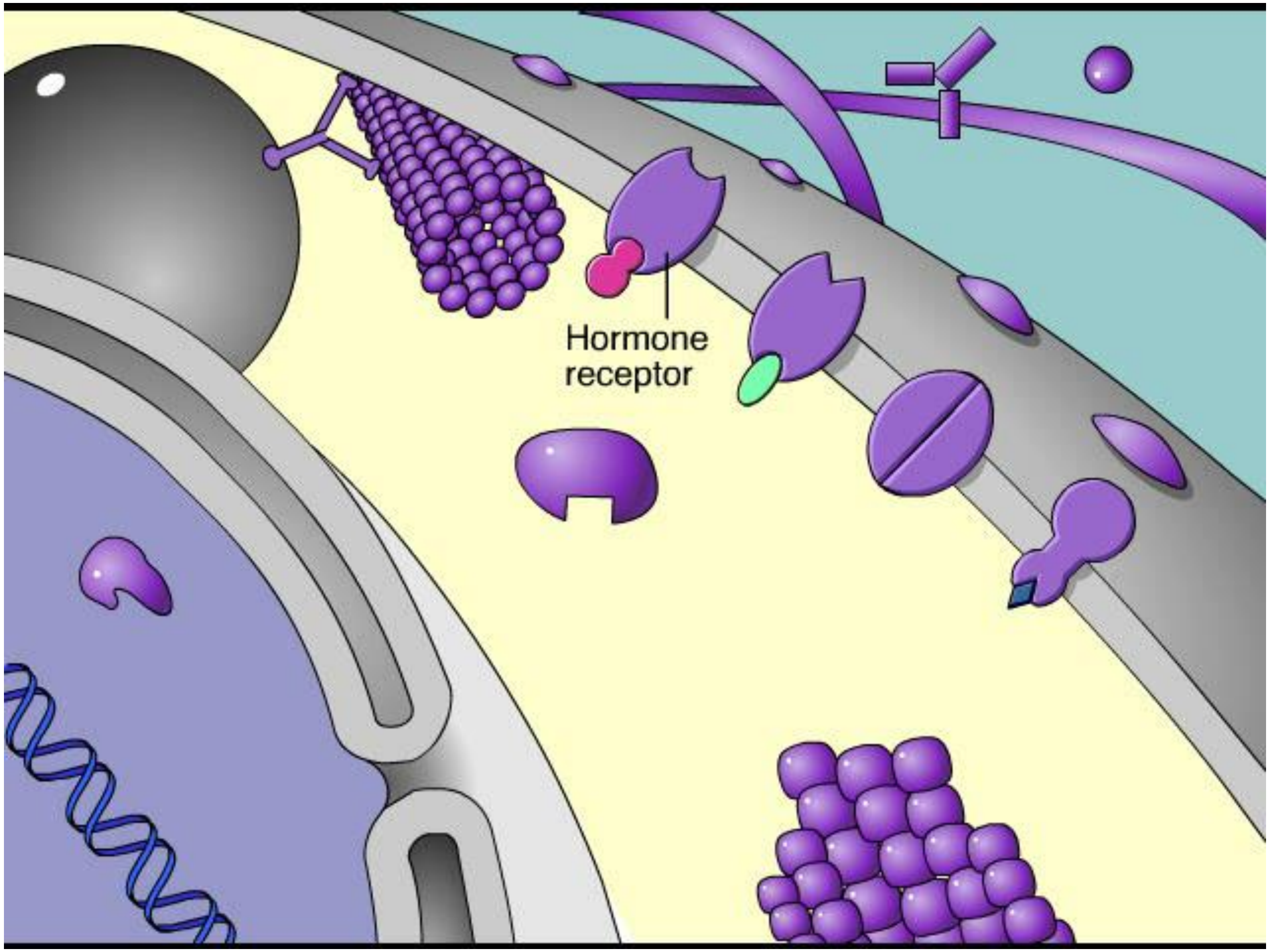
# Animation: Enzymes



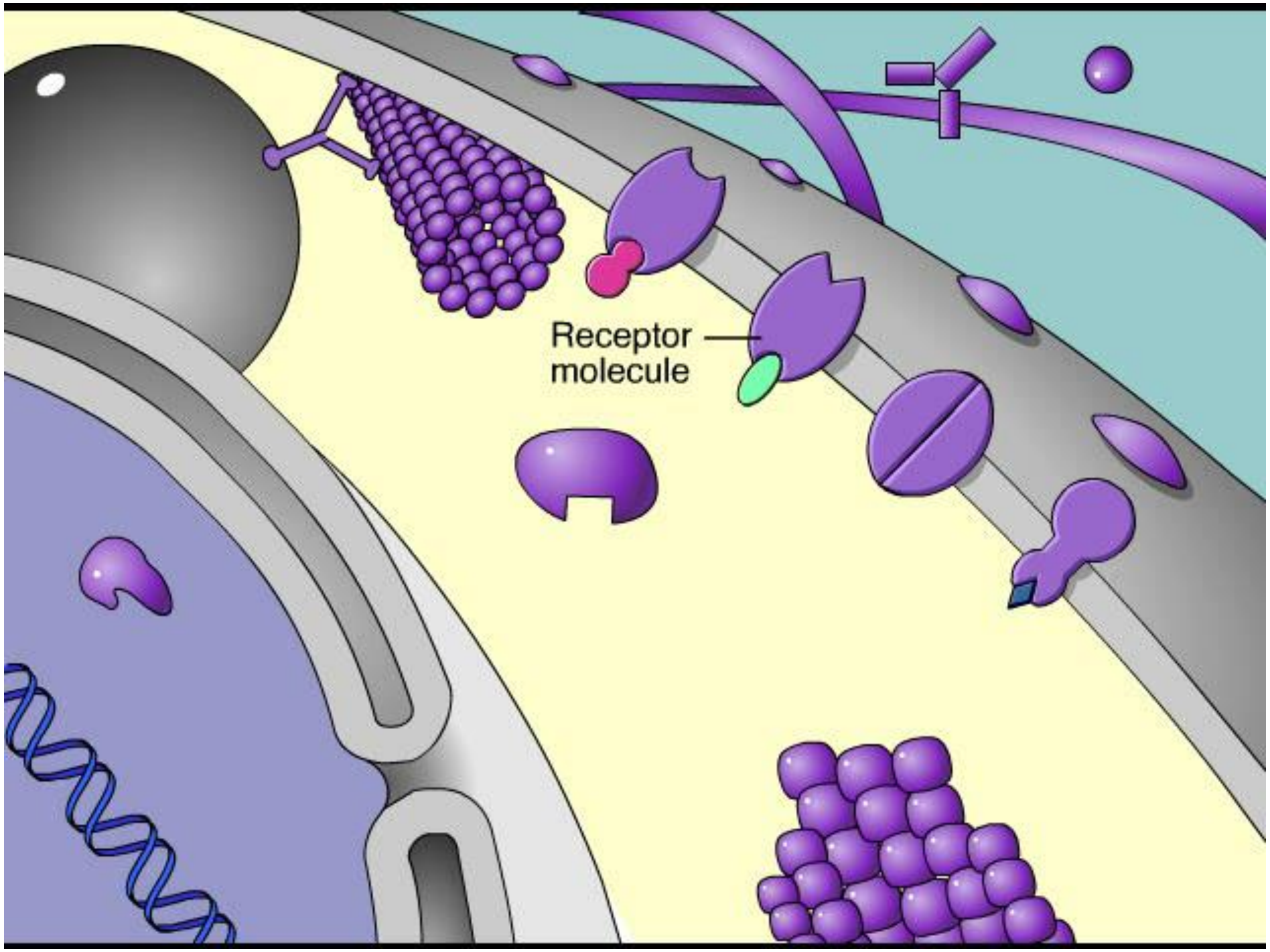
# Animation: Gene Regulatory Proteins



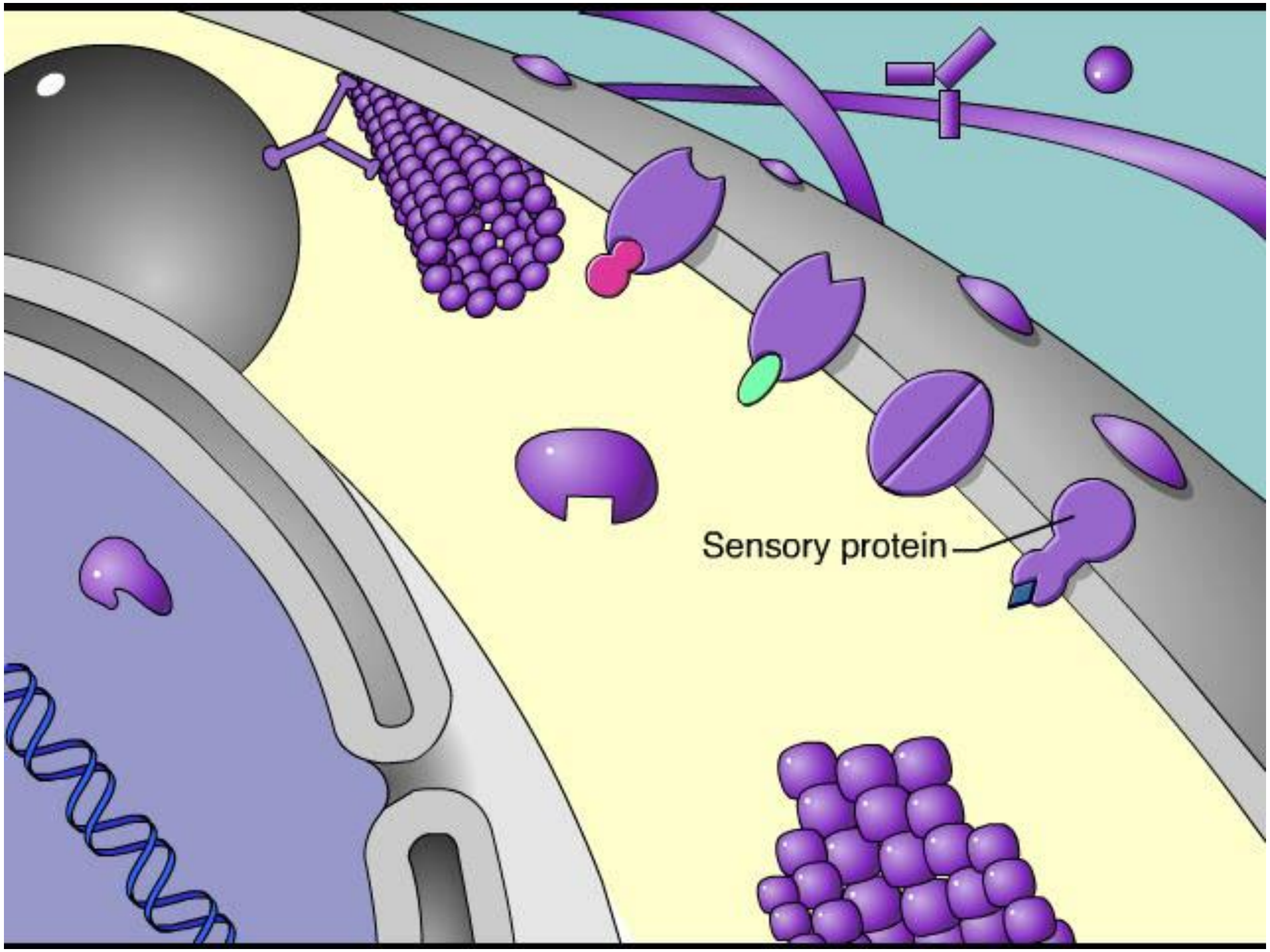
# Animation: Hormonal Proteins



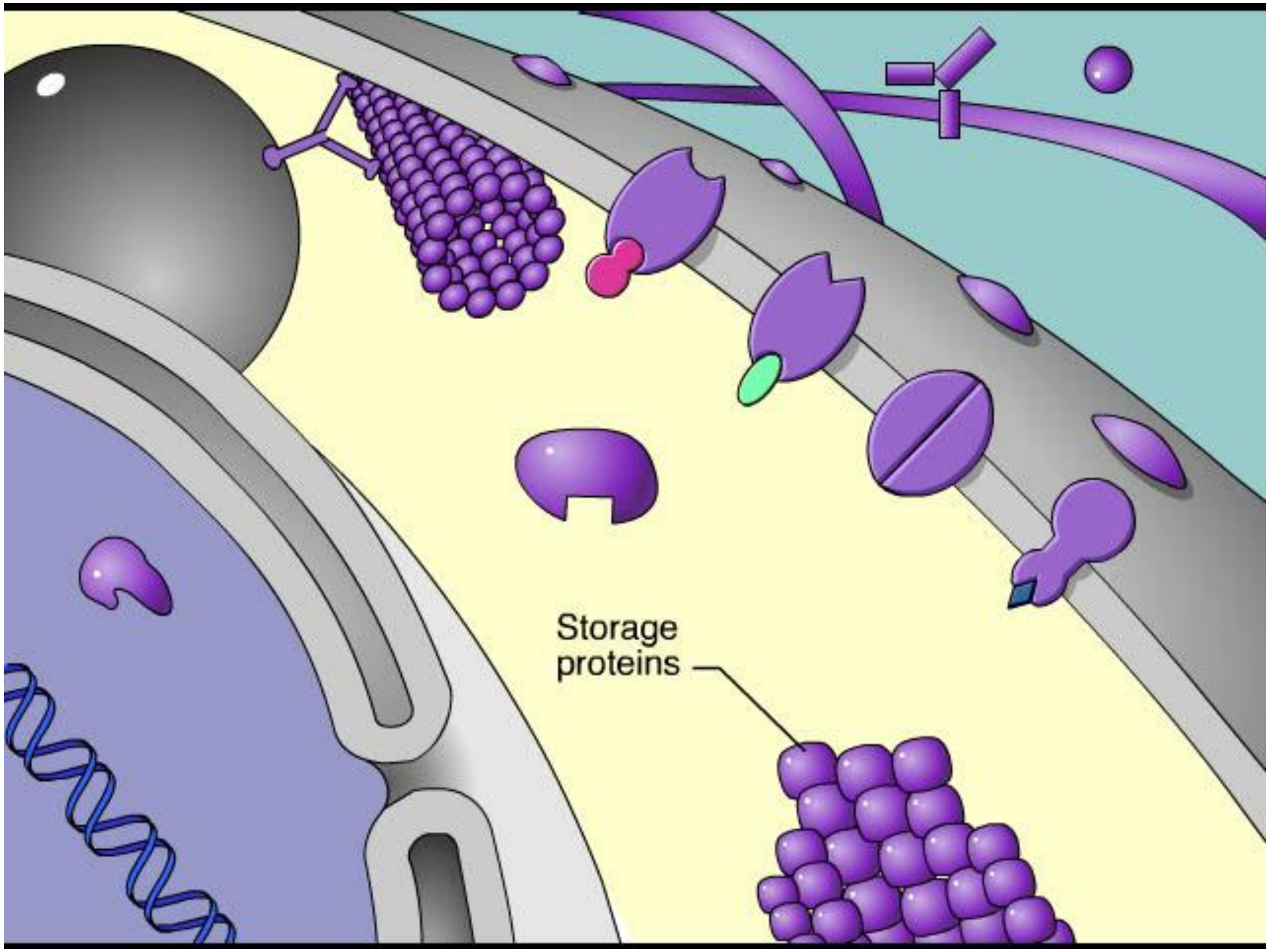
# Animation: Receptor Proteins



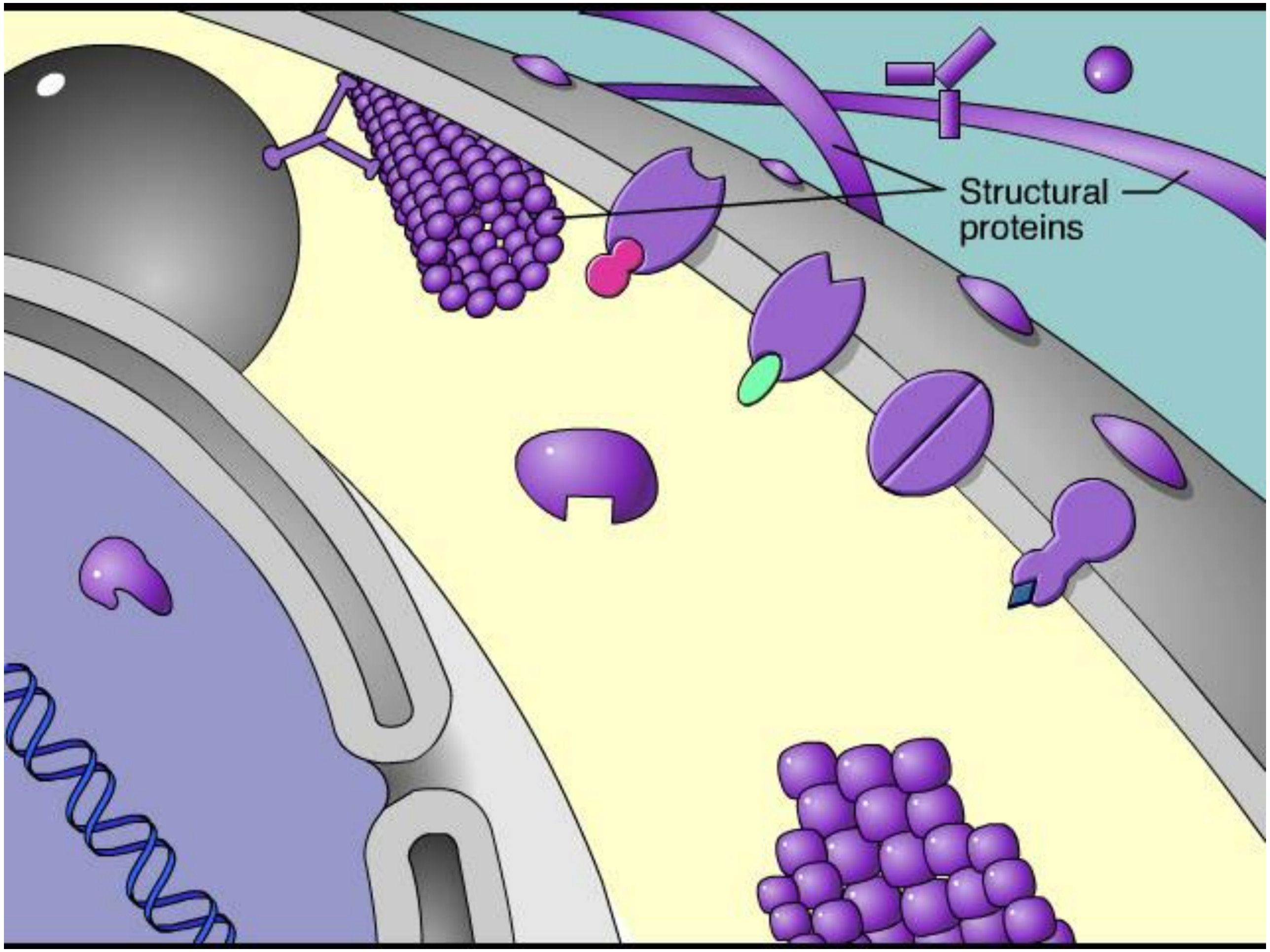
# Animation: Sensory Proteins



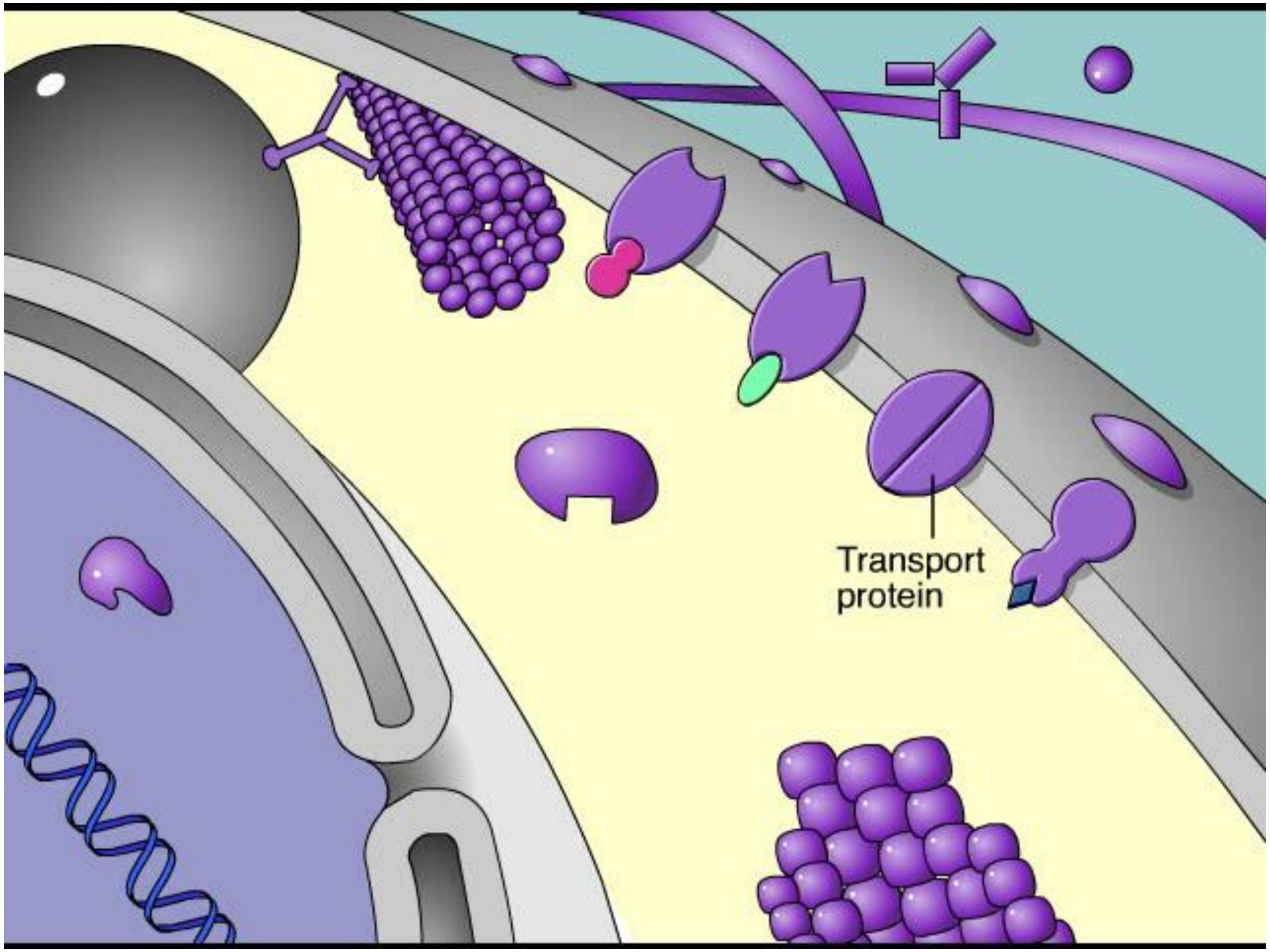
# Animation: Storage Proteins



# Animation: Structural Proteins



# Animation: Transport Proteins



- Enzymes are proteins that act as **catalysts** to speed up chemical reactions
- Enzymes can perform their functions repeatedly, functioning as workhorses that carry out the processes of life

- Proteins are all constructed from the same set of 20 amino acids
- **Polypeptides** are unbranched polymers built from these 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 amino and carboxyl groups
- Amino acids differ in their properties due to differing side chains, called R groups

Figure 5.UN01

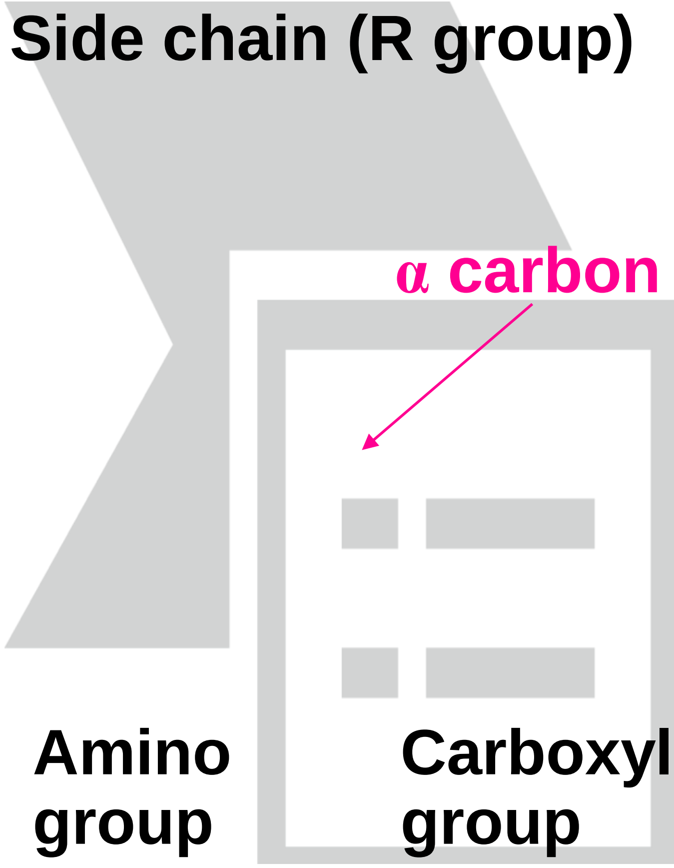


Figure 5.14

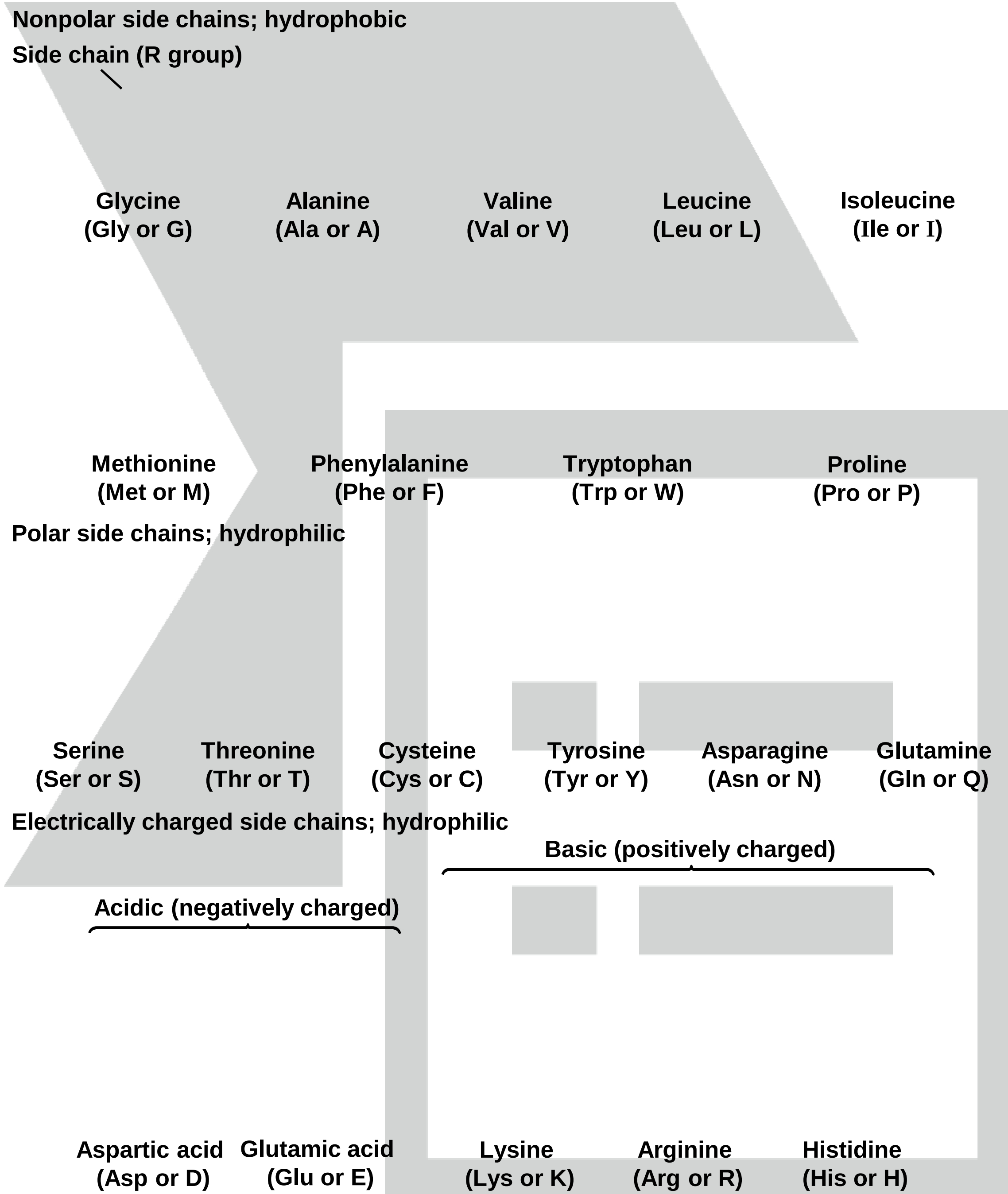

Nonpolar side chains; hydrophobic
Side chain (R group)
Glycine (Gly or G)
Alanine (Ala or A)
Valine (Val or V)
Leucine (Leu or L)
Isoleucine (Ile or I)
Methionine (Met or M)
Phenylalanine (Phe or F)
Tryptophan (Trp or W)
Proline (Pro or P)
Polar side chains; hydrophilic
Serine (Ser or S)
Threonine (Thr 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)

Figure 5.14a

**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)**

Figure 5.14b

**Polar side chains; hydrophilic**

**Serine (Ser or S)**

**Threonine (Thr or T)**

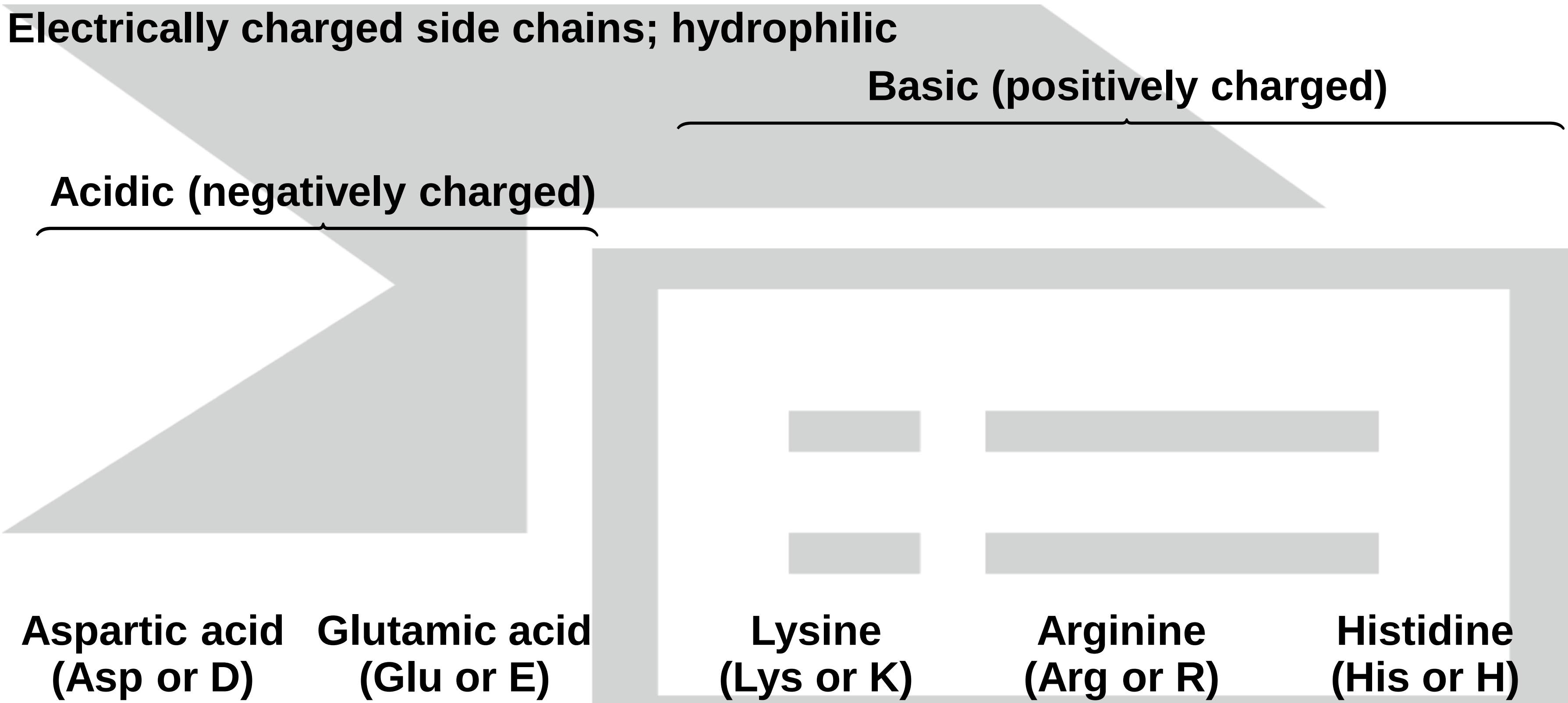
**Cysteine (Cys or C)**

**Tyrosine (Tyr or Y)**

**Asparagine (Asn or N)**

**Glutamine (Gln or Q)**

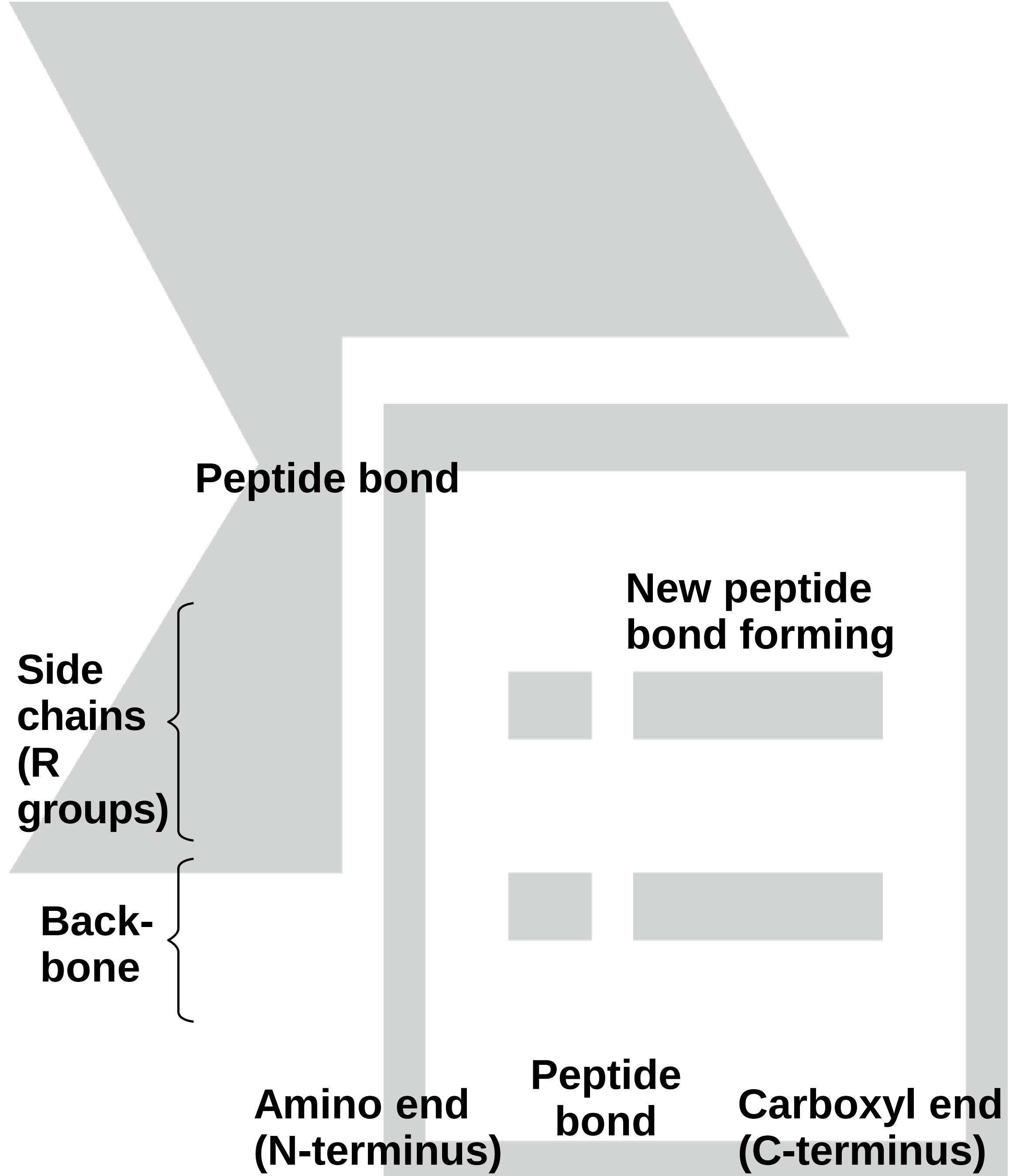
Figure 5.14c


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)

# Polypeptides (Amino Acid Polymers)

- Amino acids are linked by covalent bonds called **peptide bonds**
- A polypeptide is a polymer of amino acids
- Polypeptides range in length from a few to more than 1,000 monomers
- Each polypeptide has a unique linear sequence of amino acids, with a carboxyl end (C-terminus) and an amino end (N-terminus)

Figure 5.15



Peptide bond
New peptide
bond forming
Side
chains
(R
groups)
Back-
bone
Amino end
(N-terminus)
Peptide
bond
Carboxyl end
(C-terminus)

Figure 5.15a

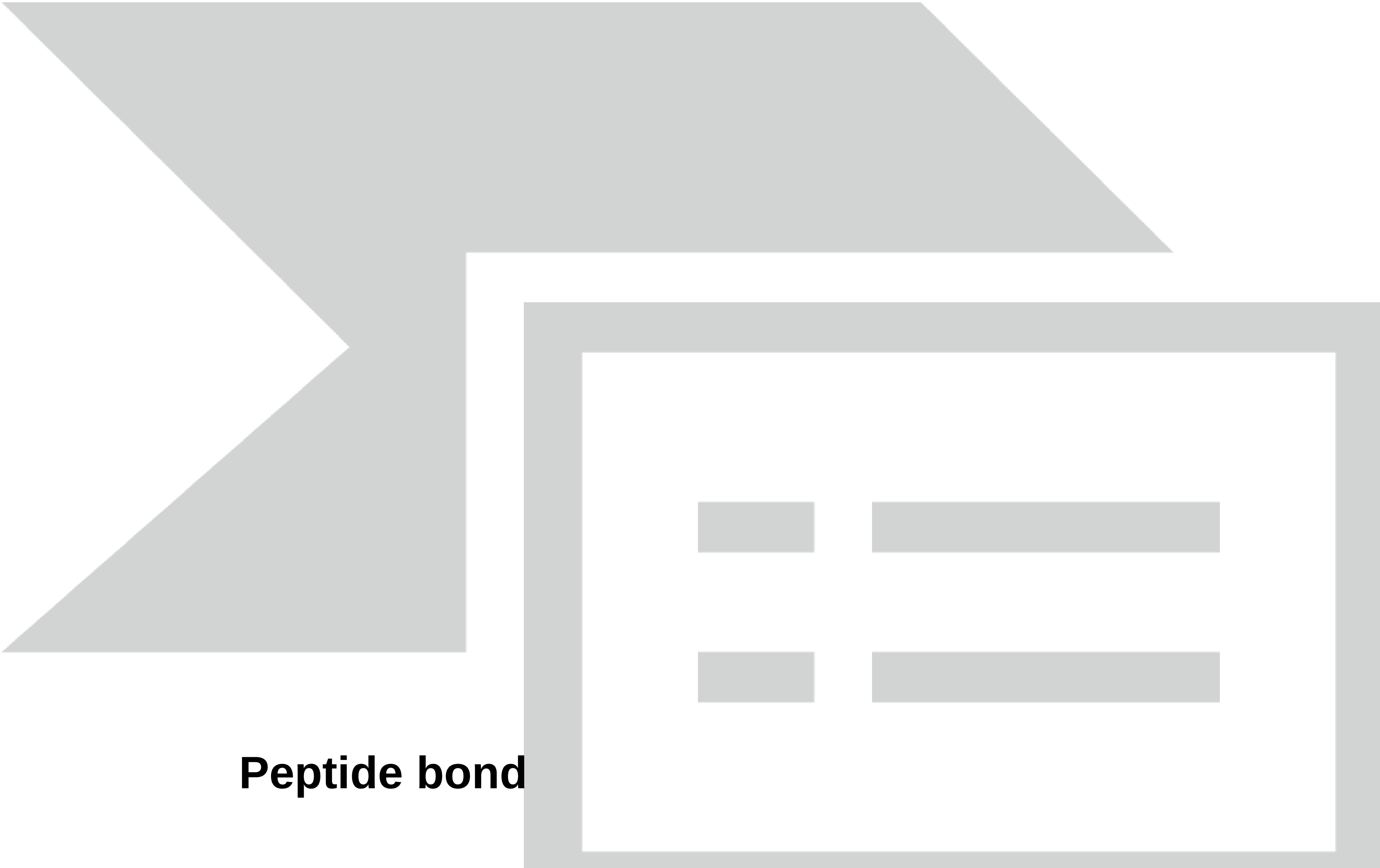
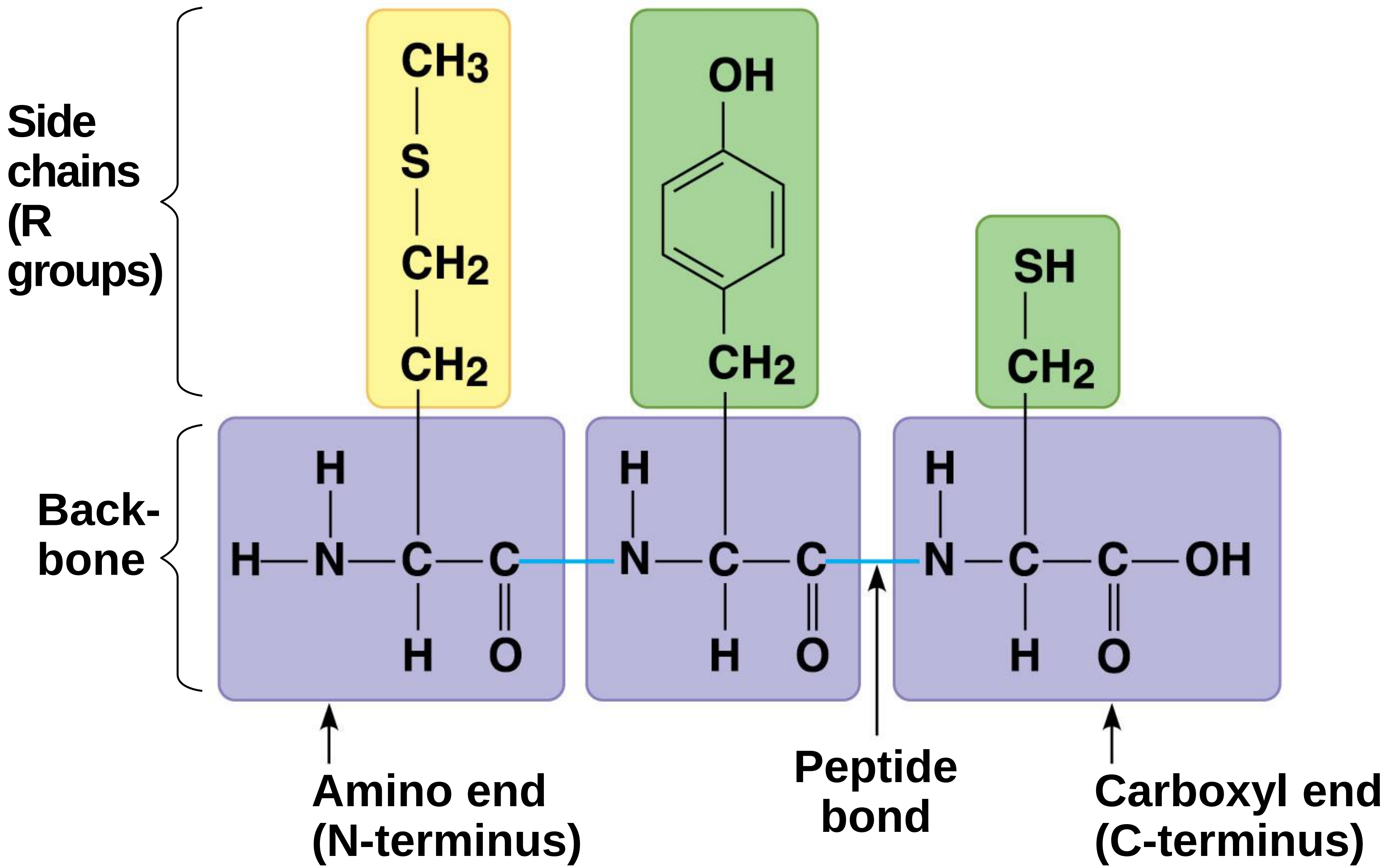


Figure 5.15b



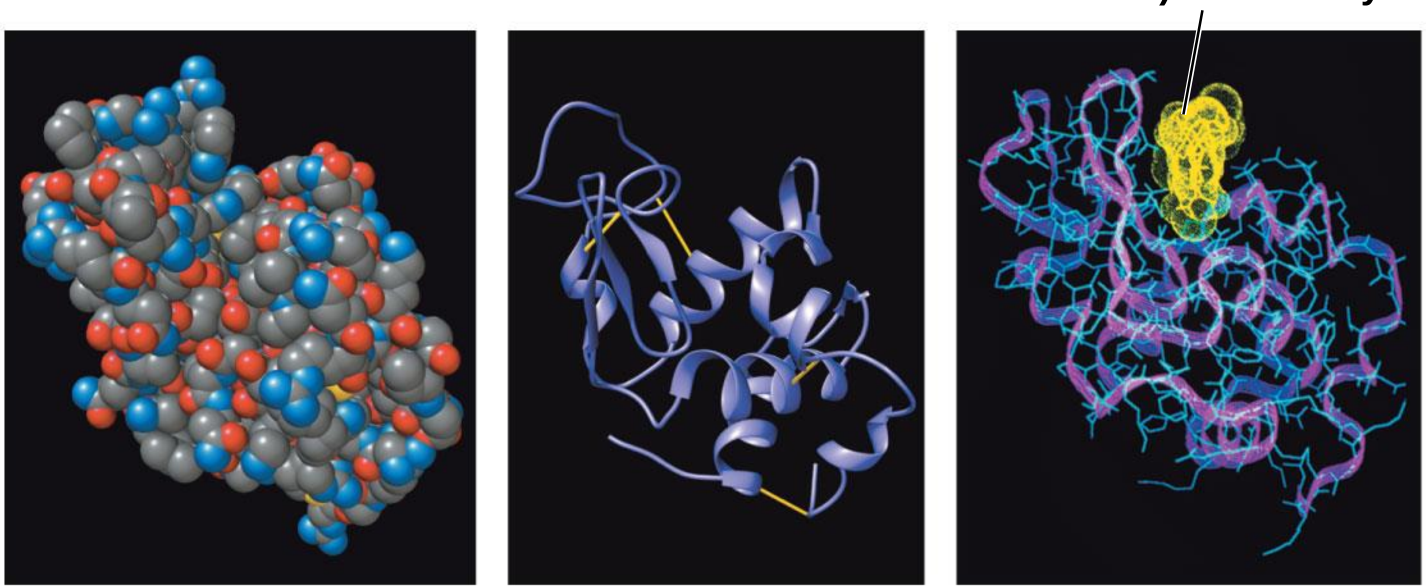
Side chains (R groups)
Back-bone
CH3
S
CH2
CH2
OH
CH2
SH
CH2
H
H—N—C—C
H O
H
N—C—C
H O
H
N—C—C—OH
H O
Amino end (N-terminus)
Peptide bond
Carboxyl end (C-terminus)

# Protein Structure and Function

- The specific activities of proteins result from their intricate three-dimensional architecture
- A functional protein consists of one or more polypeptides precisely twisted, folded, and coiled into a unique shape

Figure 5.16

## Structural Models

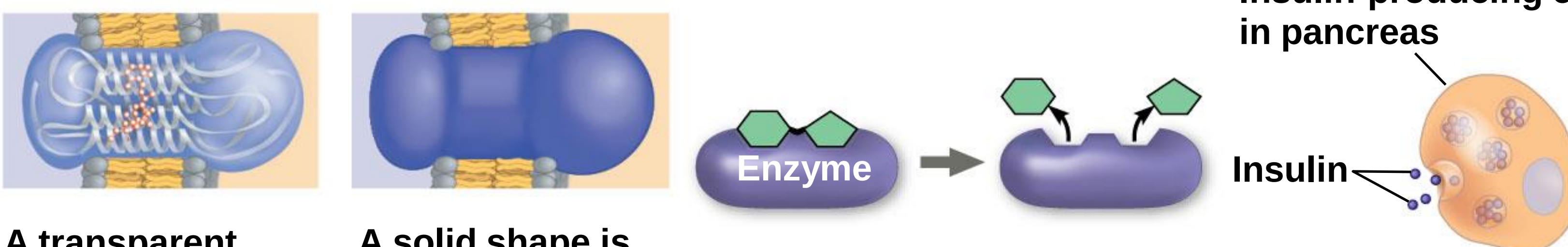



Space-filling model

Ribbon model

Wire-frame model (blue)

## Simplified Diagrams




A transparent shape shows the overall shape of the molecule and some internal details.

A solid shape is used when structural details are not needed.

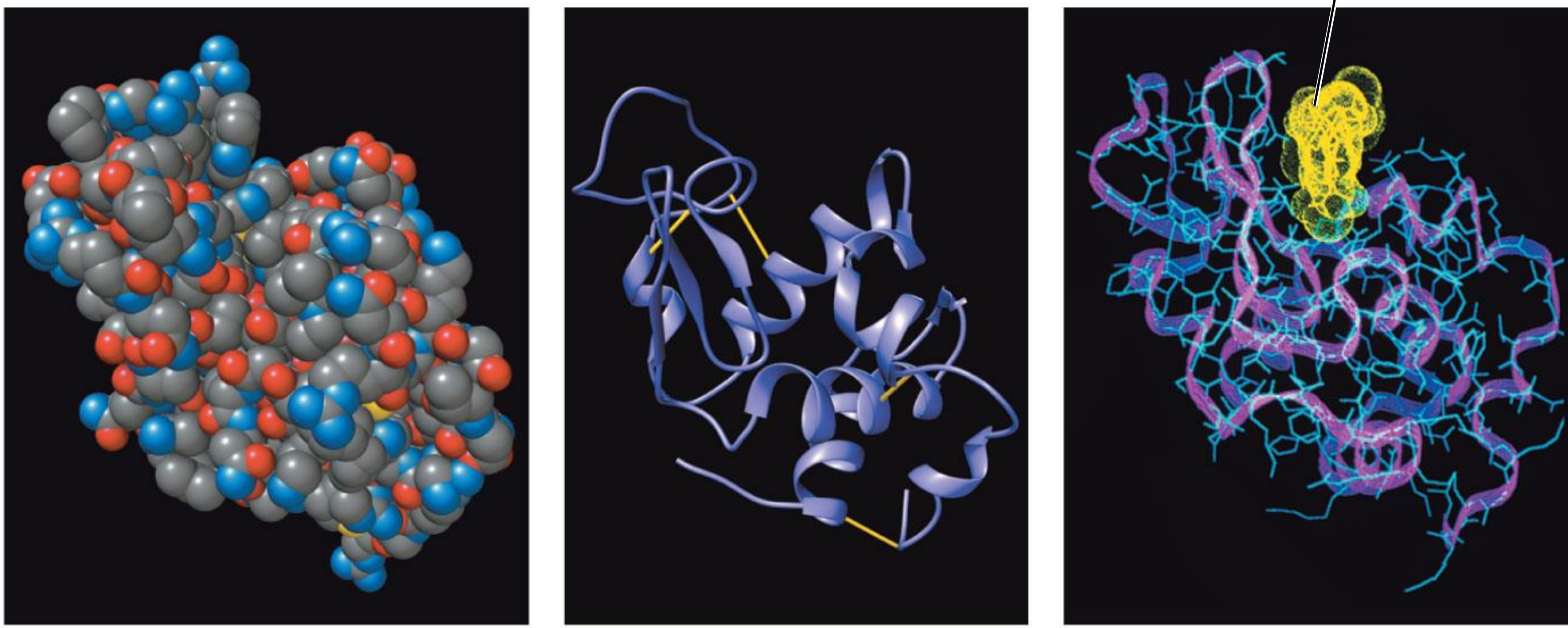
A simple shape is used here to represent a generic enzyme.

A protein can be represented simply as a dot.

Figure 5.16a

## Structural Models

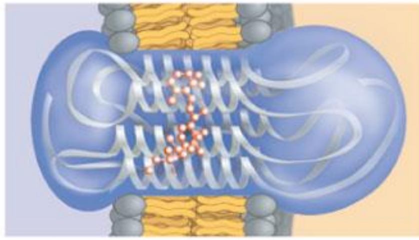
Target molecule (on bacterial cell surface) bound to lysozyme



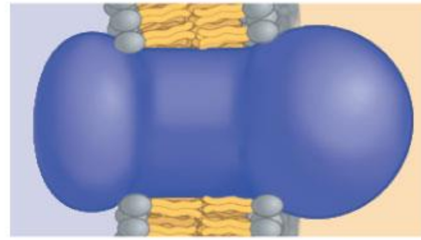
**Space-filling model** **Ribbon model** **Wire-frame model (blue)**

Figure 5.16b

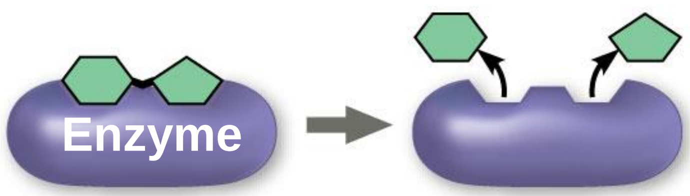
## Simplified Diagrams



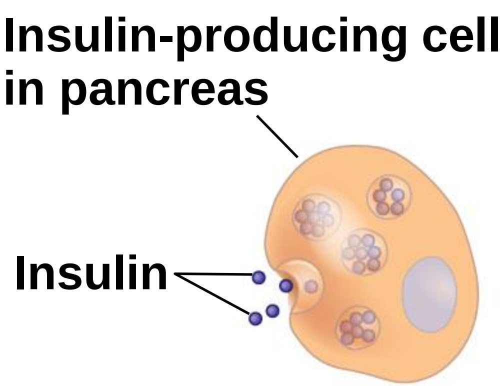
A transparent shape shows the overall shape of the molecule and some internal details.



A solid shape is used when structural details are not needed.

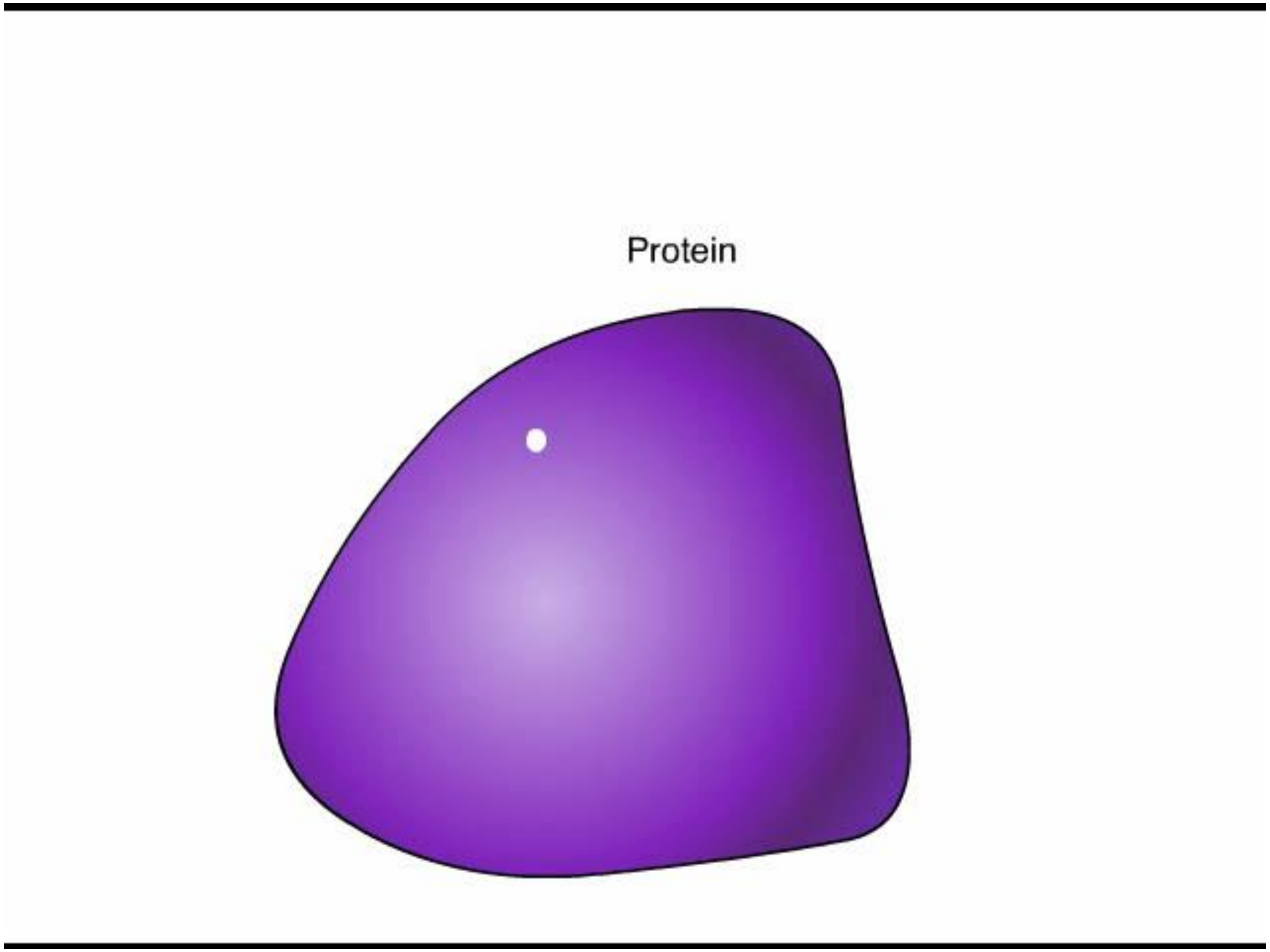



A simple shape is used here to represent a generic enzyme.



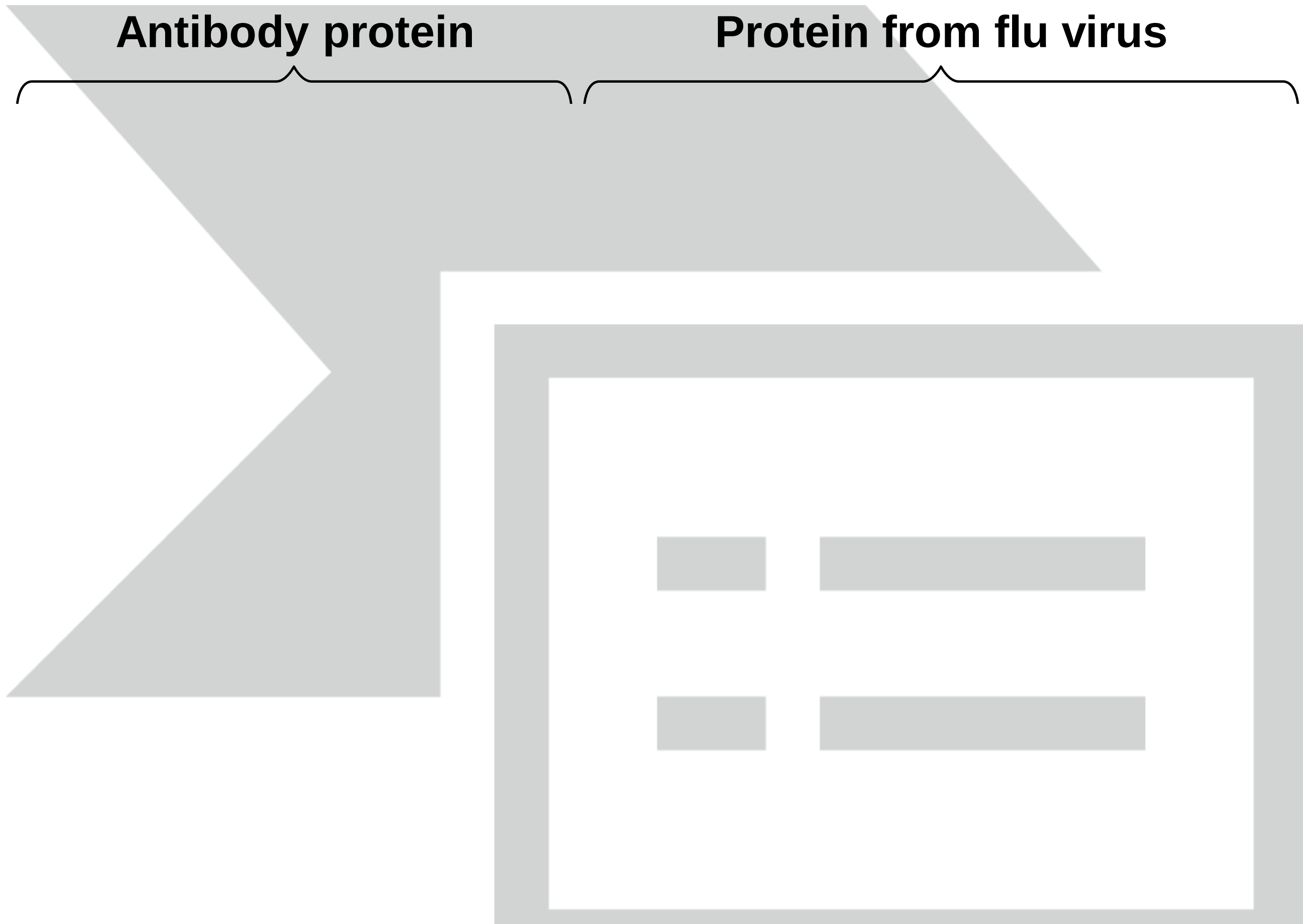

A protein can be represented simply as a dot.

# Animation: Protein Structure Introduction



- The sequence of amino acids determines a protein’s three-dimensional structure
- A protein’s structure determines how it works
- The function of a protein usually depends on its ability to recognize and bind to some other molecule

Figure 5.17



# *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 5.18a

# Primary Structure

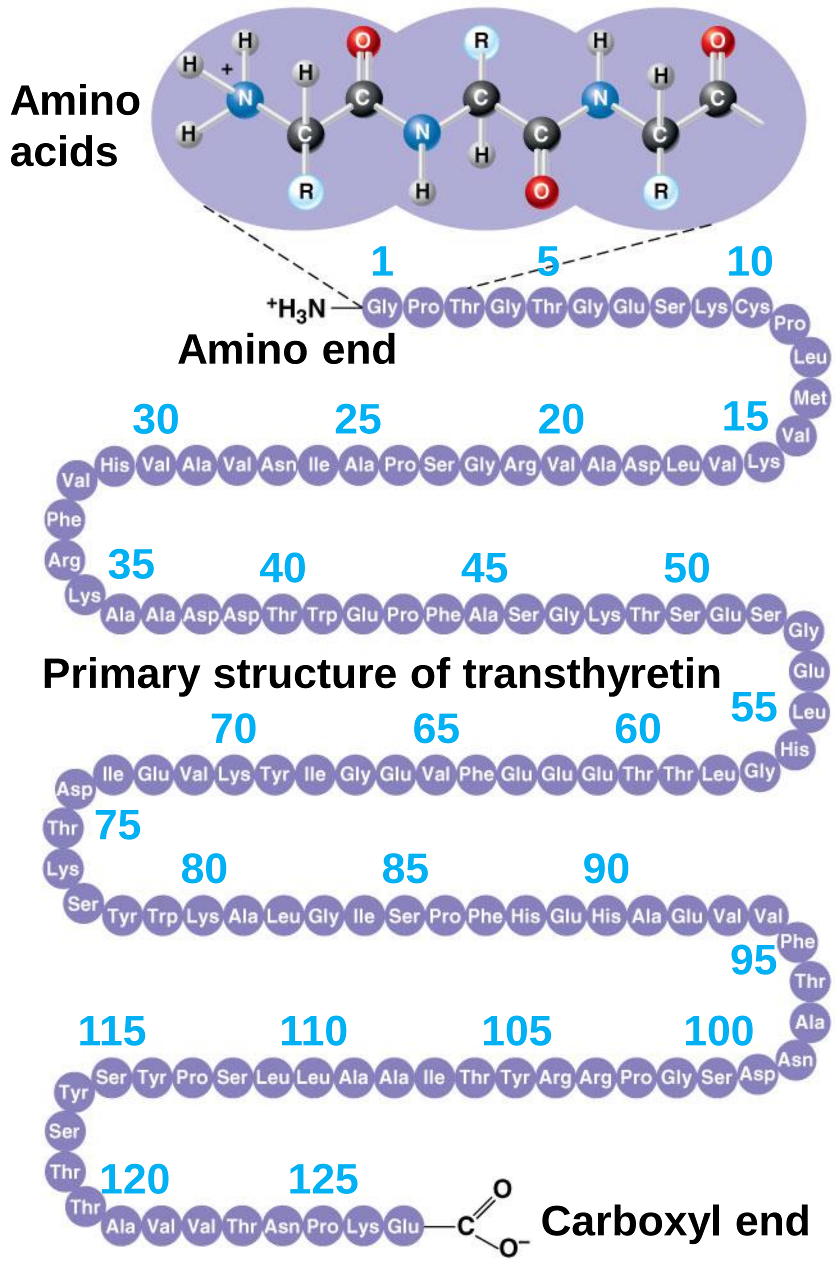


Figure 5.18aa

# Primary Structure

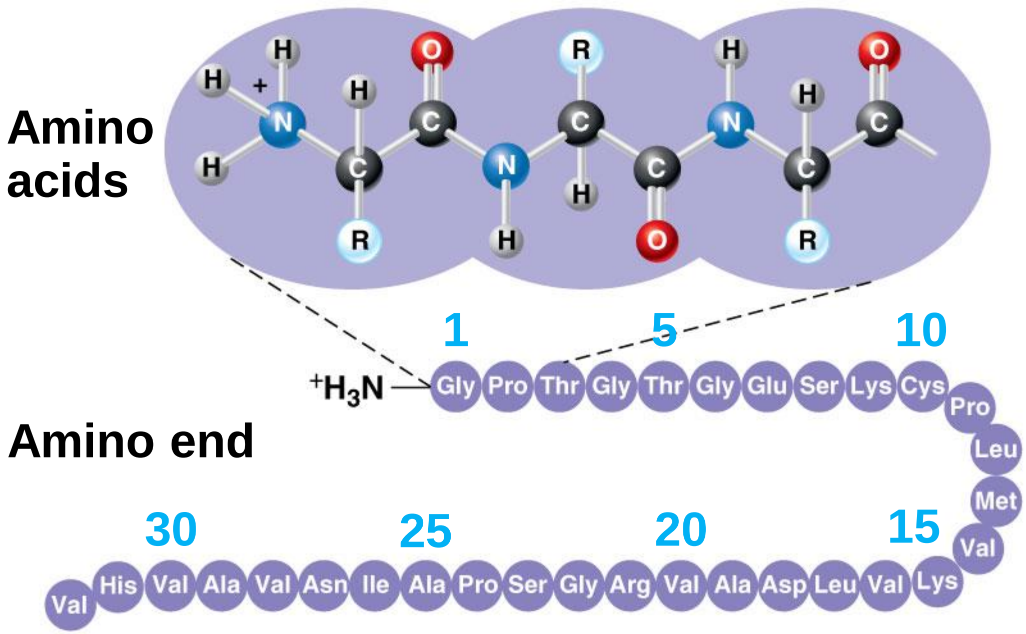


Figure 5.18b

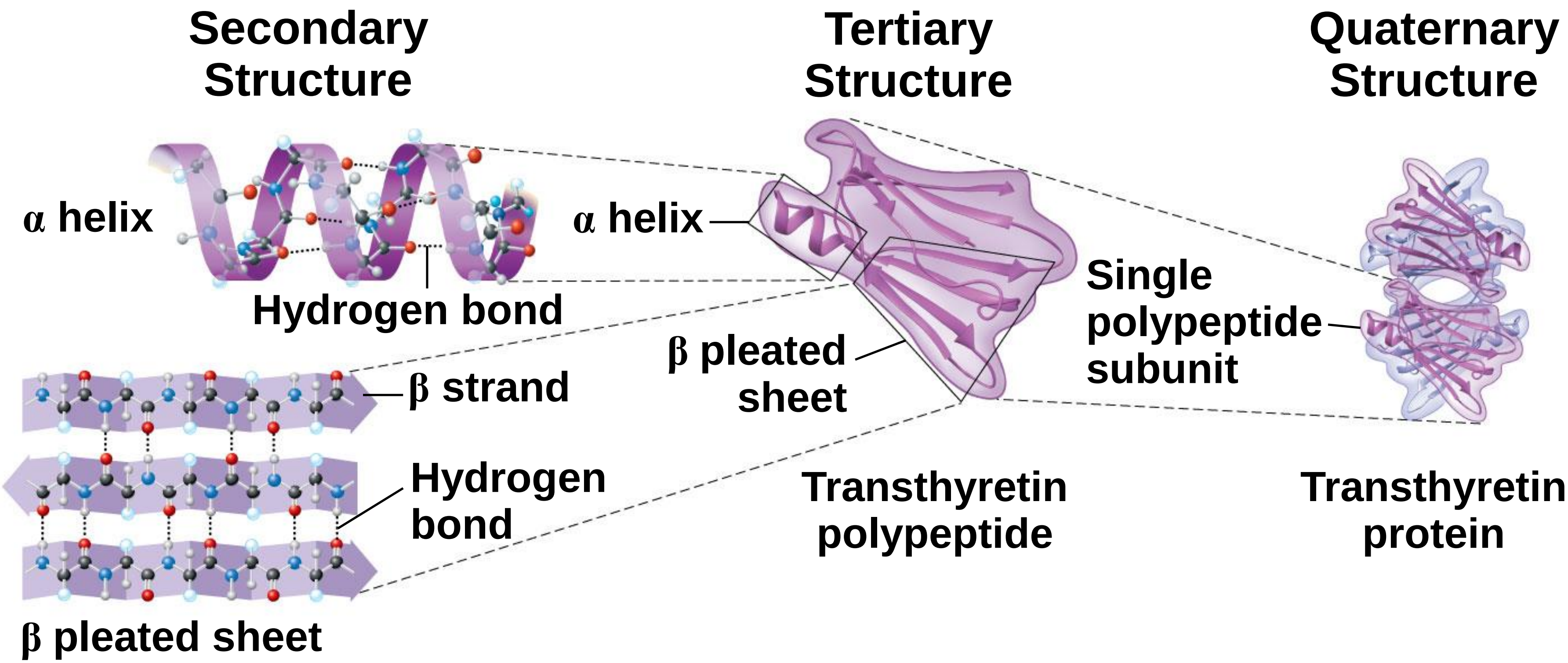

Secondary Structure
Tertiary Structure
Quaternary Structure
α helix
Hydrogen bond
α helix
β strand
β pleated sheet
Hydrogen bond
β pleated sheet
Single polypeptide subunit
Transthyretin polypeptide
Transthyretin protein

Figure 5.18ba

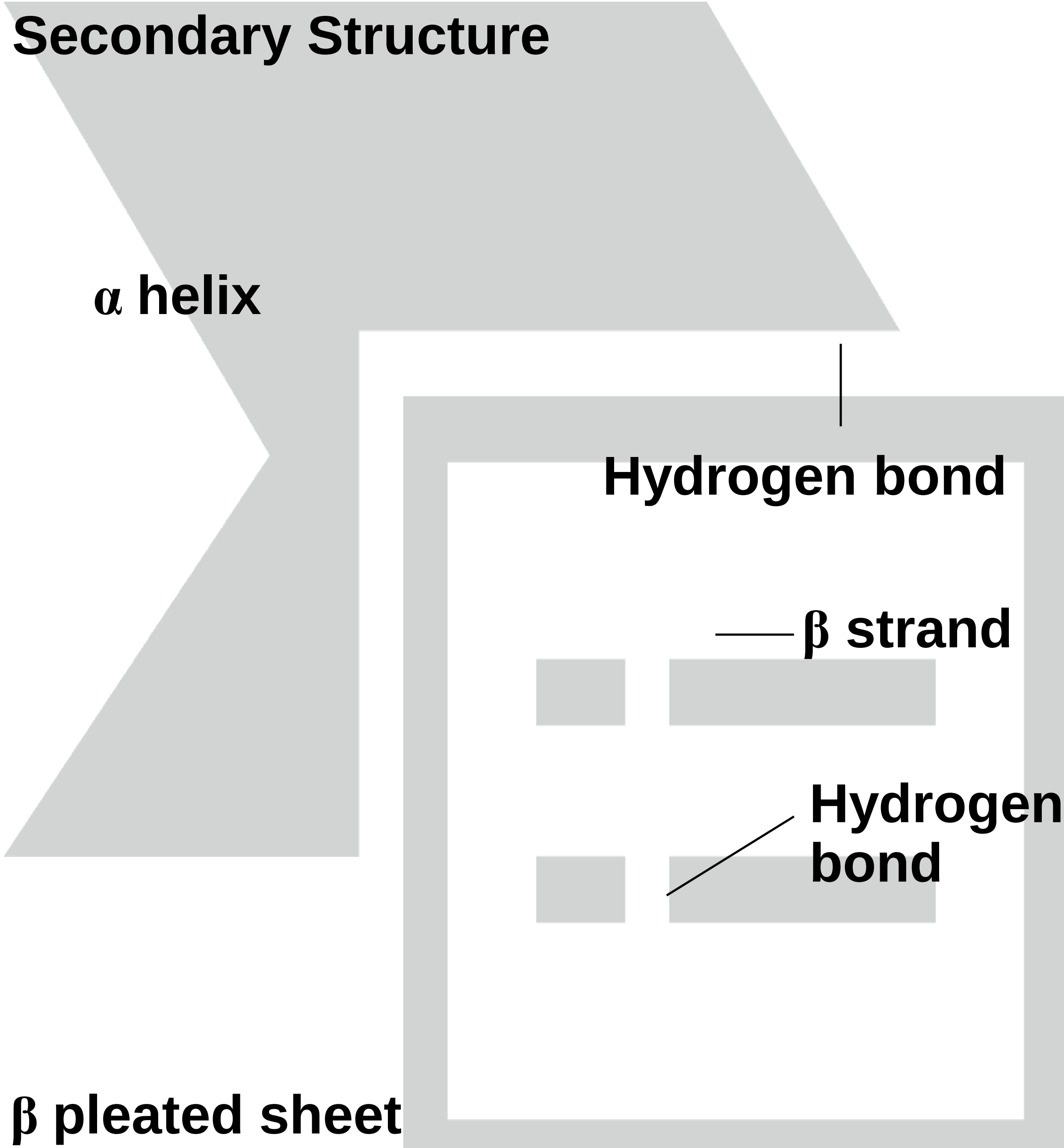


Figure 5.18bb

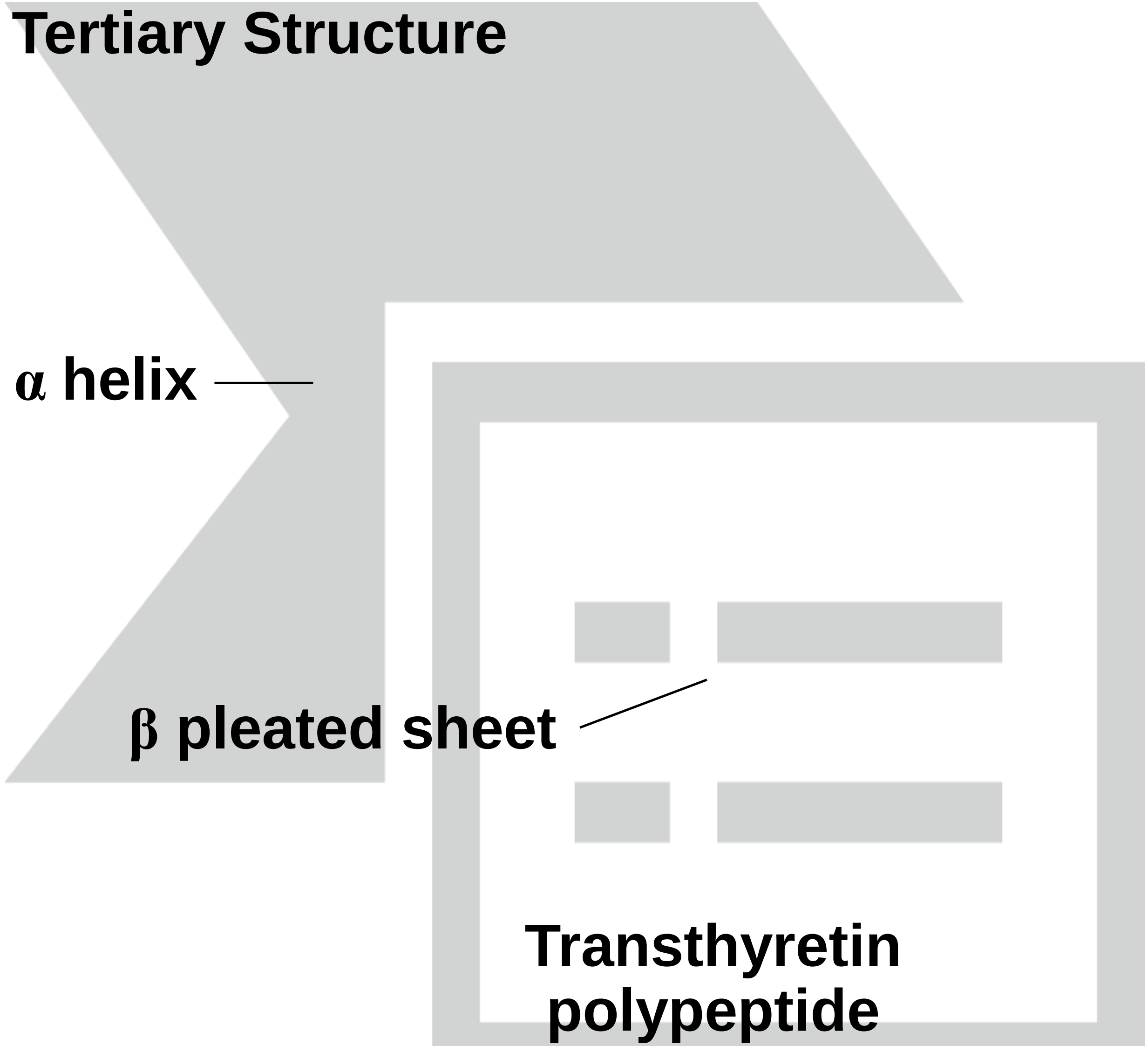


Figure 5.18bc

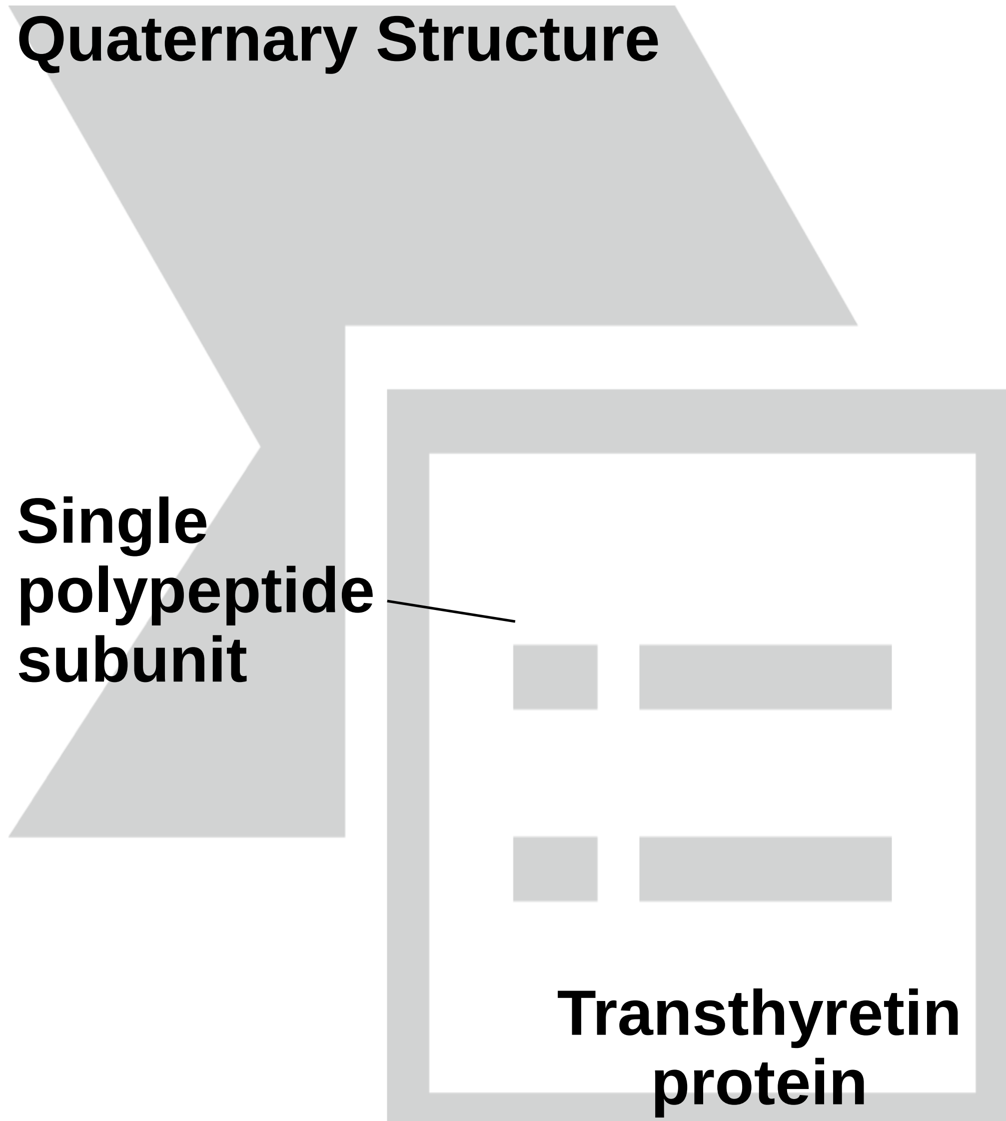


Figure 5.18c

Figure 5.18d

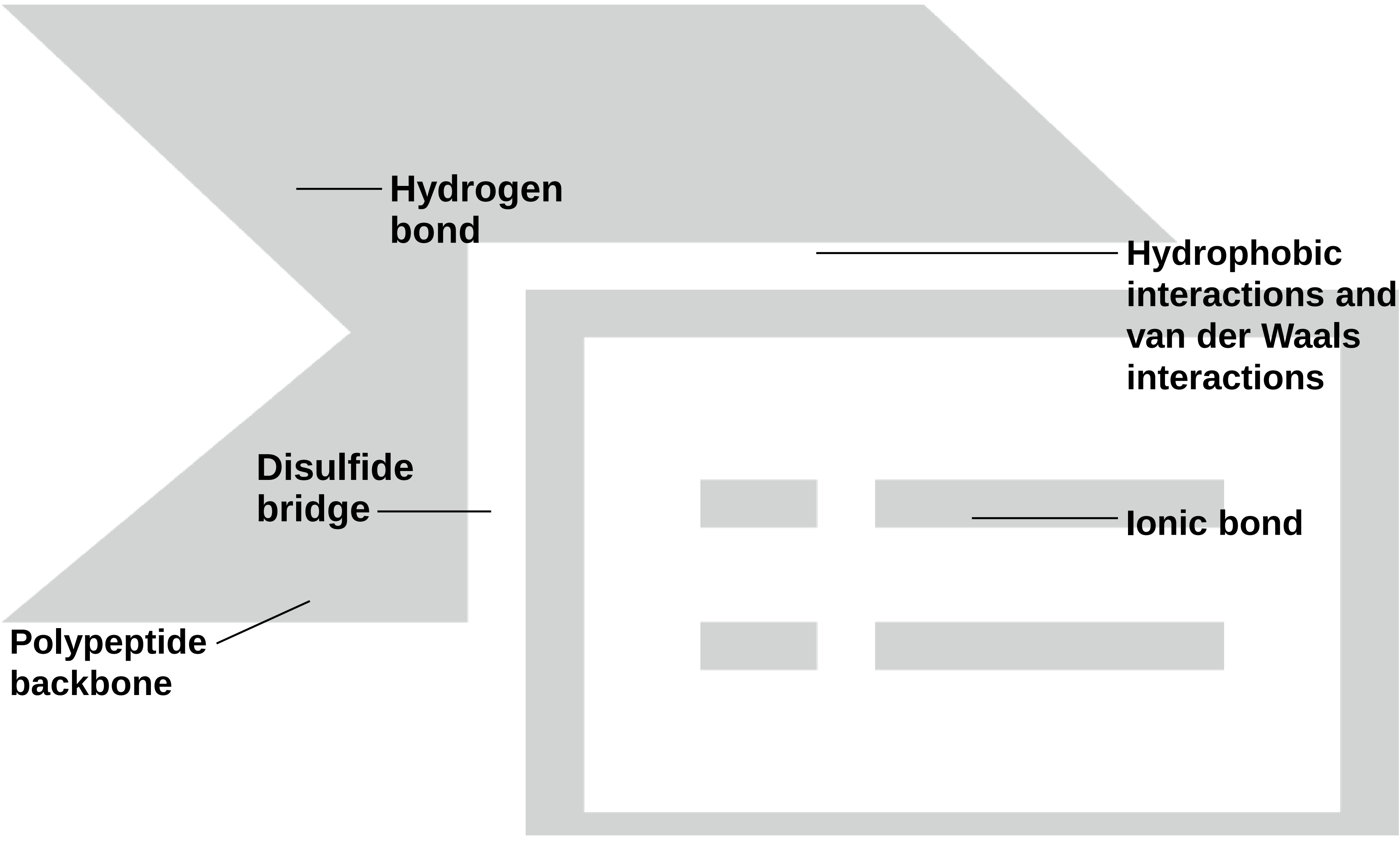
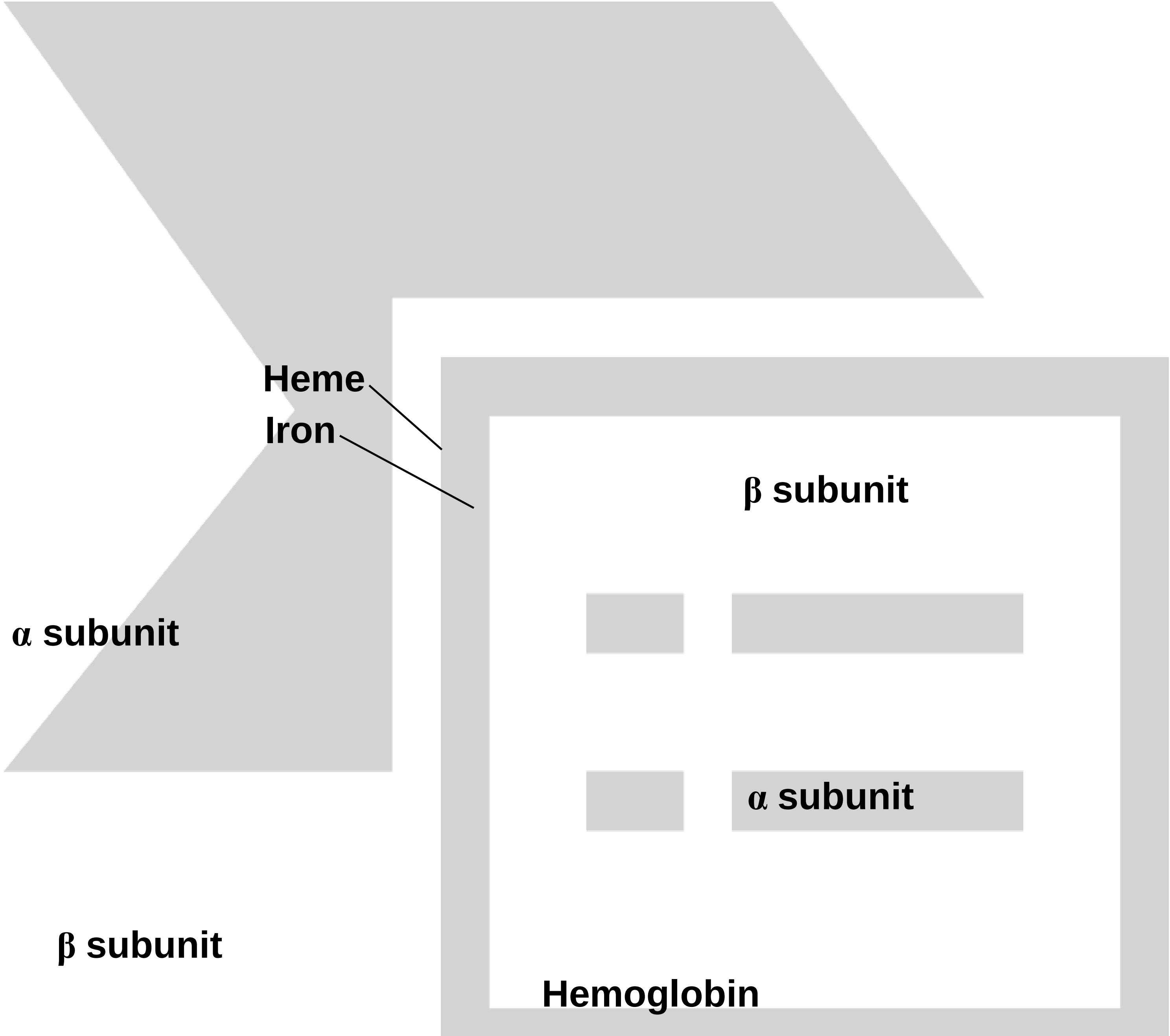

Hydrogen bond
Hydrophobic interactions and van der Waals interactions
Disulfide bridge
Ionic bond
Polypeptide backbone

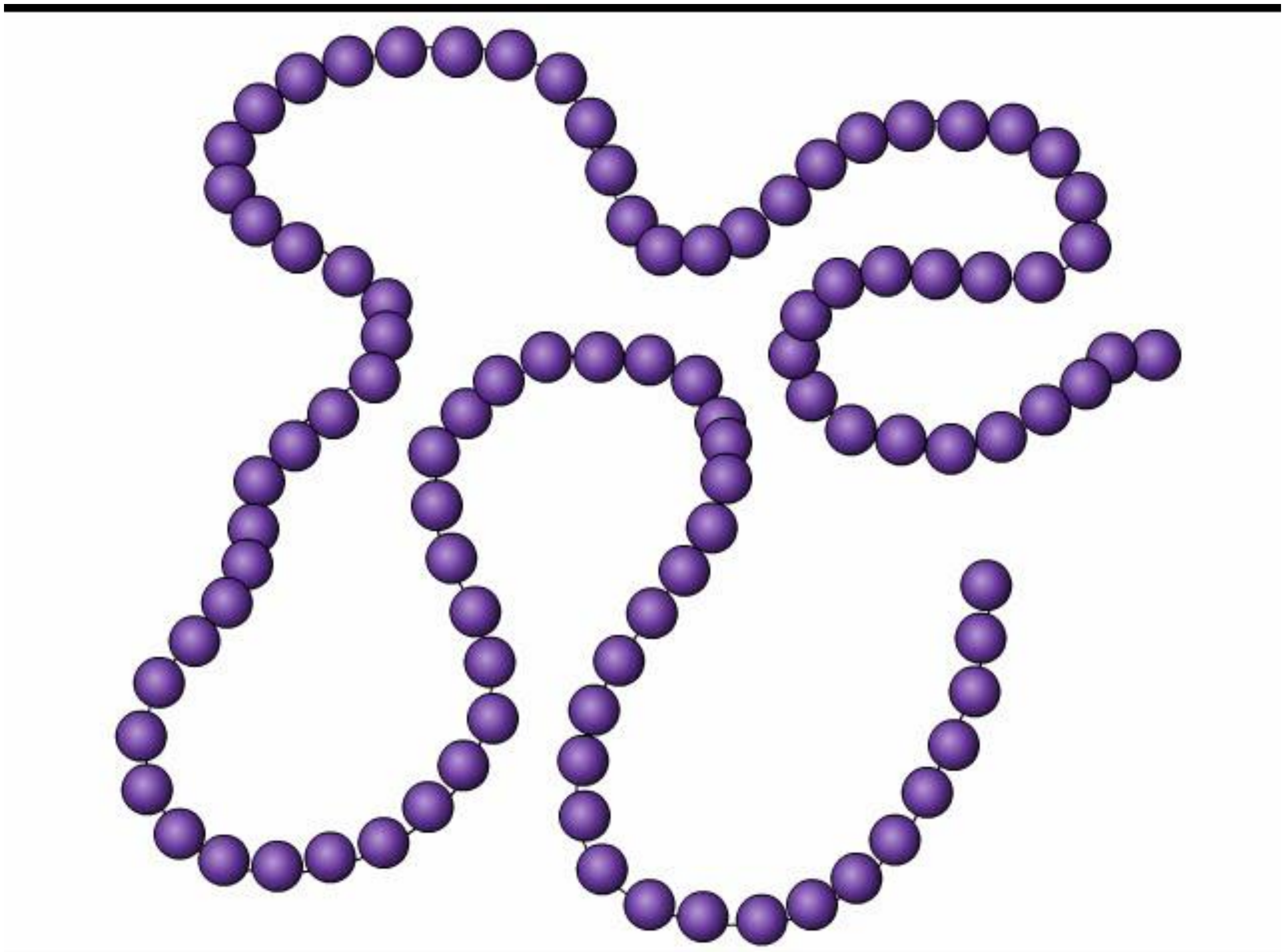
Figure 5.18e

Figure 5.18f


Heme
Iron
β subunit
α subunit
α subunit
β subunit
Hemoglobin

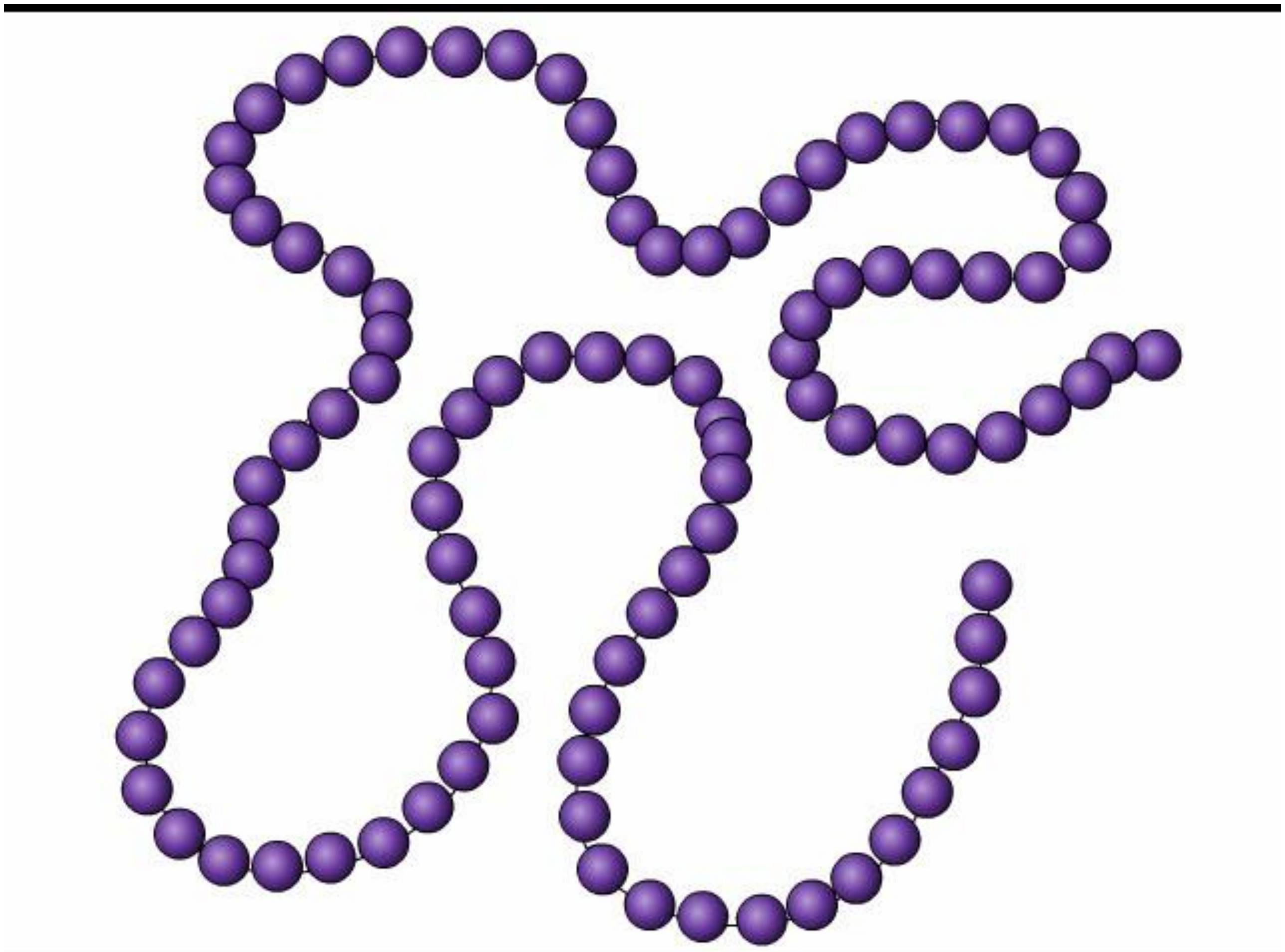
- The **primary structure** of a protein is its sequence of amino acids
- Primary structure is like the order of letters in a long word
- Primary structure is determined by inherited genetic information

# Animation: Primary Protein Structure

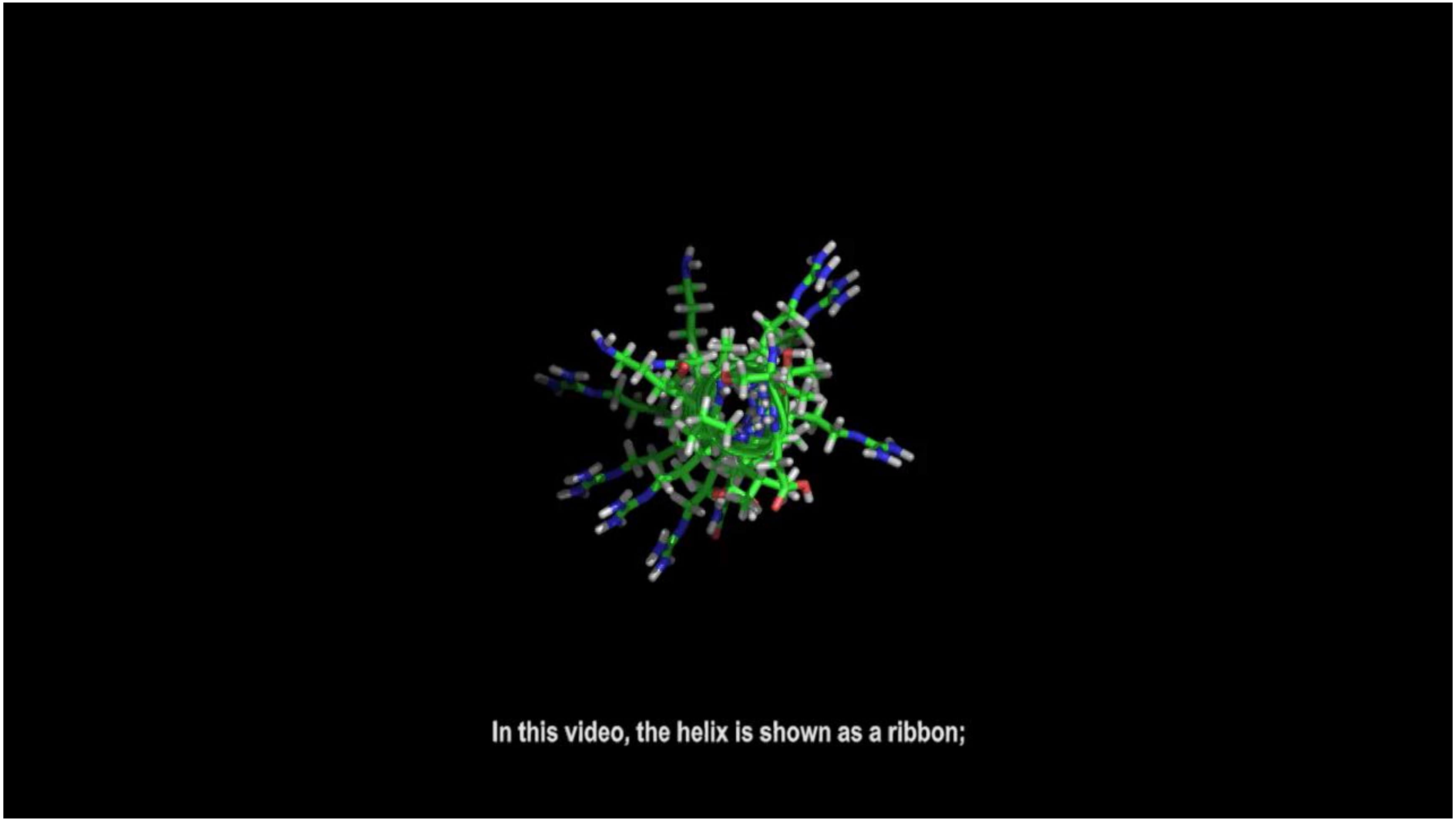


- The coils and folds of **secondary structure** result from hydrogen bonds between repeating constituents of the polypeptide backbone
- Typical secondary structures are a coil called an **α helix** and a folded structure called a **β pleated sheet**

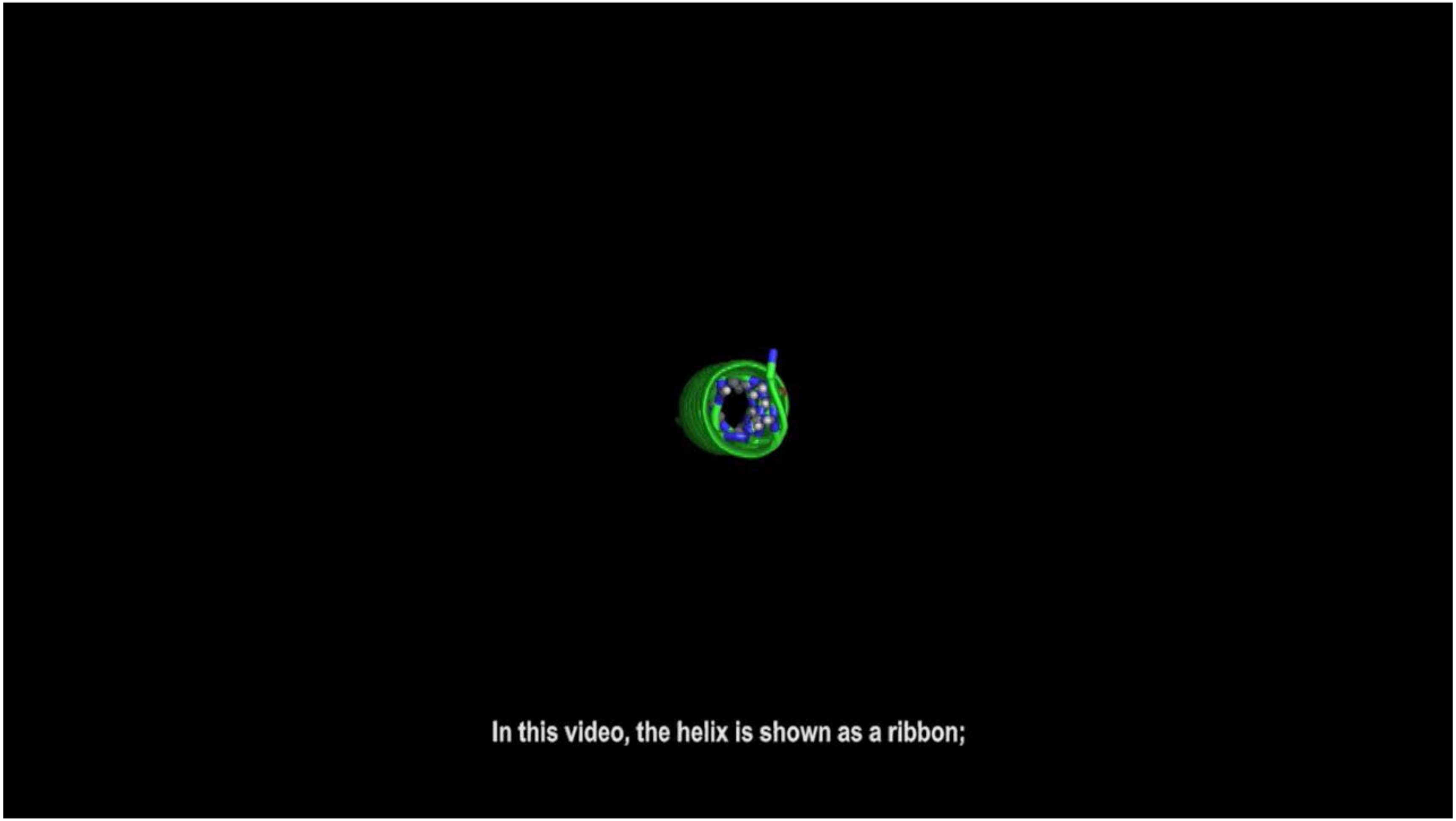
# Animation: Secondary Protein Structure



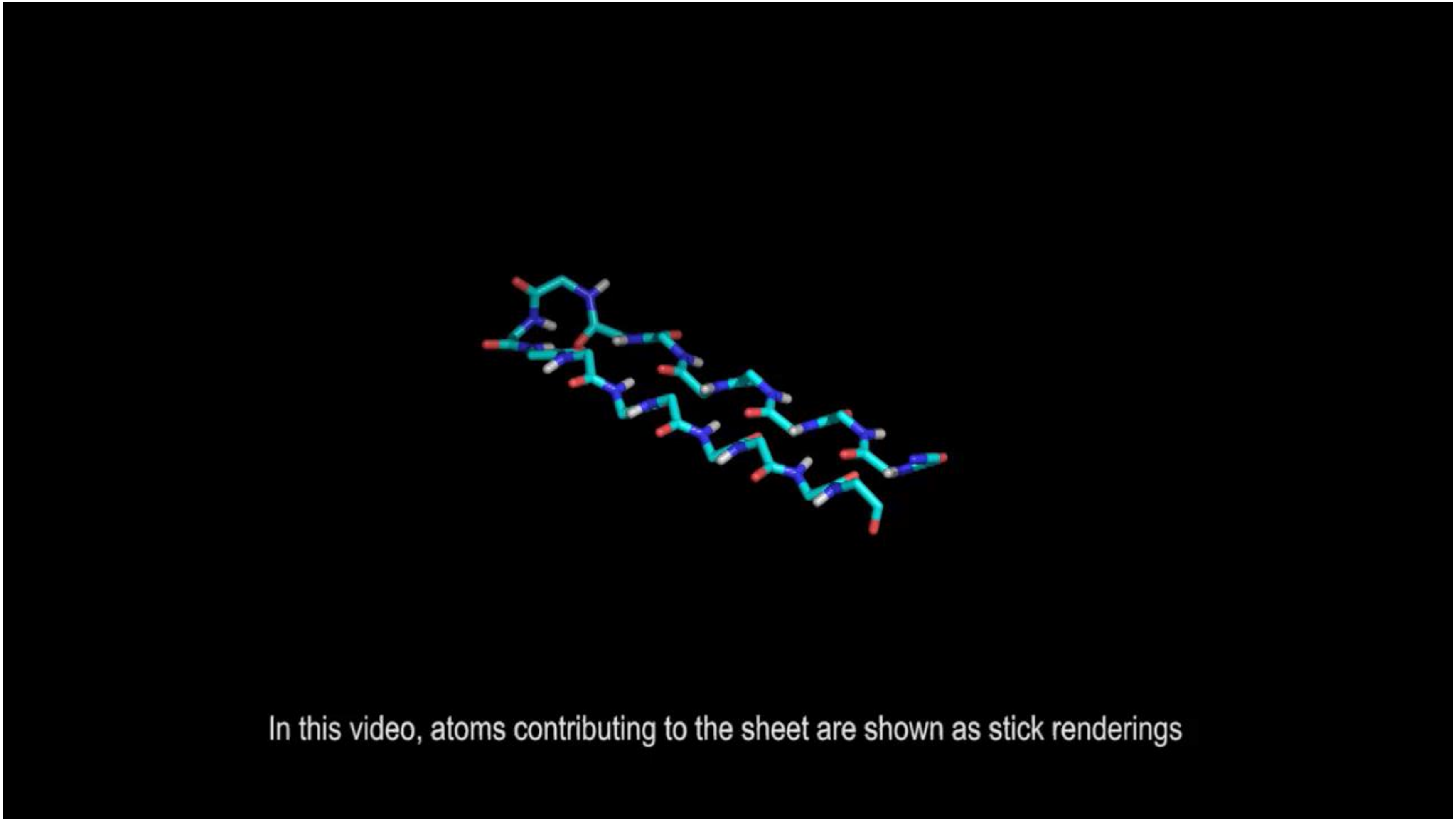
# Video: An Idealized α Helix



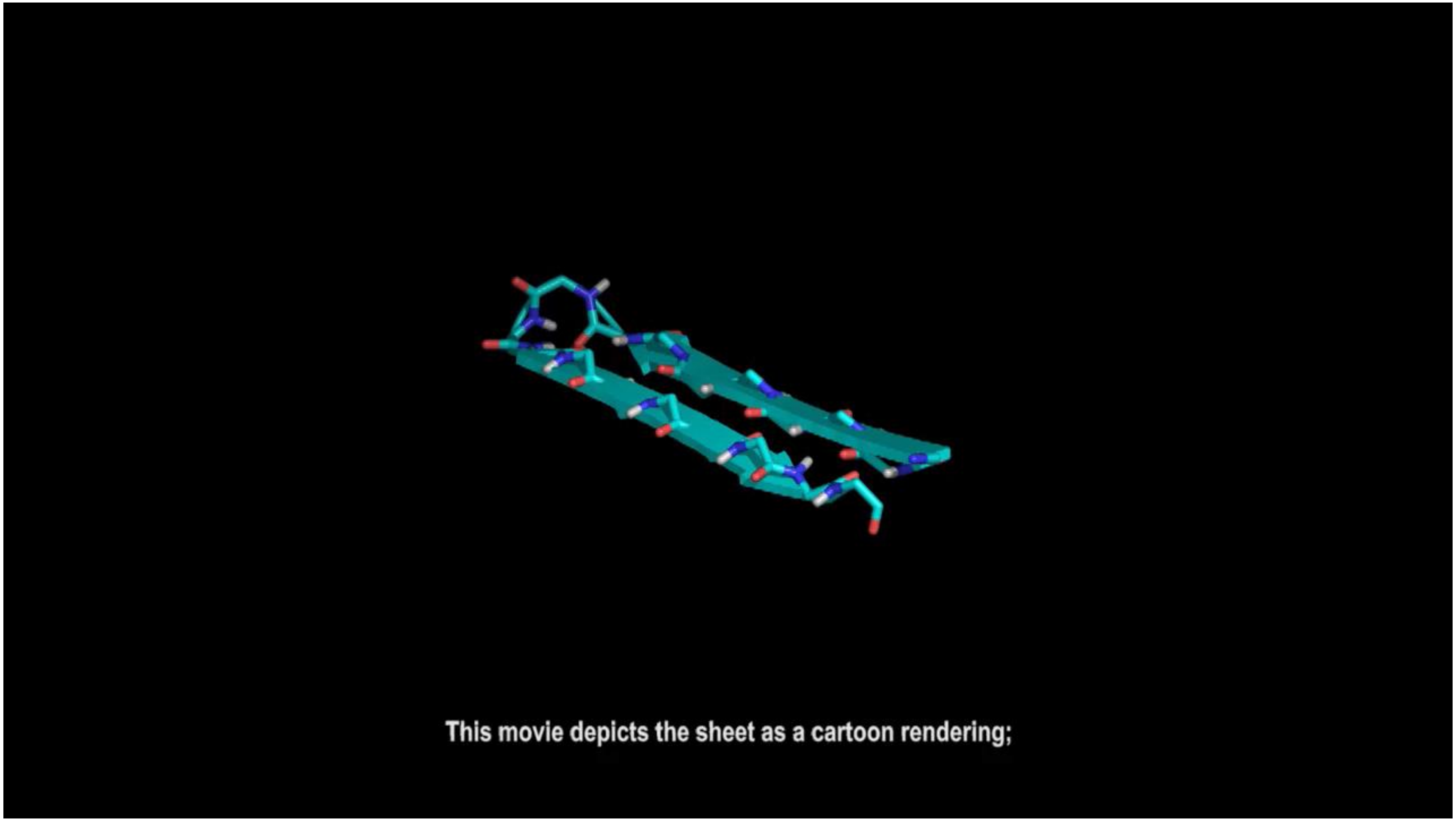
# Video: An Idealized α Helix: No Sidechains



# Video: An Idealized β Pleated Sheet

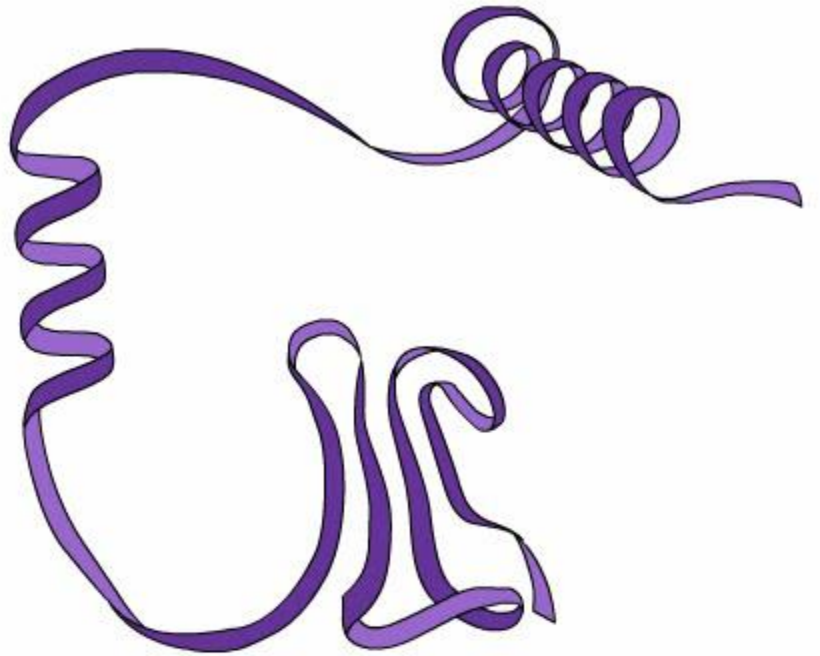


# Video: An Idealized β Pleated Sheet Cartoon



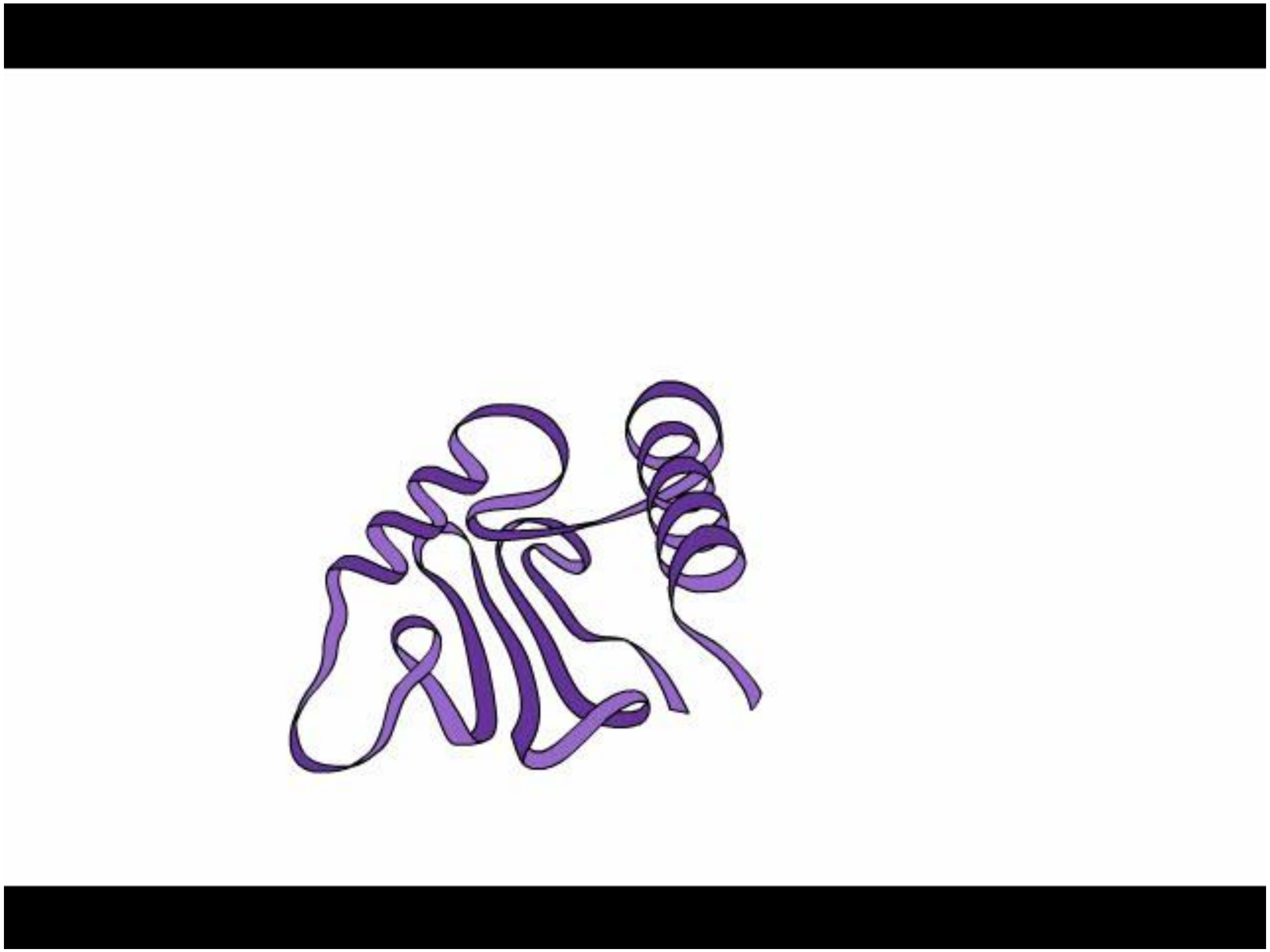
- **Tertiary structure**, the overall shape of a polypeptide, results from interactions between R groups, rather than interactions between backbone constituents
- These interactions include hydrogen bonds, ionic bonds, **hydrophobic interactions**, and van der Waals interactions
- Strong covalent bonds called **disulfide bridges** may reinforce the protein's structure

# Animation: Tertiary Protein Structure



- **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 $\beta$ subunits

# Animation: Quaternary Protein 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
- The abnormal hemoglobin molecules cause the red blood cells to aggregate into chains and to deform into a sickle shape

Figure 5.19

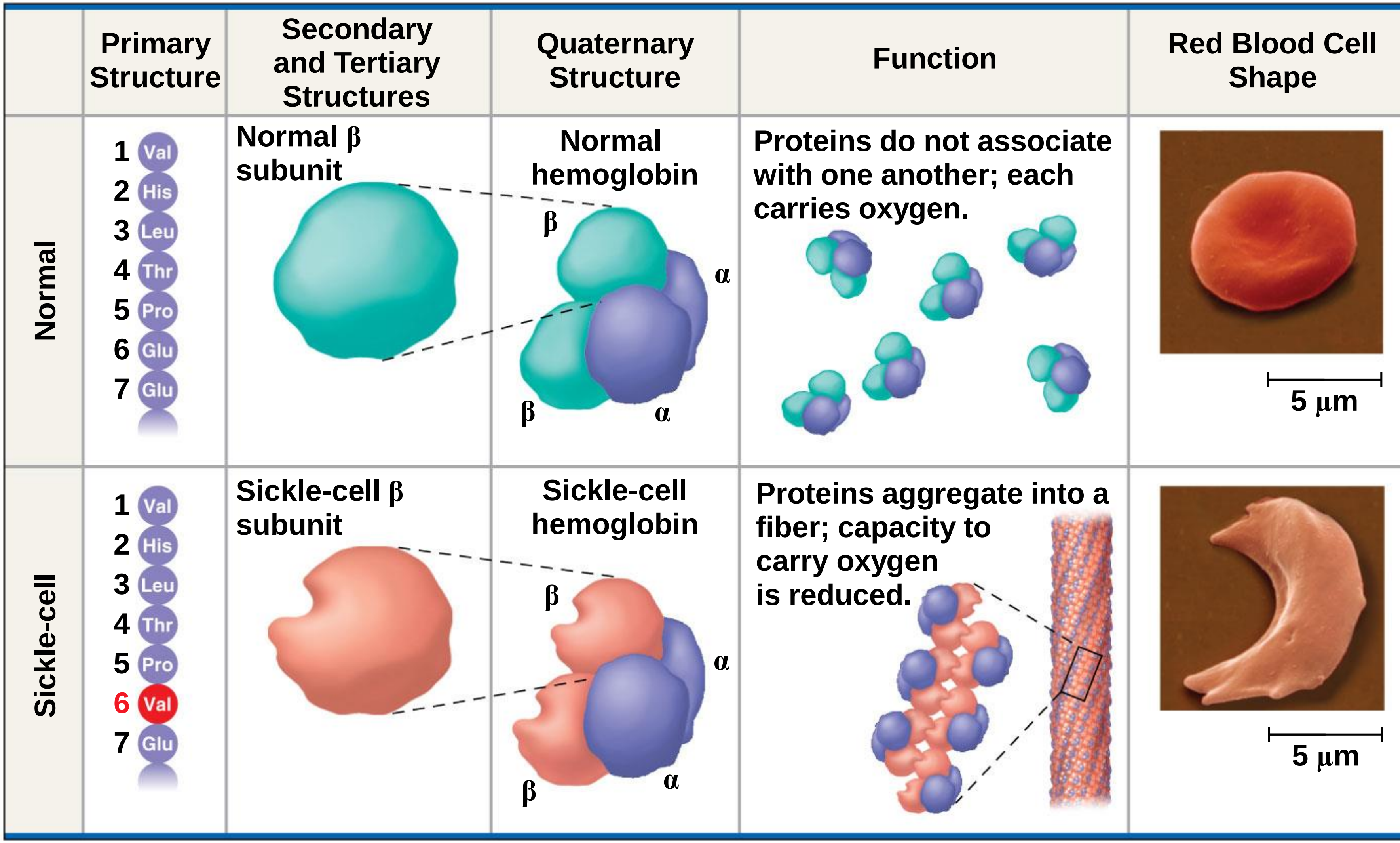

Primary Structure
Secondary and Tertiary Structures
Quaternary Structure
Function
Red Blood Cell Shape
Normal
1 Val
2 His
3 Leu
4 Thr
5 Pro
6 Glu
7 Glu
Normal β subunit
Normal hemoglobin
β
α
β
α
Proteins do not associate with one another; each carries oxygen.
5 µm
Sickle-cell
1 Val
2 His
3 Leu
4 Thr
5 Pro
6 Val
7 Glu
Sickle-cell β subunit
Sickle-cell hemoglobin
β
α
β
α
Proteins aggregate into a fiber; capacity to carry oxygen is reduced.
5 µm

Figure 5.19a

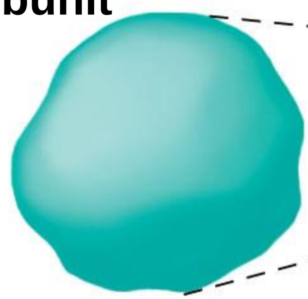
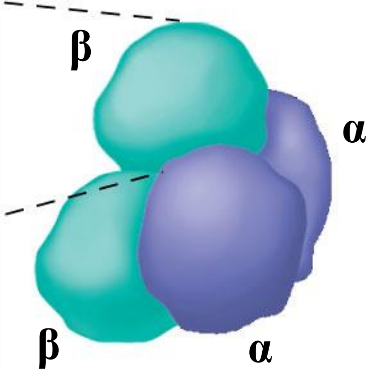
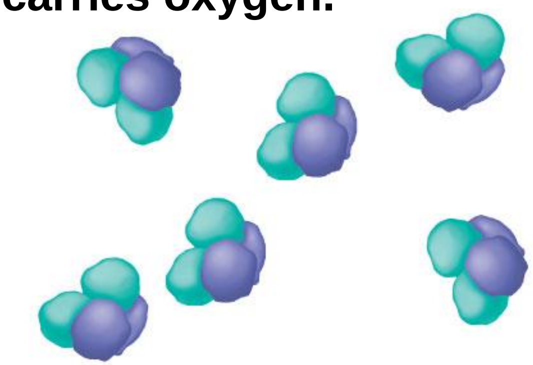
| | Primary Structure | Secondary and Tertiary Structures | Quaternary Structure | Function |
|---|---|---|---|---|
| Normal | 1 Val<br>2 His<br>3 Leu<br>4 Thr<br>5 Pro<br>6 Glu<br>7 Glu | Normal β subunit<br> | Normal hemoglobin<br><br> | Proteins do not associate with one another; each carries oxygen.<br> |

Figure 5.19aa

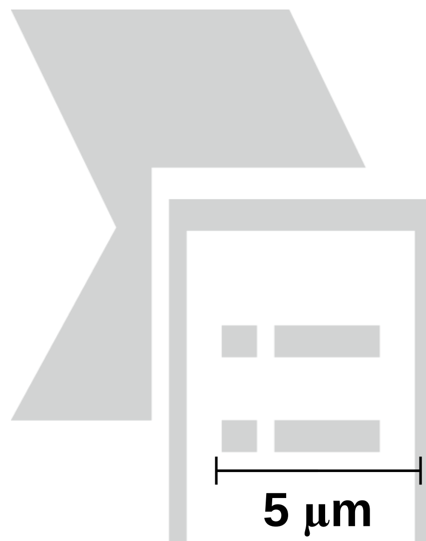


Figure 5.19b

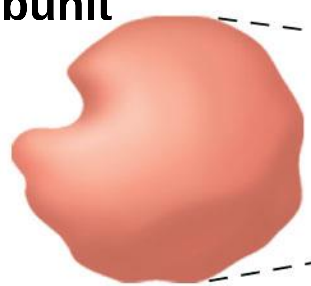
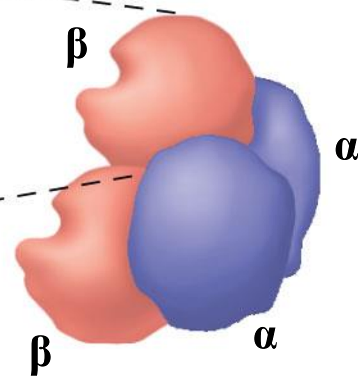
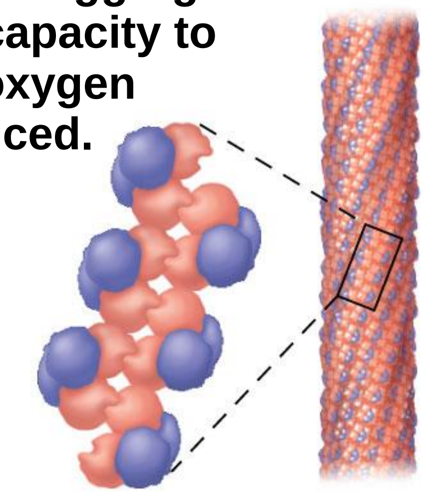
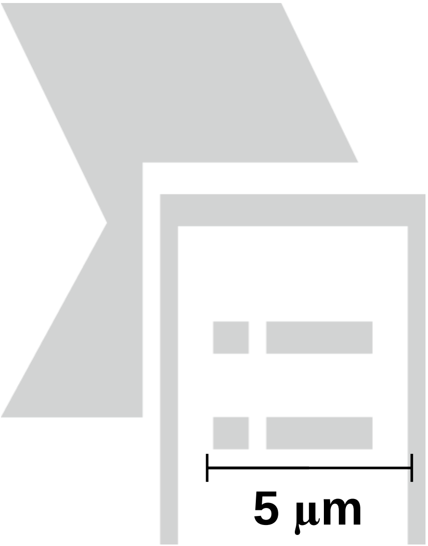
| | Primary Structure | Secondary and Tertiary Structures | Quaternary Structure | Function |
|---|---|---|---|---|
| Sickle-cell | 1 Val<br>2 His<br>3 Leu<br>4 Thr<br>5 Pro<br>6 Val<br>7 Glu | Sickle-cell β subunit  | Sickle-cell hemoglobin   | Proteins aggregate into a fiber; capacity to carry oxygen is reduced.  |

Figure 5.19ba



# ***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

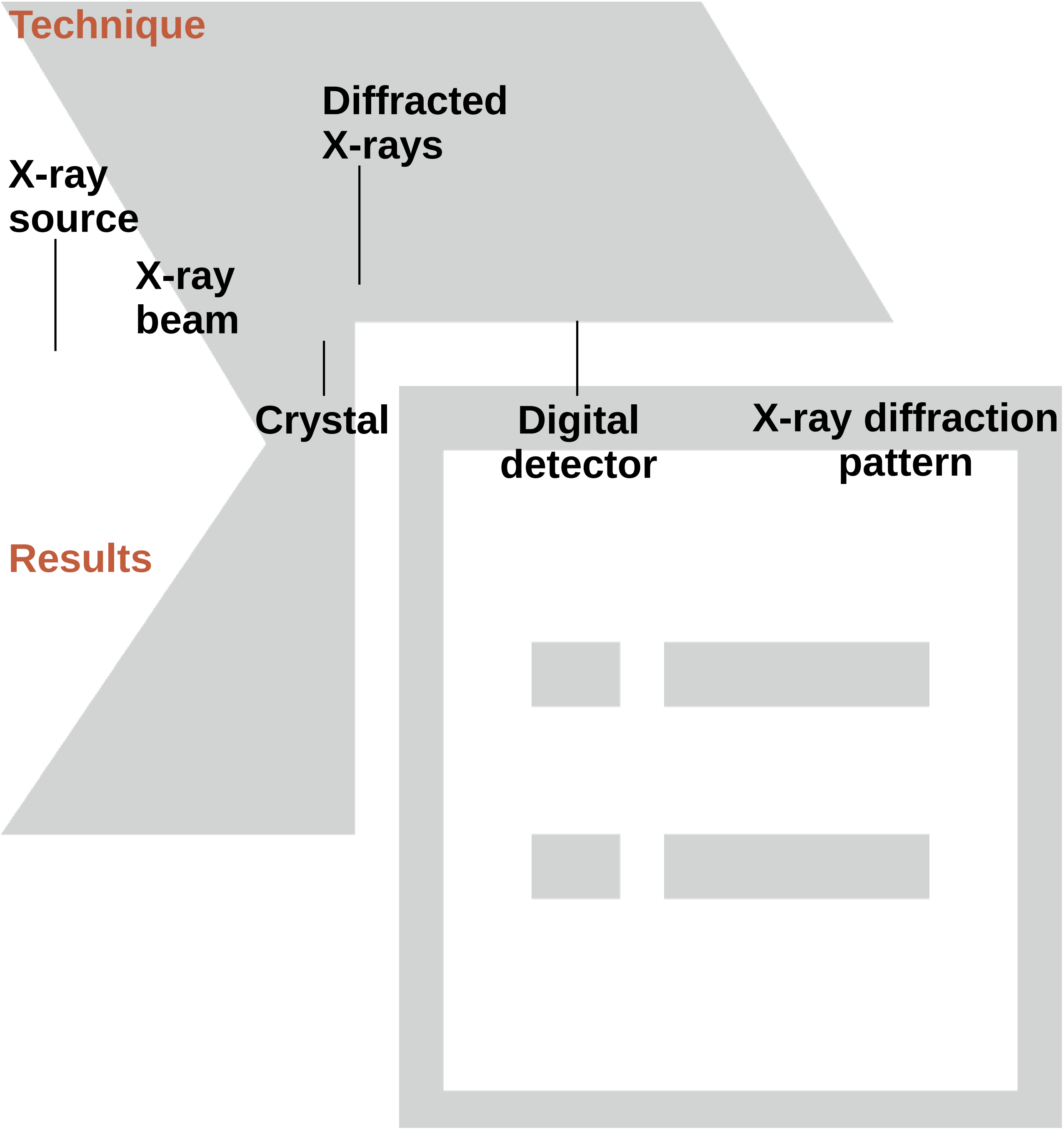
Figure 5.20

# *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
- Diseases such as Alzheimer’s, Parkinson’s, and mad cow disease are associated with misfolded proteins

- Scientists use **X-ray crystallography** to determine a protein’s structure
- Another method is nuclear magnetic resonance (NMR) spectroscopy, which does not require protein crystallization
- Bioinformatics is another approach to prediction of protein structure from amino acid sequences

Figure 5.21



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

# 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 consist 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
- This process is called **gene expression**

Figure 5.22_1

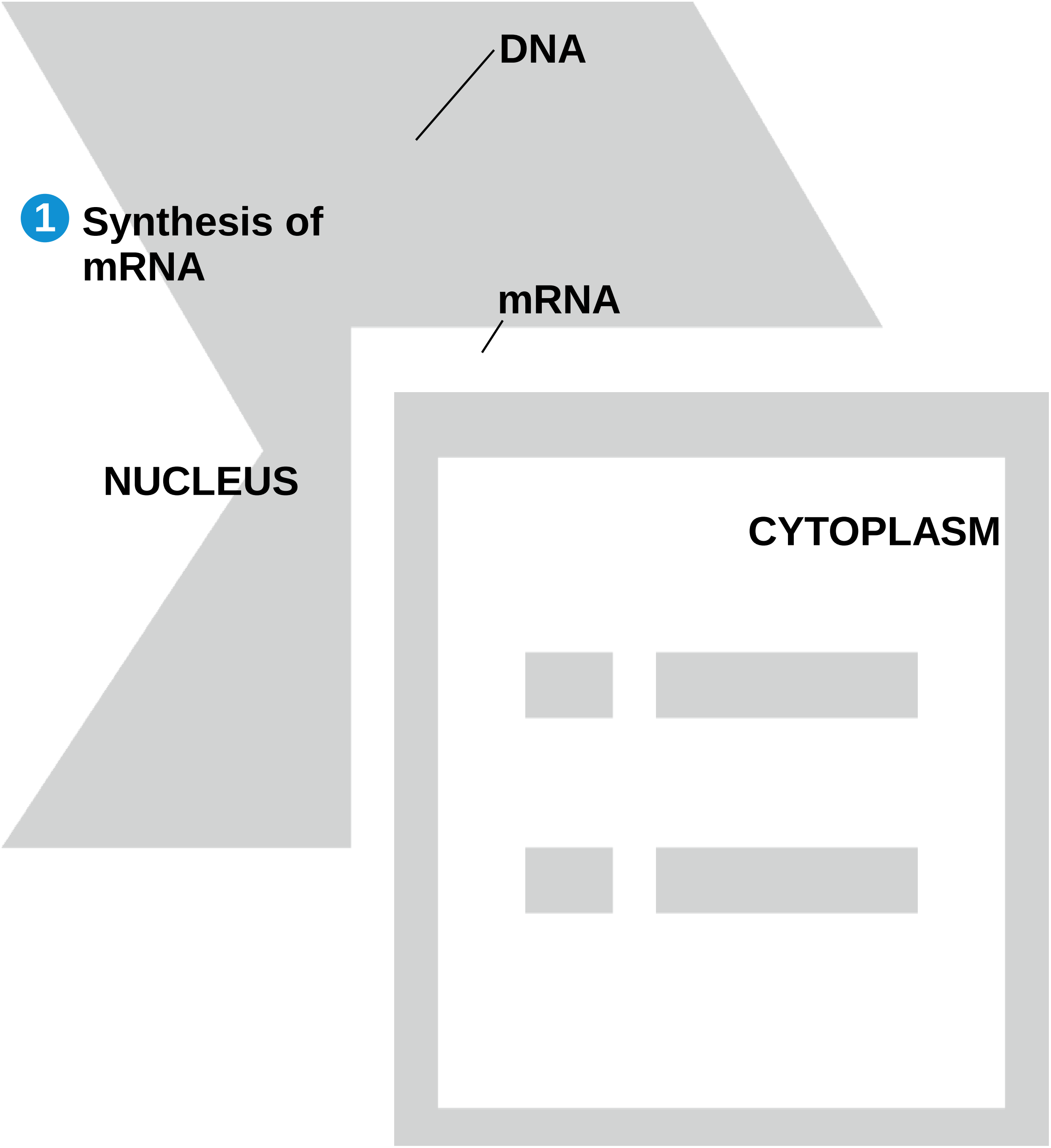


Figure 5.22_2

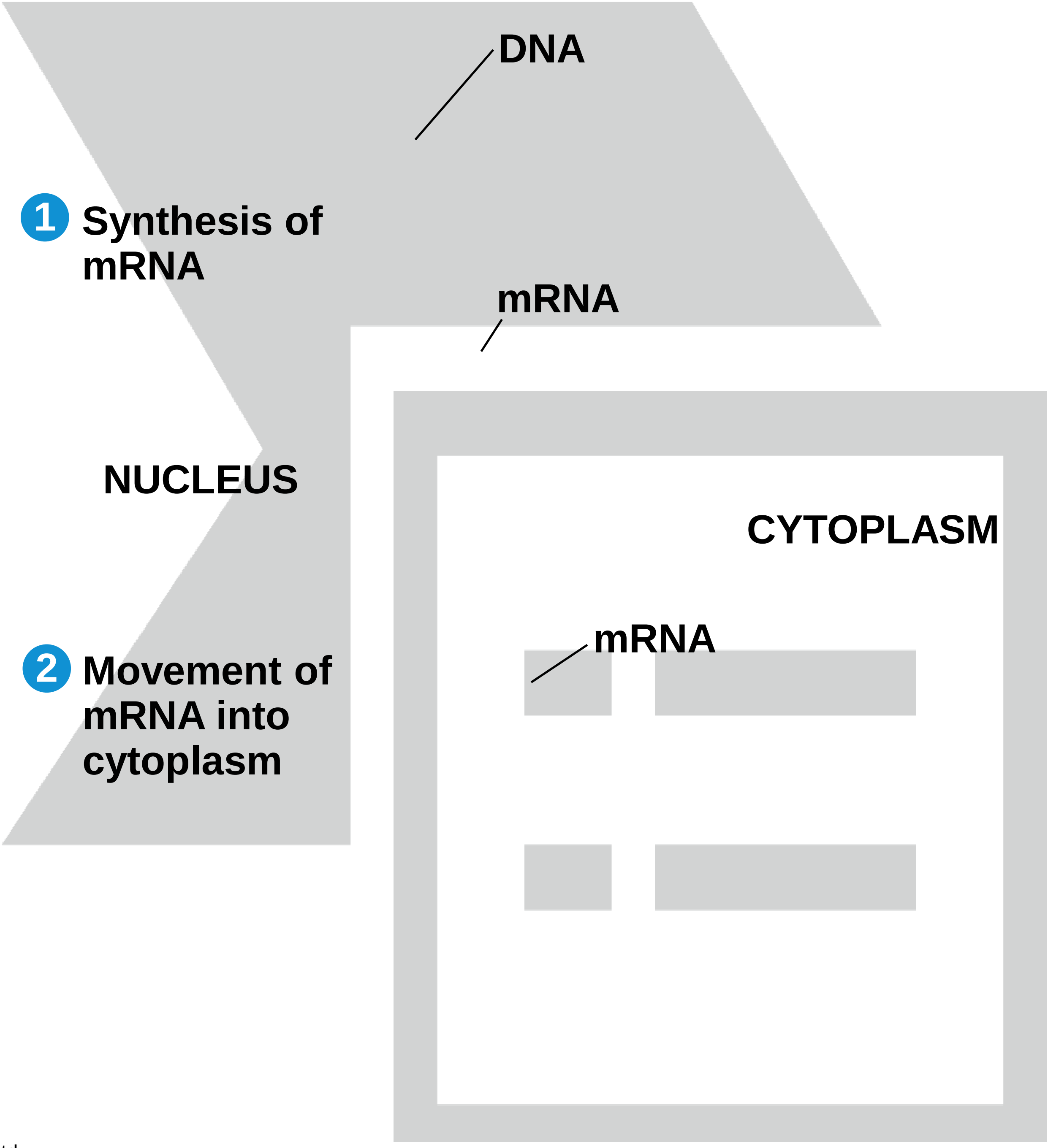
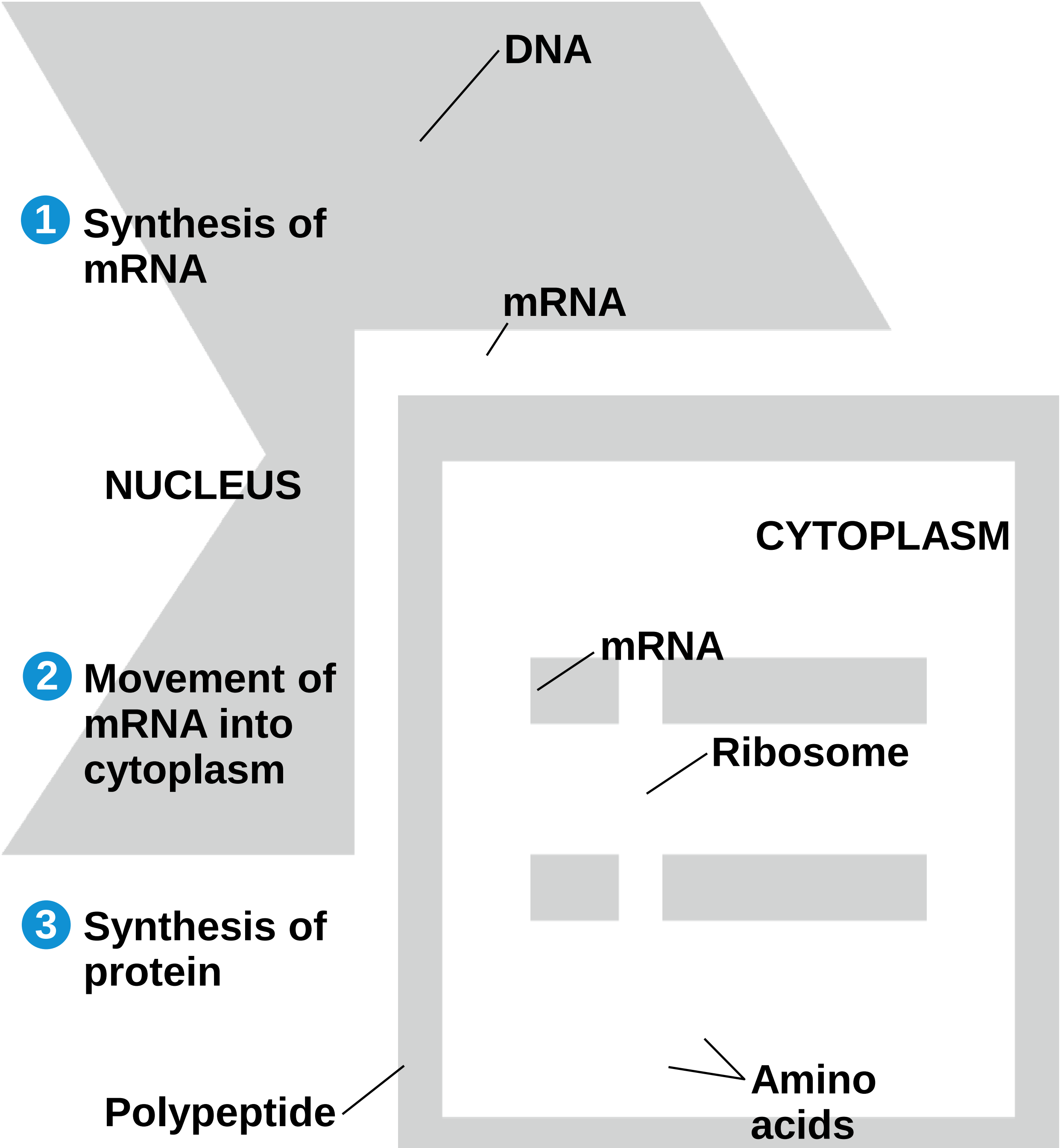

DNA
1 Synthesis of mRNA
mRNA
NUCLEUS
CYTOPLASM
mRNA
2 Movement of mRNA into cytoplasm

Figure 5.22_3


DNA
1 Synthesis of mRNA
mRNA
NUCLEUS
CYTOPLASM
mRNA
2 Movement of mRNA into cytoplasm
Ribosome
3 Synthesis of protein
Polypeptide
Amino acids

- Each gene along a DNA molecule directs synthesis of a messenger RNA (mRNA)
- The mRNA molecule interacts with the cell's protein-synthesizing machinery to direct production of a polypeptide
- The flow of genetic information can be summarized as DNA → RNA → protein

# 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

- 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

Figure 5.23

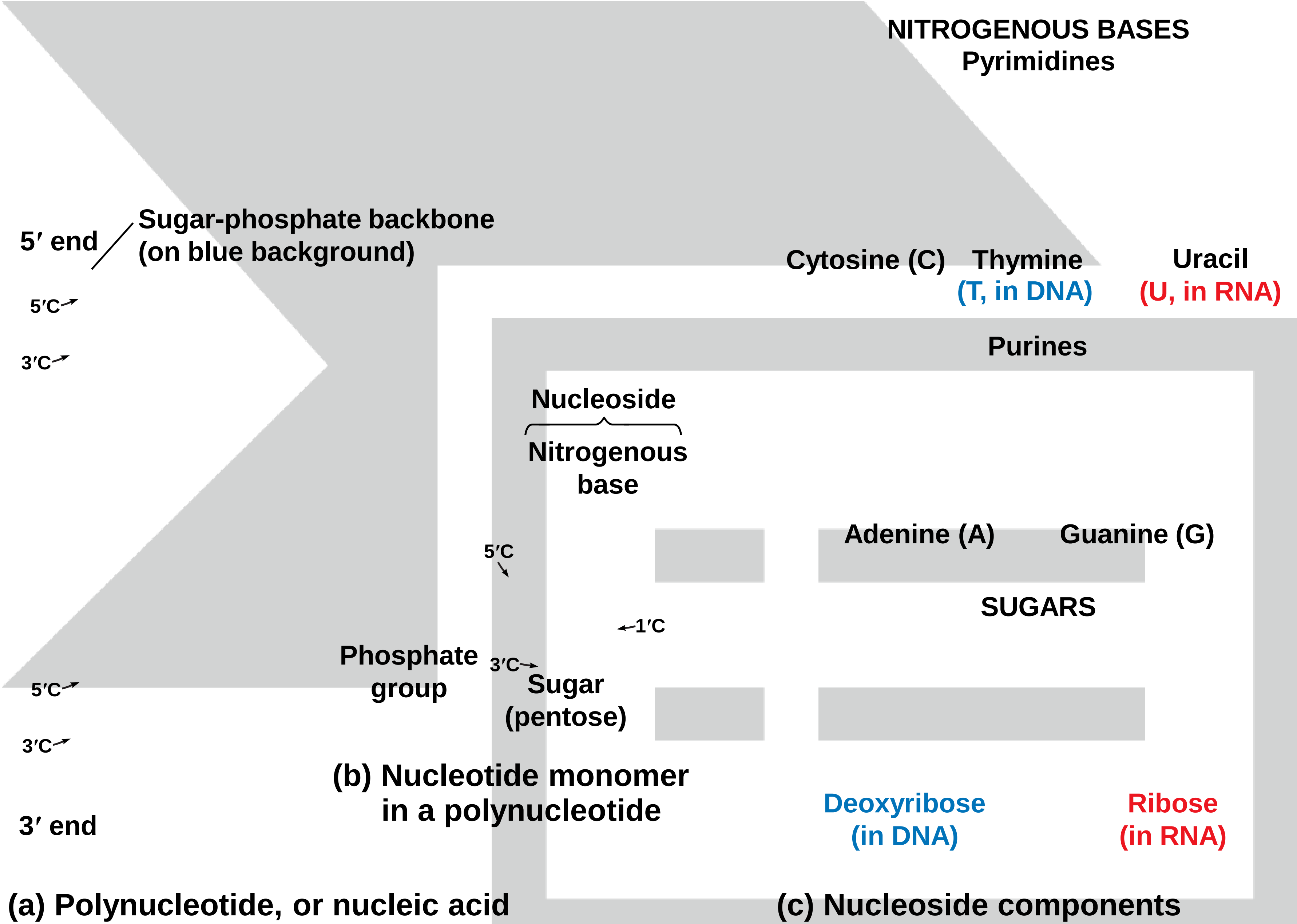
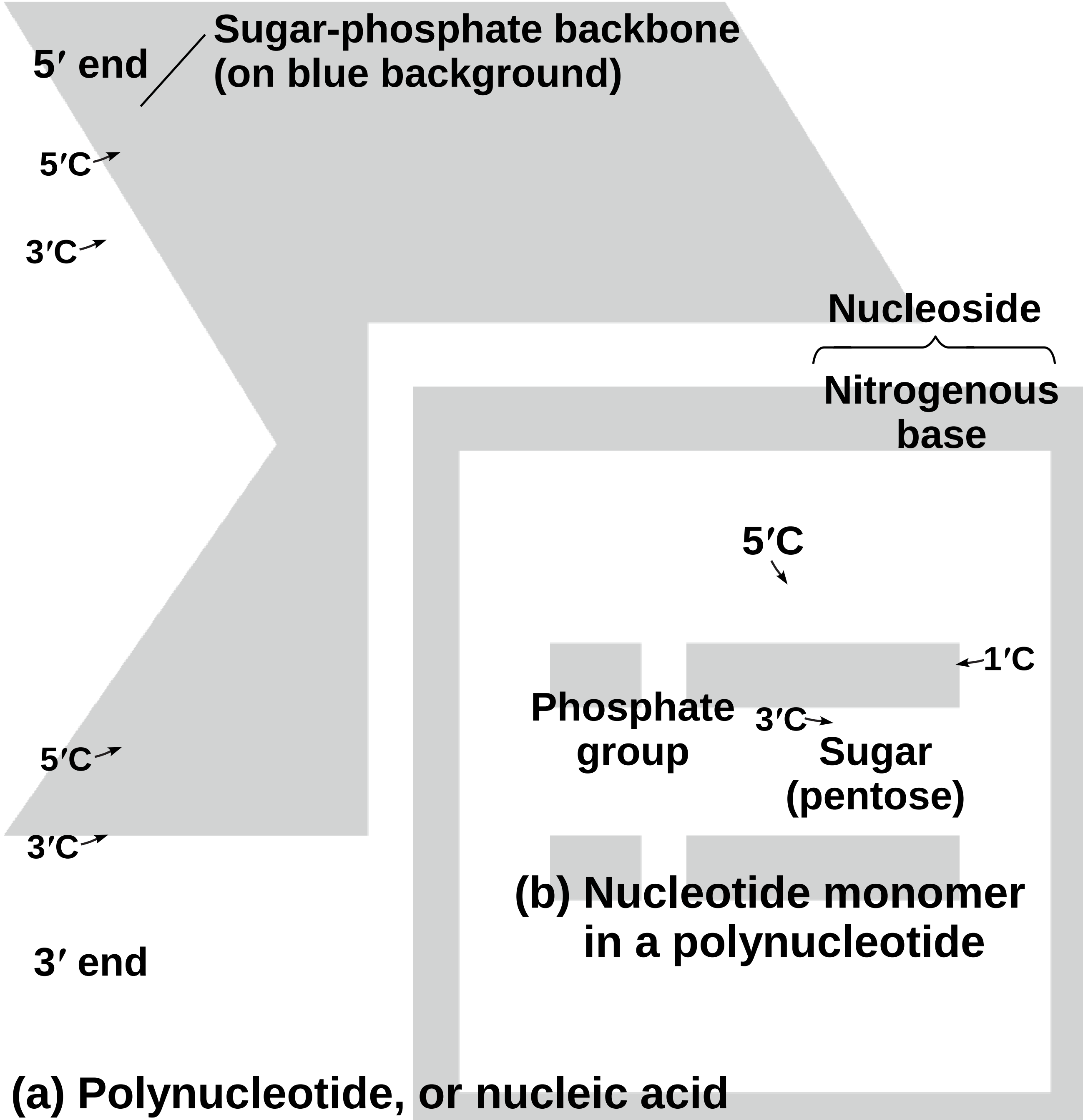

NITROGENOUS BASES
Pyrimidines
Sugar-phosphate backbone
(on blue background)
5′ end
5′C
3′C
Cytosine (C)
Thymine
(T, in DNA)
Uracil
(U, in RNA)
Purines
Nucleoside
Nitrogenous
base
5′C
Adenine (A)
Guanine (G)
SUGARS
1′C
Phosphate
group
3′C
Sugar
(pentose)
5′C
3′C
(b) Nucleotide monomer
in a polynucleotide
Deoxyribose
(in DNA)
Ribose
(in RNA)
3′ end
(a) Polynucleotide, or nucleic acid
(c) Nucleoside components

Figure 5.23a




(a) Polynucleotide, or nucleic acid

Figure 5.23b

## NITROGENOUS BASES

### Pyrimidines

Cytosine (C)

Thymine
(T, in DNA)

Uracil
(U, in RNA)

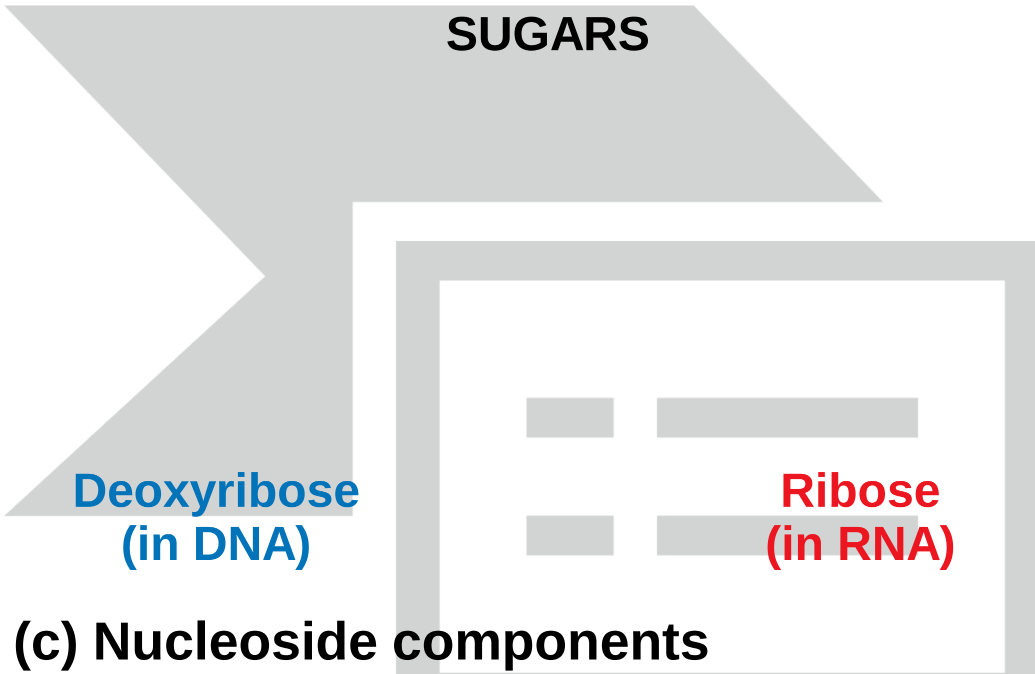
### Purines

Adenine (A)

Guanine (G)

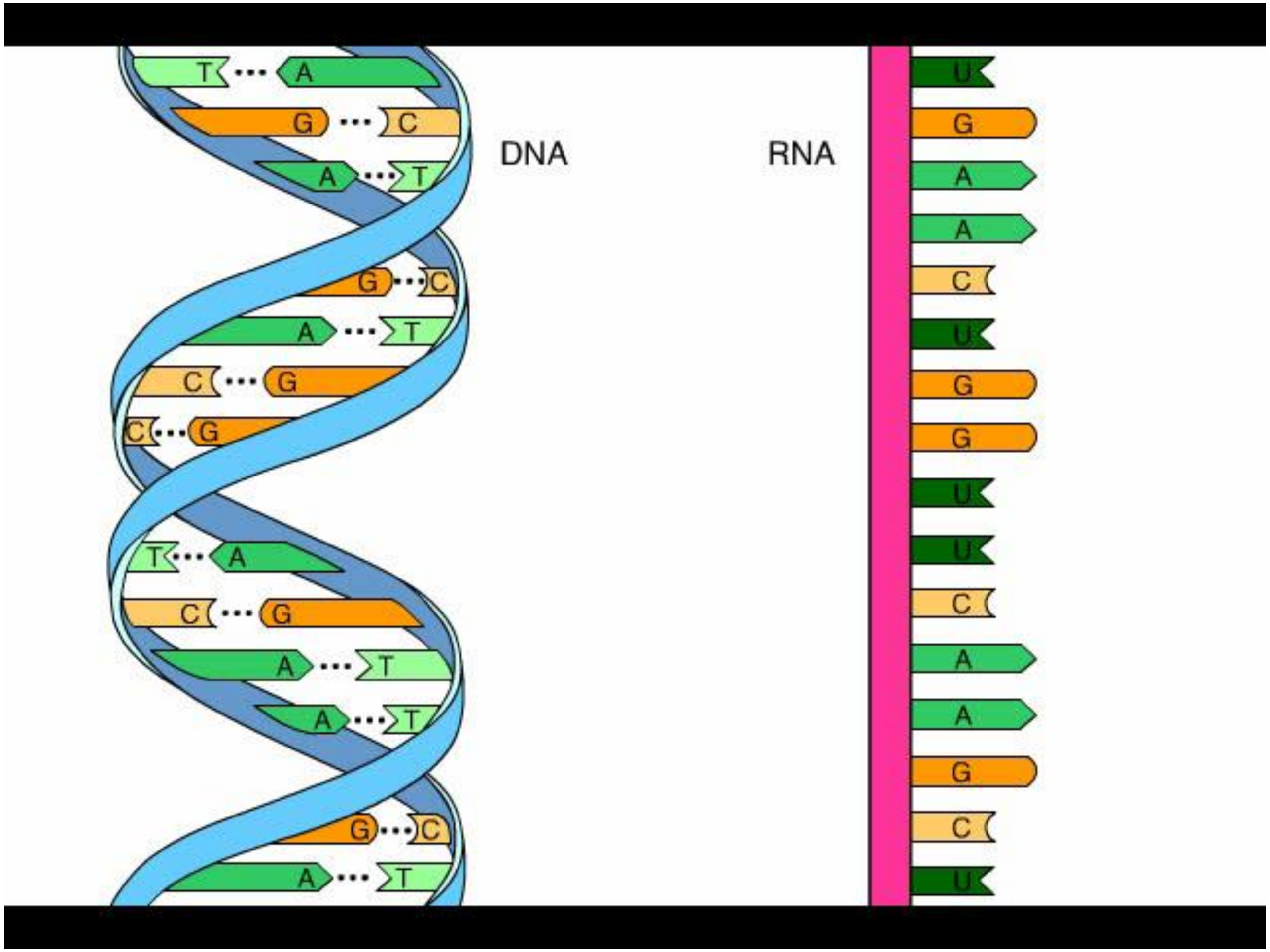
**(c) Nucleoside components**

Figure 5.23c




**(c) Nucleoside components**

# Animation: DNA and RNA Structure



# Nucleotide Polymers

- Nucleotides are linked together by a phosphodiester linkage to build a polynucleotide
- A phosphodiester linkage consists of a phosphate group that links the sugars of two nucleotides
- 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

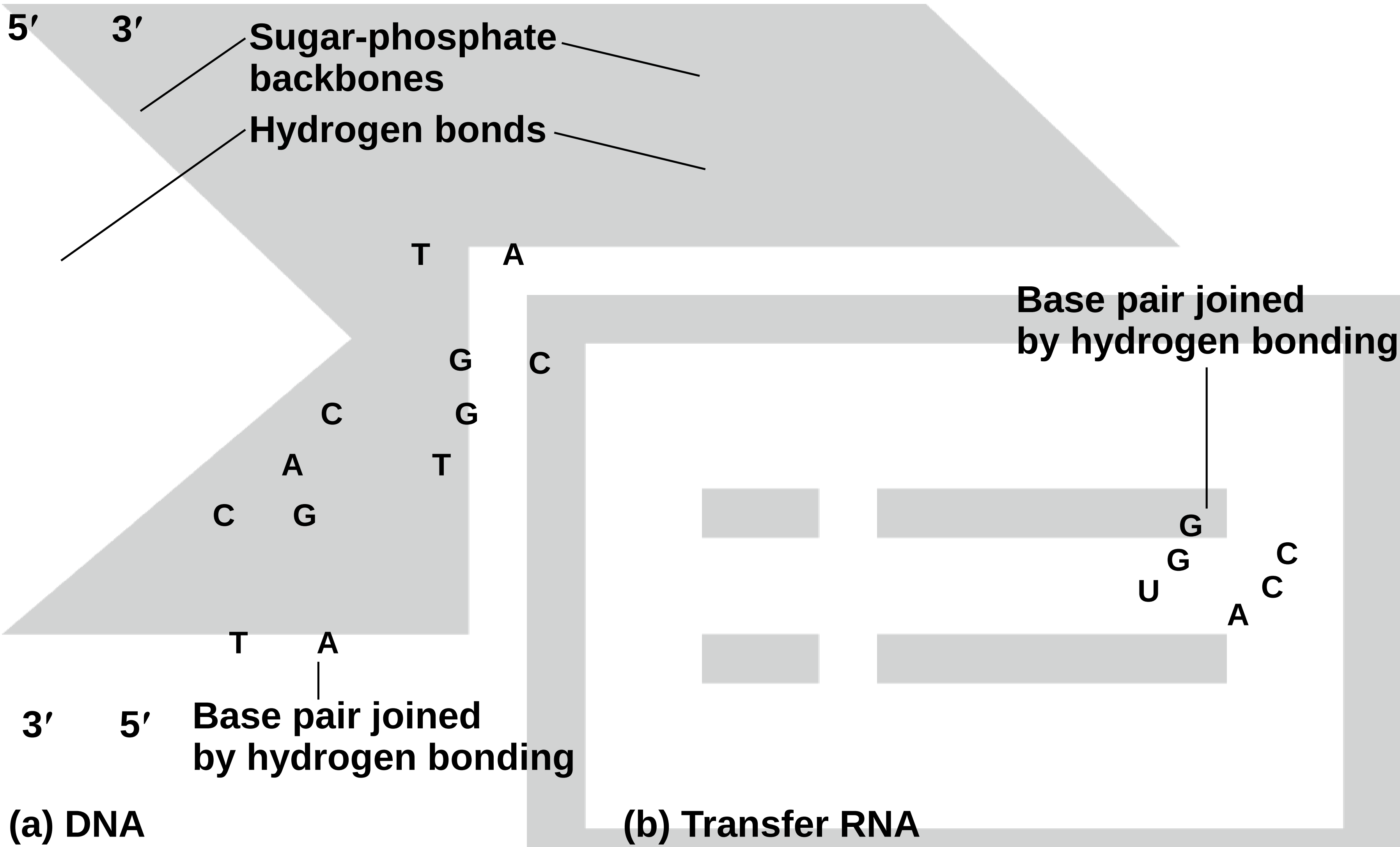
# The Structures of DNA and RNA Molecules

- DNA molecules have two polynucleotides spiraling around an imaginary axis, forming a **double helix**
- The backbones run in opposite 5′ → 3′ directions from each other, an arrangement referred to as **antiparallel**
- One DNA molecule includes many genes

- Only certain 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
- This feature of DNA structure makes it possible to generate two identical copies of each DNA molecule in a cell preparing to divide

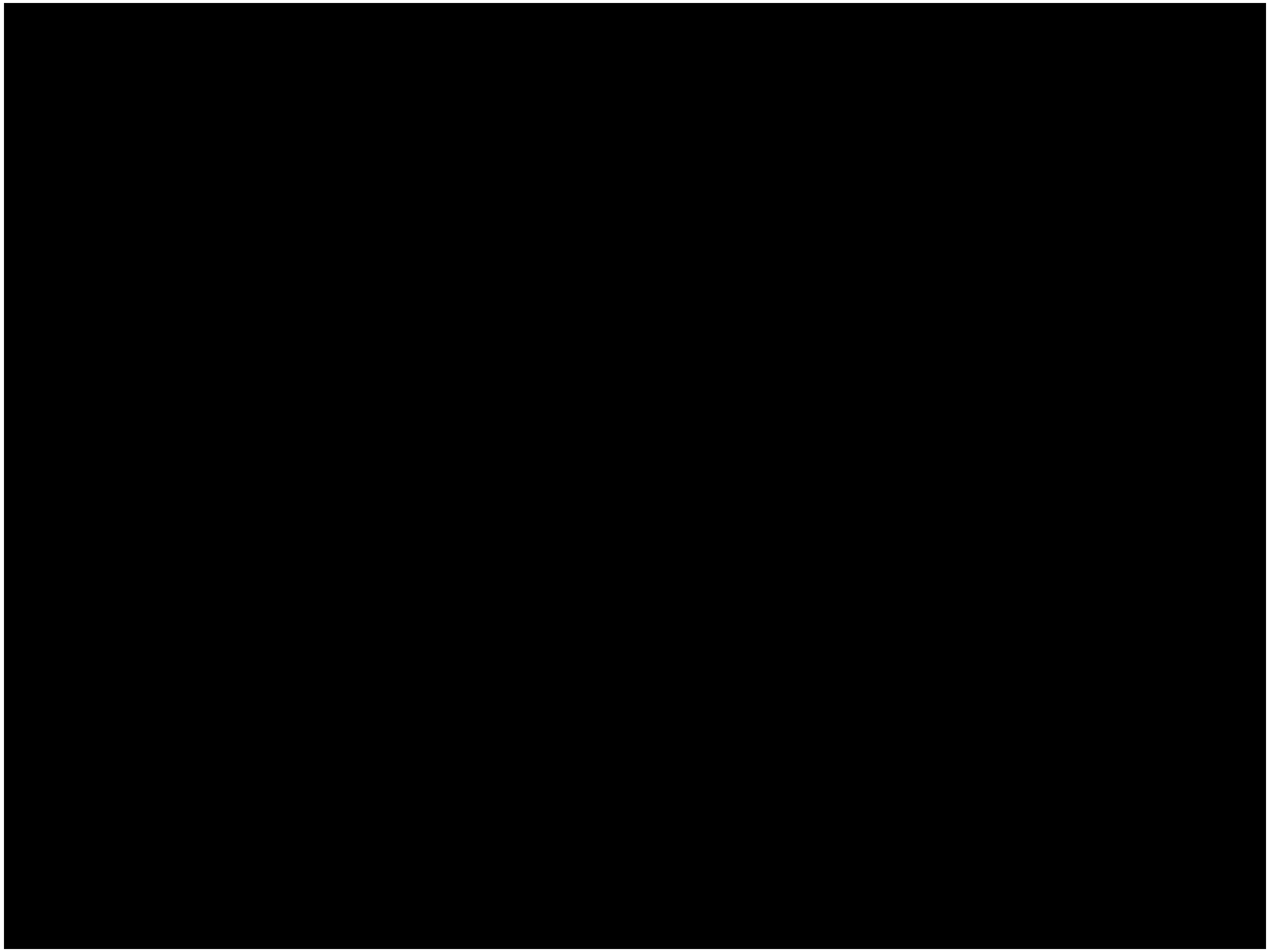
- RNA, in contrast to DNA, is single-stranded
- Complementary pairing can also occur between two RNA molecules or between parts of the same molecule
- In RNA, thymine is replaced by uracil (U), so A and U pair
- While DNA always exists as a double helix, RNA molecules are more variable in form

Figure 5.24



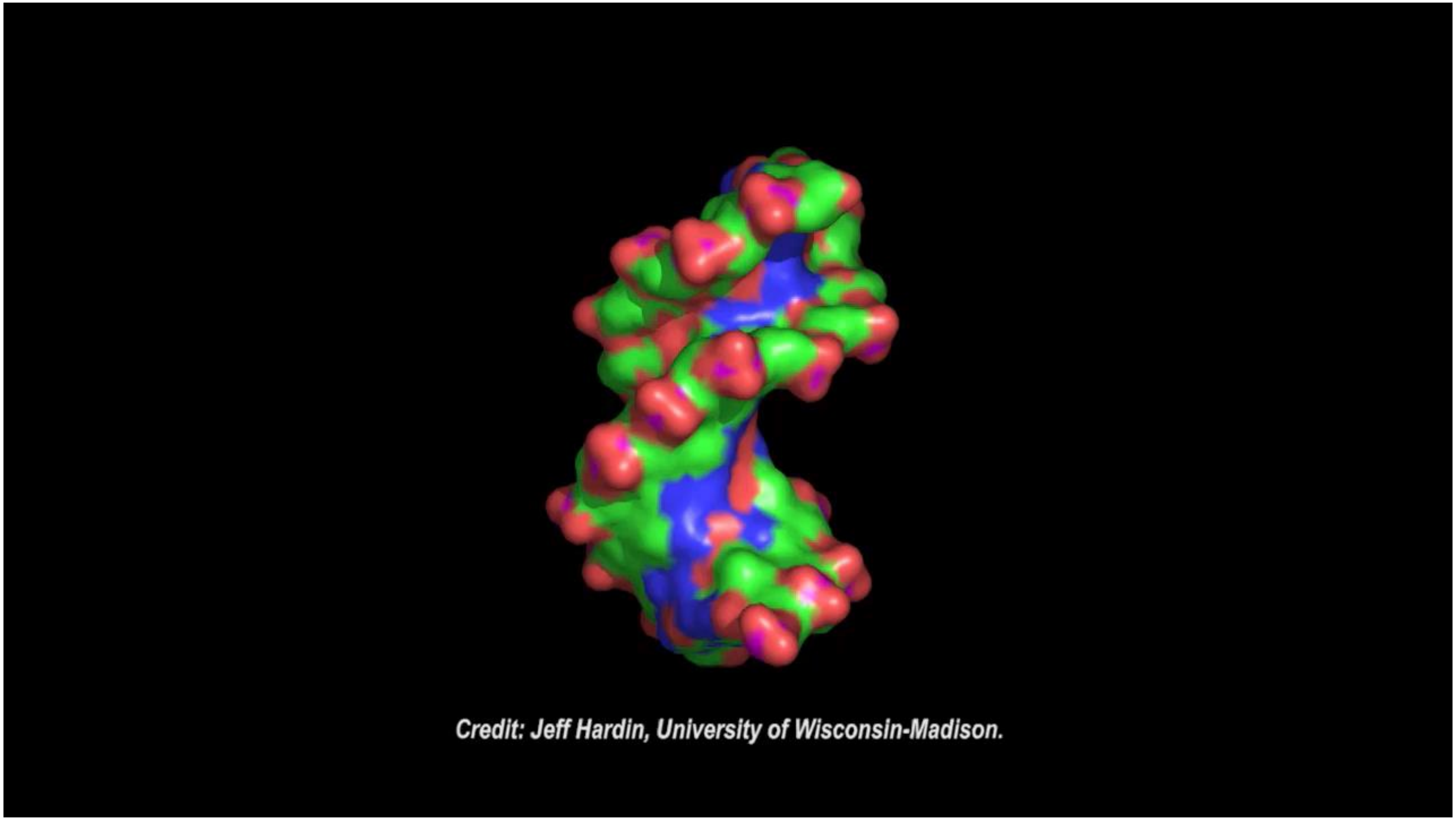
5′
3′
Sugar-phosphate backbones
Hydrogen bonds
T A
G C
C G
A T
C G
T A
3′
5′
Base pair joined by hydrogen bonding
(a) DNA
Base pair joined by hydrogen bonding
G
G C
U C
A
(b) Transfer RNA

# Animation: DNA Double Helix



# Video: Stick Model of DNA (Deoxyribonucleic Acid)

# Video: Surface Model of DNA (Deoxyribonucleic Acid)

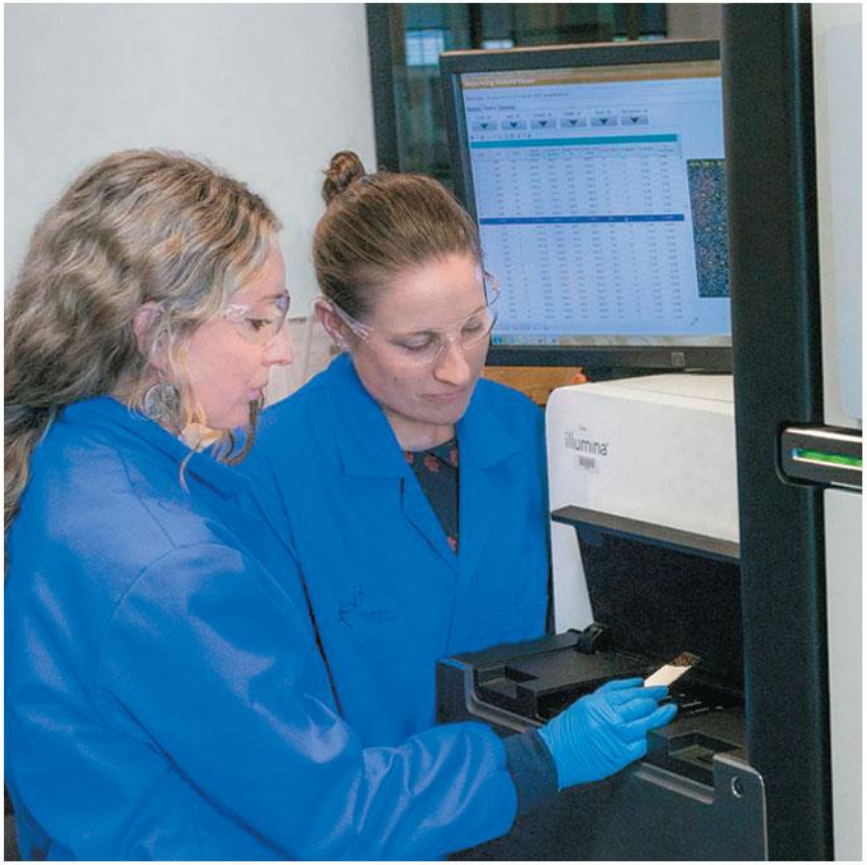


# Concept 5.6: Genomics and proteomics have transformed biological inquiry and applications

- Once the structure of DNA and its relationship to amino acid sequence was understood, biologists sought to “decode” genes by learning their base sequences
- The first chemical techniques for DNA sequencing were developed in the 1970s and refined over the next 20 years

- It is enlightening to sequence the full complement of DNA in an organism’s genome
- The rapid development of faster and less expensive methods of sequencing was a side effect of the Human Genome Project
- Many genomes have been sequenced, generating large sets of data

Figure 5.25



- **Bioinformatics** uses computer software and other computational tools to deal with the data resulting from sequencing many genomes
- Analyzing large sets of genes or even comparing whole genomes of different species is called **genomics**
- A similar analysis of large sets of proteins including their sequences is called **proteomics**

Figure 5.26

# MAKE CONNECTIONS:
# Contributions of Genomics and Proteomics to Biology

**Paleontology**

**Evolution**

**Hippopotamus**

**Short-finned pilot whale**

**Medical Science**

**Conservation Biology**

**Species Interactions**

Figure 5.26a

Figure 5.26b

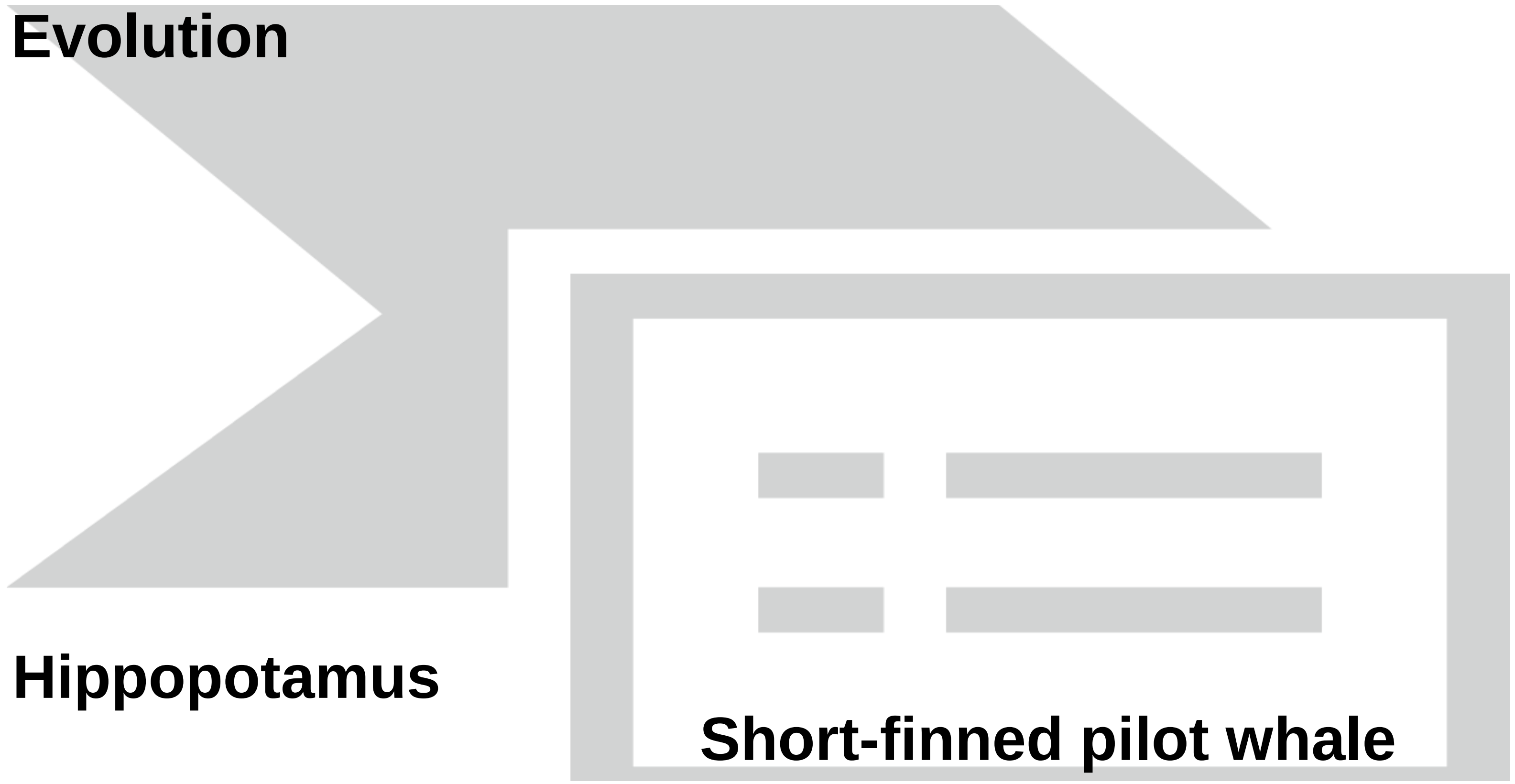


Figure 5.26ba

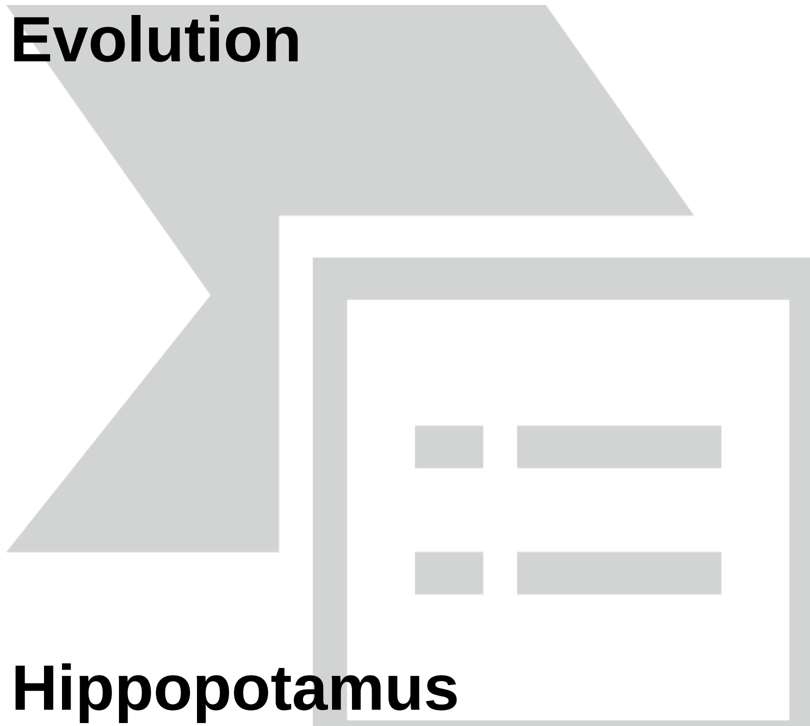


Figure 5.26bb

# Evolution

## Short-finned pilot whale

Figure 5.26c

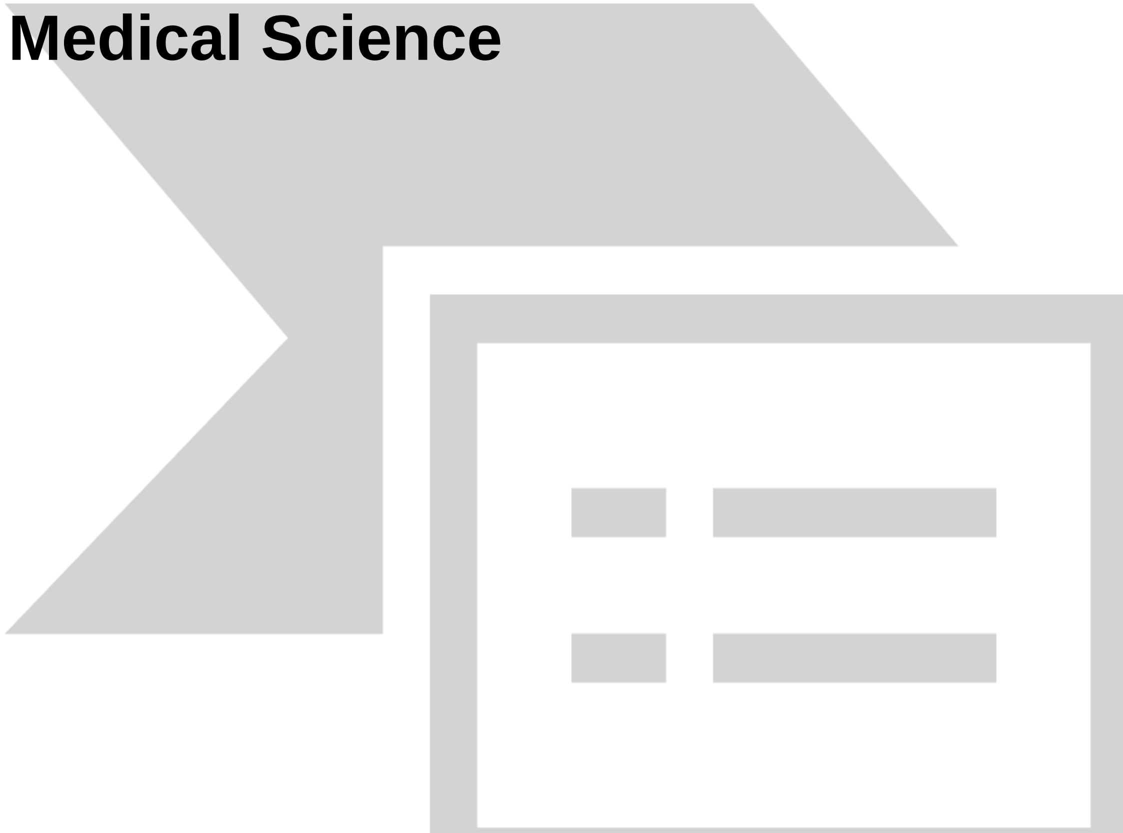
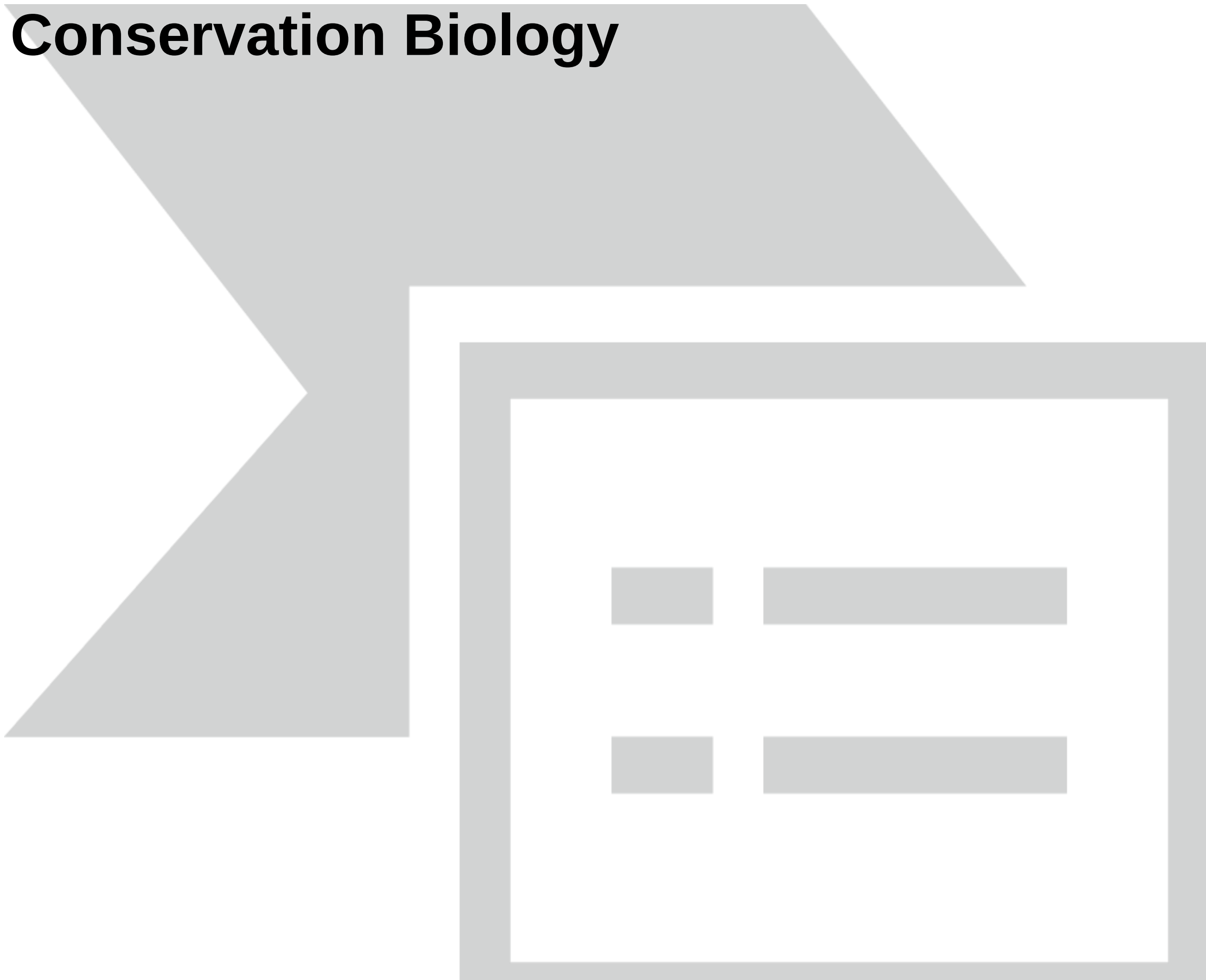


Figure 5.26d

# Conservation Biology



# Species Interactions

# DNA and Proteins as Tape Measures of Evolution

- Sequences of genes and their protein products document the hereditary background of an organism
- Linear sequences of DNA molecules are passed from parents to offspring
- We can extend the concept of “molecular genealogy” to relationships between species
- Molecular biology has added a new measure to the toolkit of evolutionary biology

Figure 5.UN02a

Figure 5.UN02b

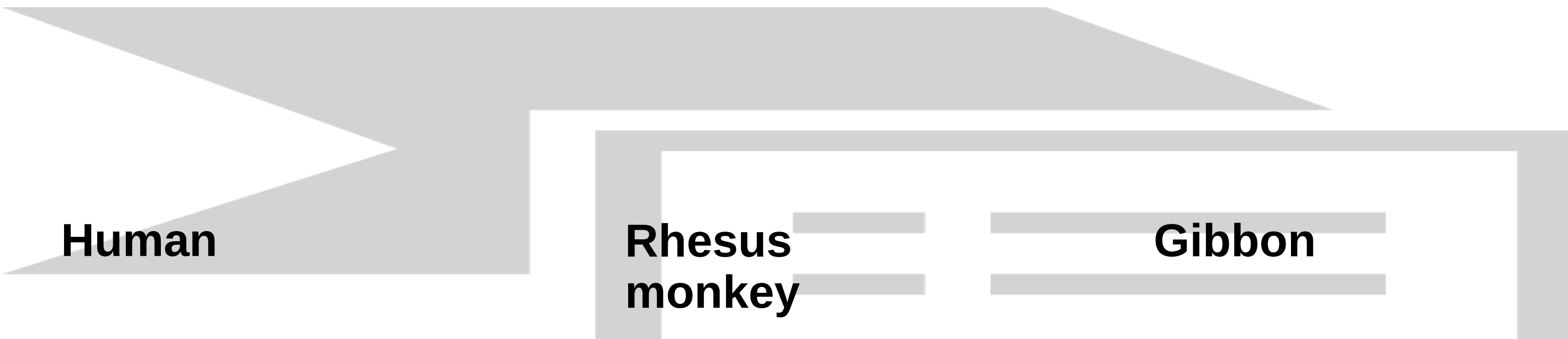


Figure 5.UN03a

Figure 5.UN03b

Figure 5.UN04

| 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) | Strengthens plant cell walls |
| | Starch (plants) | Stores glucose for energy |
| | Glycogen (animals) | Stores glucose for energy |
| | Chitin (animals and fungi) | Strengthens exoskeletons and fungal cell walls |

Figure 5.UN05

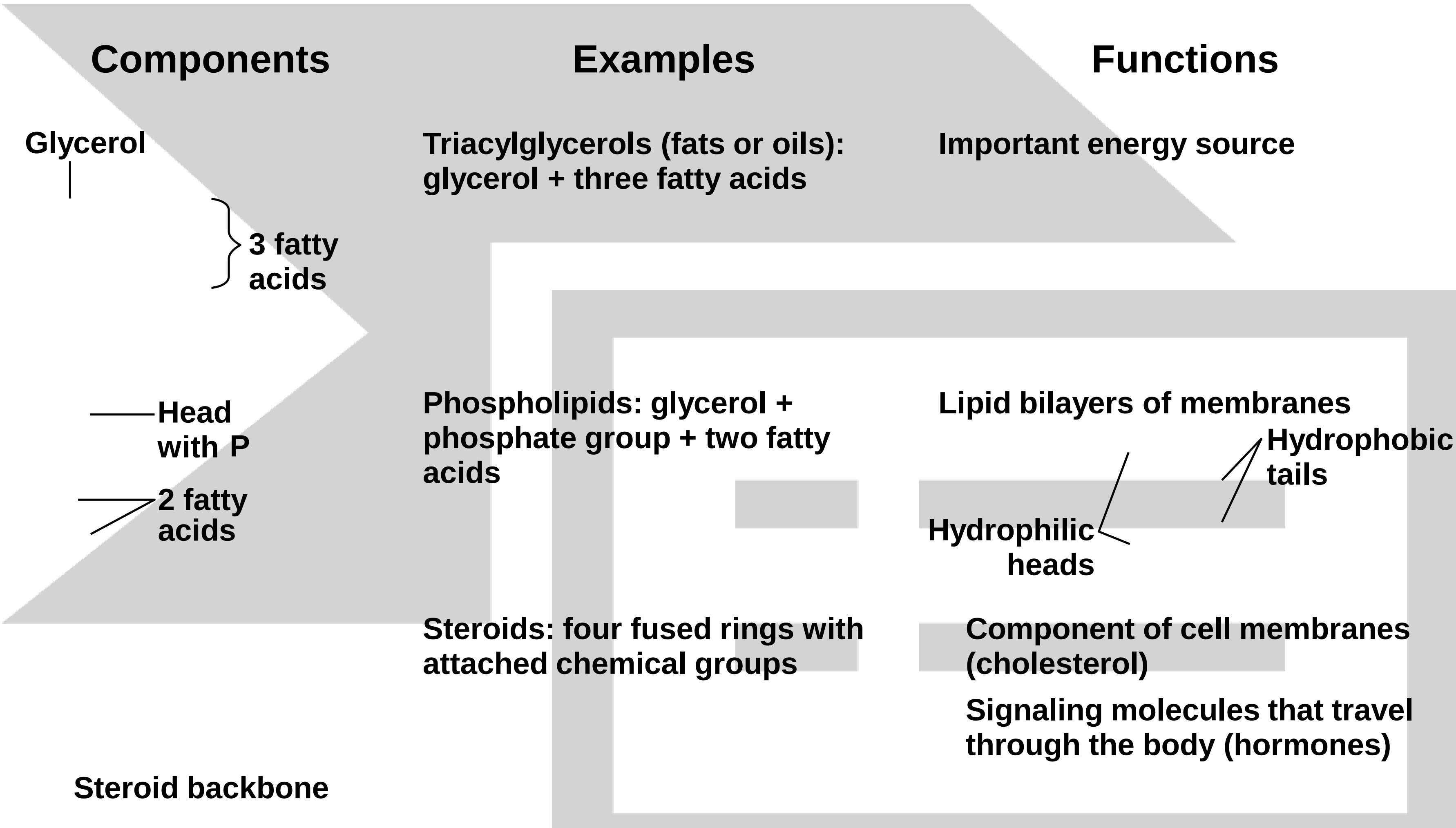


Figure 5.UN06

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

Figure 5.UN07

| Components | Examples | Functions |
| --- | --- | --- |
| Nitrogenous base<br>Phosphate group<br>P<br>Sugar<br>Nucleotide (monomer of a polynucleotide) | **DNA:**<br>Sugar = deoxyribose<br>Nitrogenous bases = C, G, A, T<br>Usually double-stranded | Stores hereditary information |
| | **RNA:**<br>Sugar = ribose<br>Nitrogenous bases = C, G, A, U<br>Usually single-stranded | Various functions in gene expression, including carrying instructions from DNA to ribosomes |

Figure 5.UN08