The Structure & Function of Large Biological Molecules

Chapter 5

Overview: The Molecules of Life

- All living things are made up of four classes of large biological molecules:

1.
2.
3.
4.

- **Macromolecules** are large molecules composed of thousands of covalently connected atoms
- Core idea to remember:

Macromolecules are polymers, built from monomers

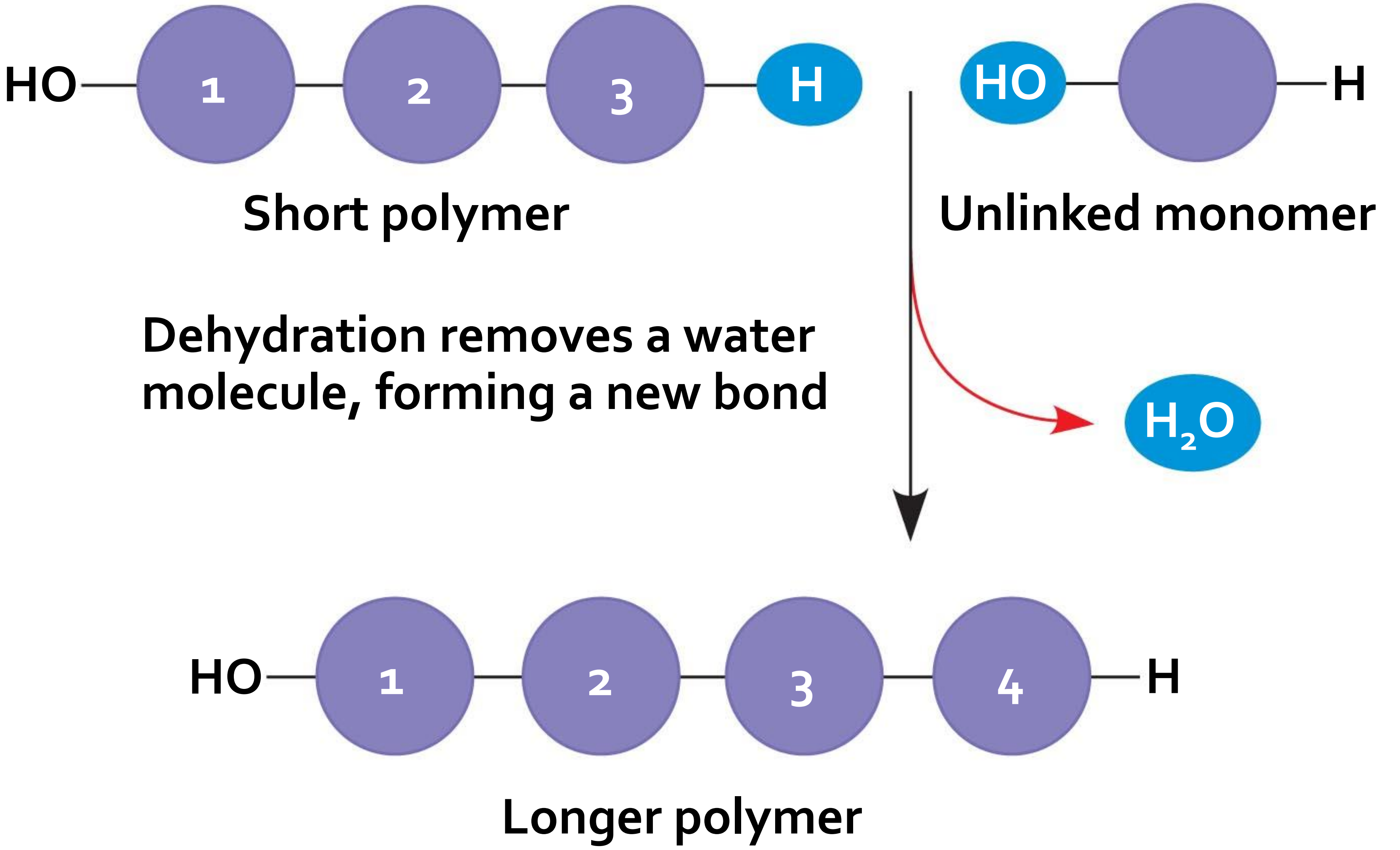
- A **polymer** is a long molecule consisting of many similar building blocks
- These small building-block molecules are called …
- Three of the four classes of life's organic molecules are polymers:

1.
2.
3.

The Synthesis and Breakdown of Polymers

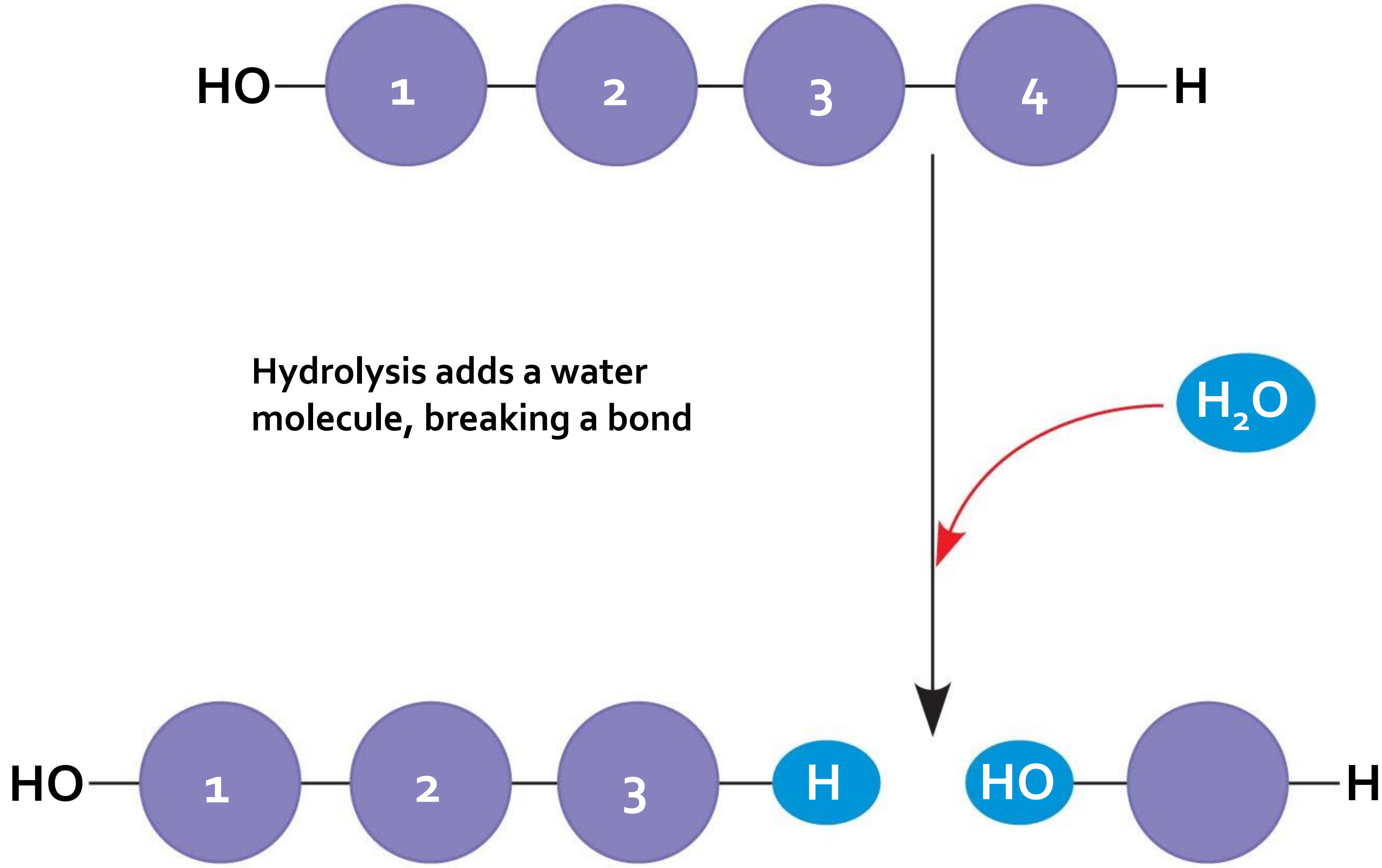
- Polymers are built through a **dehydration reaction**
  - when two monomers bond together at a hydroxyl and a carboxyl group
  - What is lost?
  - **Enzymes** speed up the dehydration process
- Polymers are disassembled to monomers by **hydrolysis**
  - Hydro =
  - Lysis =
  - Therefore…

Fig. 5-2a



(a) Dehydration reaction in the synthesis of a polymer

Fig. 5-2b



(b) Hydrolysis of a polymer

Carbohydrates

- sugars and the polymers of sugars
- simplest carbohydrates are monosaccharides, or single 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
  - Most occur in ring form
- Carbohydrate macromolecules are polysaccharides, polymers composed of many sugar building blocks

Fig. 5-3

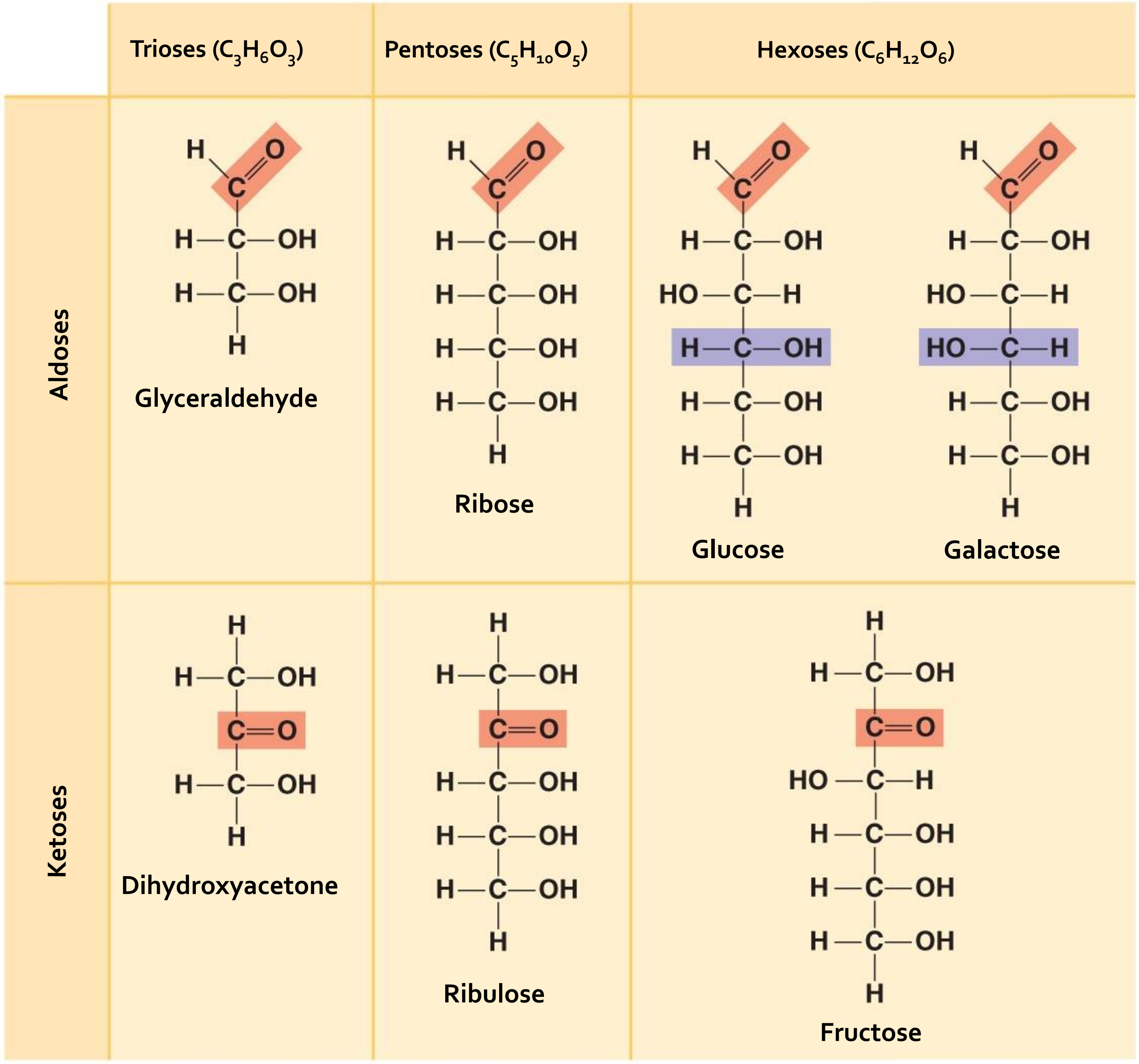
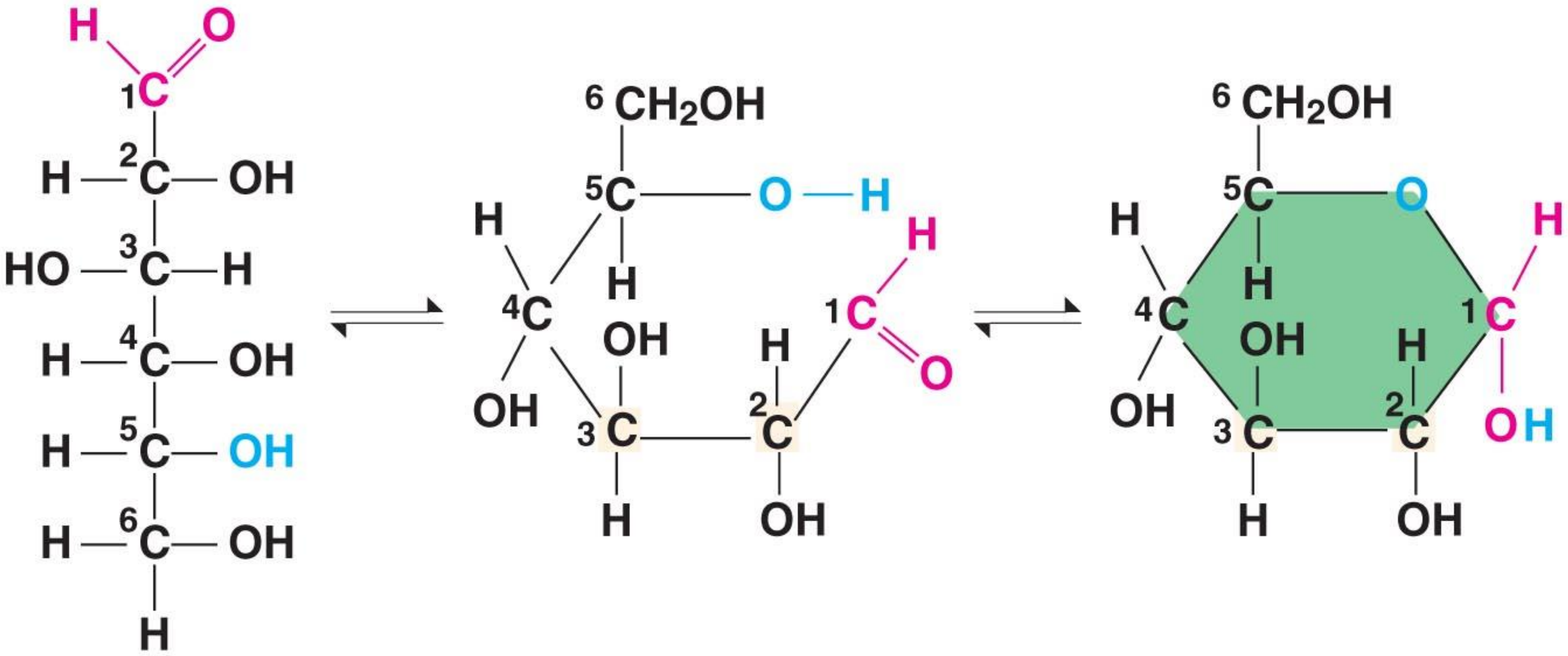
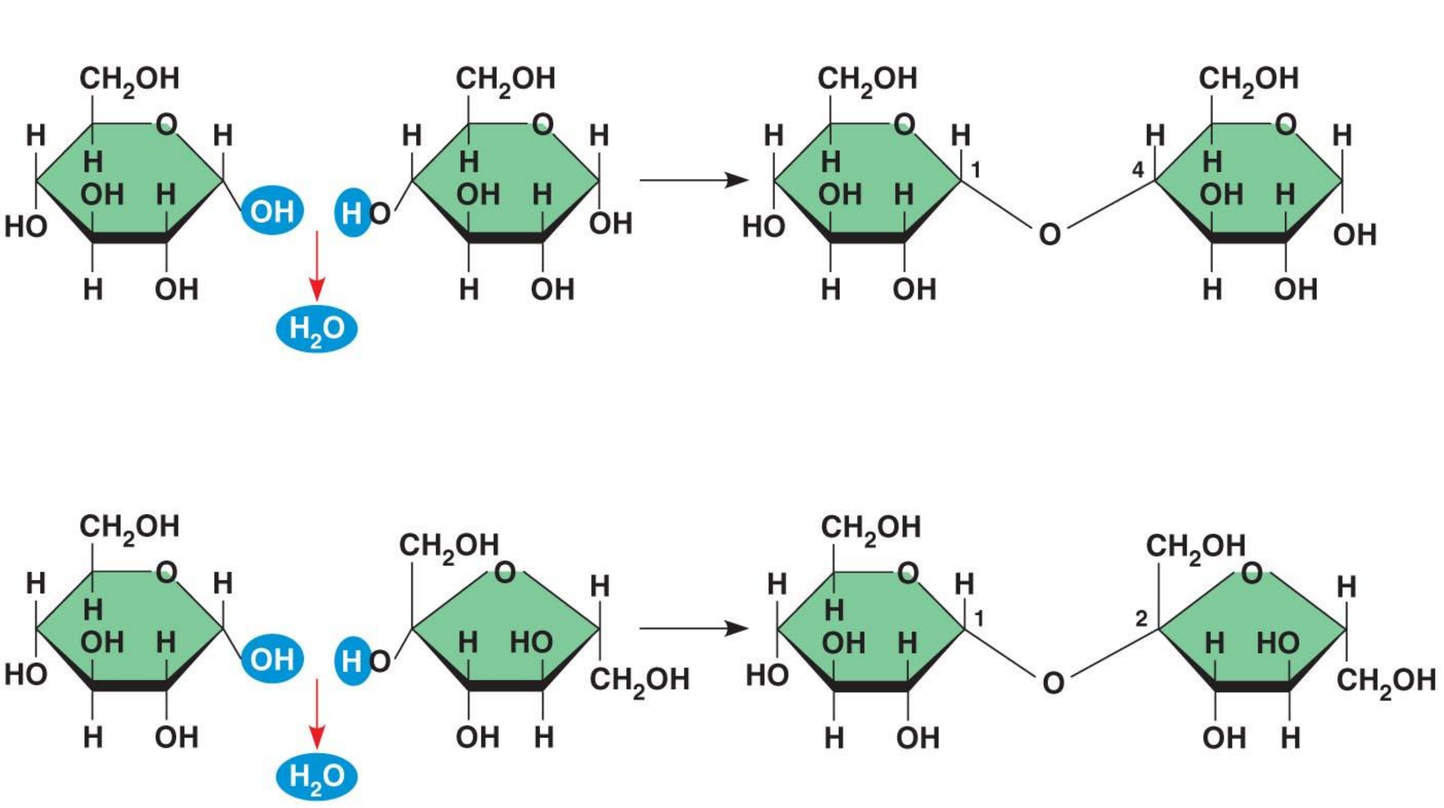

Trioses ($C_3H_6O_3$)
Pentoses ($C_5H_{10}O_5$)
Hexoses ($C_6H_{12}O_6$)
Aldoses
Ketoses
Glyceraldehyde
Ribose
Glucose
Galactose
Dihydroxyacetone
Ribulose
Fructose

Fig. 5-4a



(a) Linear and ring forms

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



Polysaccharides

- **Polysaccharides** have storage and structural roles
  - structure and function of a polysaccharide are determined by its sugar monomers and the positions of glycosidic linkages
- **Storage**
  - **Starch**, a storage polysaccharide of plants, consists entirely of glucose monomers
    - Plants store surplus starch as granules within chloroplasts and other plastids
  - **Glycogen** is a storage polysaccharide in animals
    - vertebrates store glycogen mainly in liver and muscle cells
- **Structural**
  - **cellulose** is a major component of the tough wall of plant cells
  - a polymer of glucose, but the glycosidic linkages differ
  - difference is based on two ring forms for glucose: alpha (α) and beta (β)

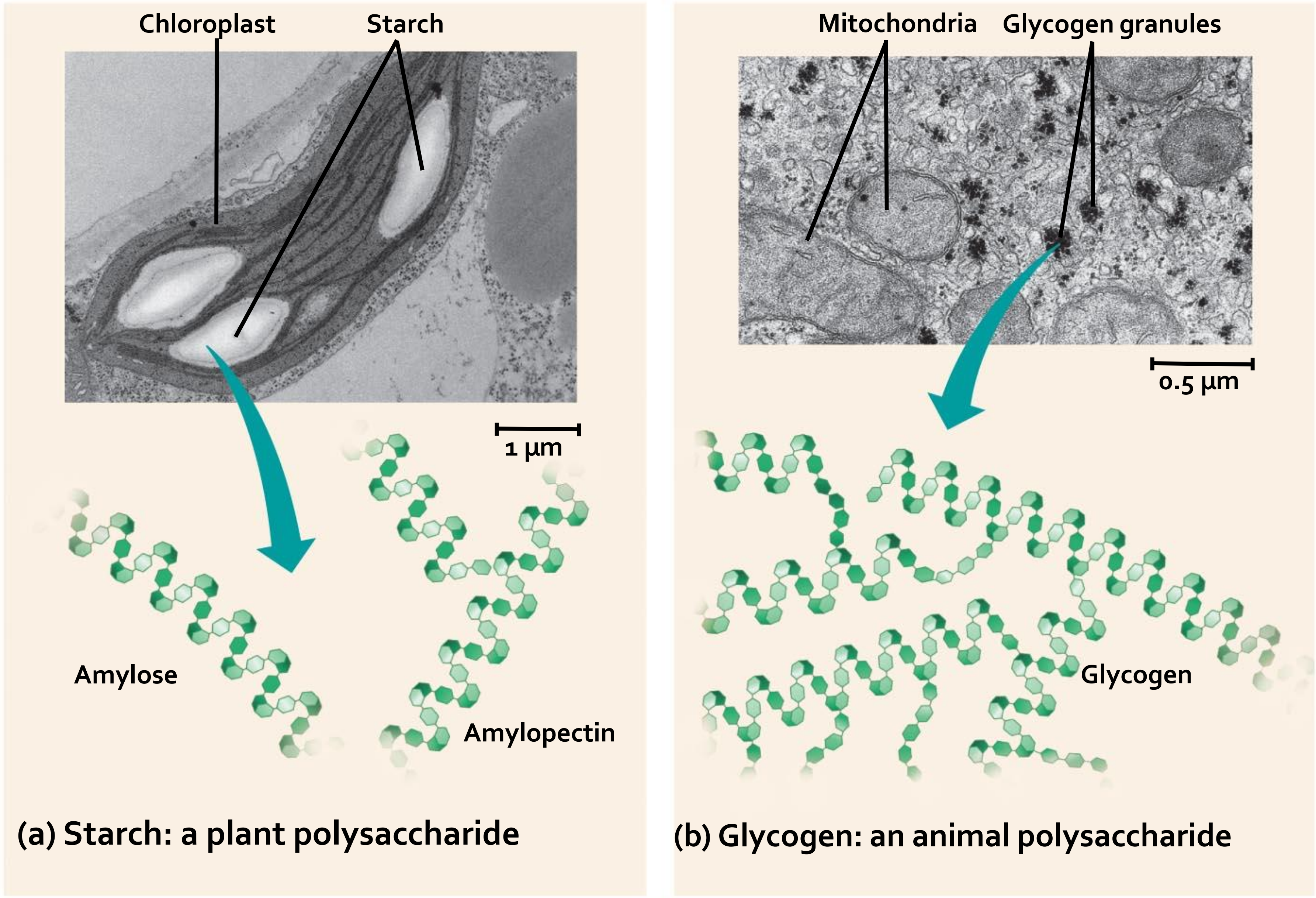
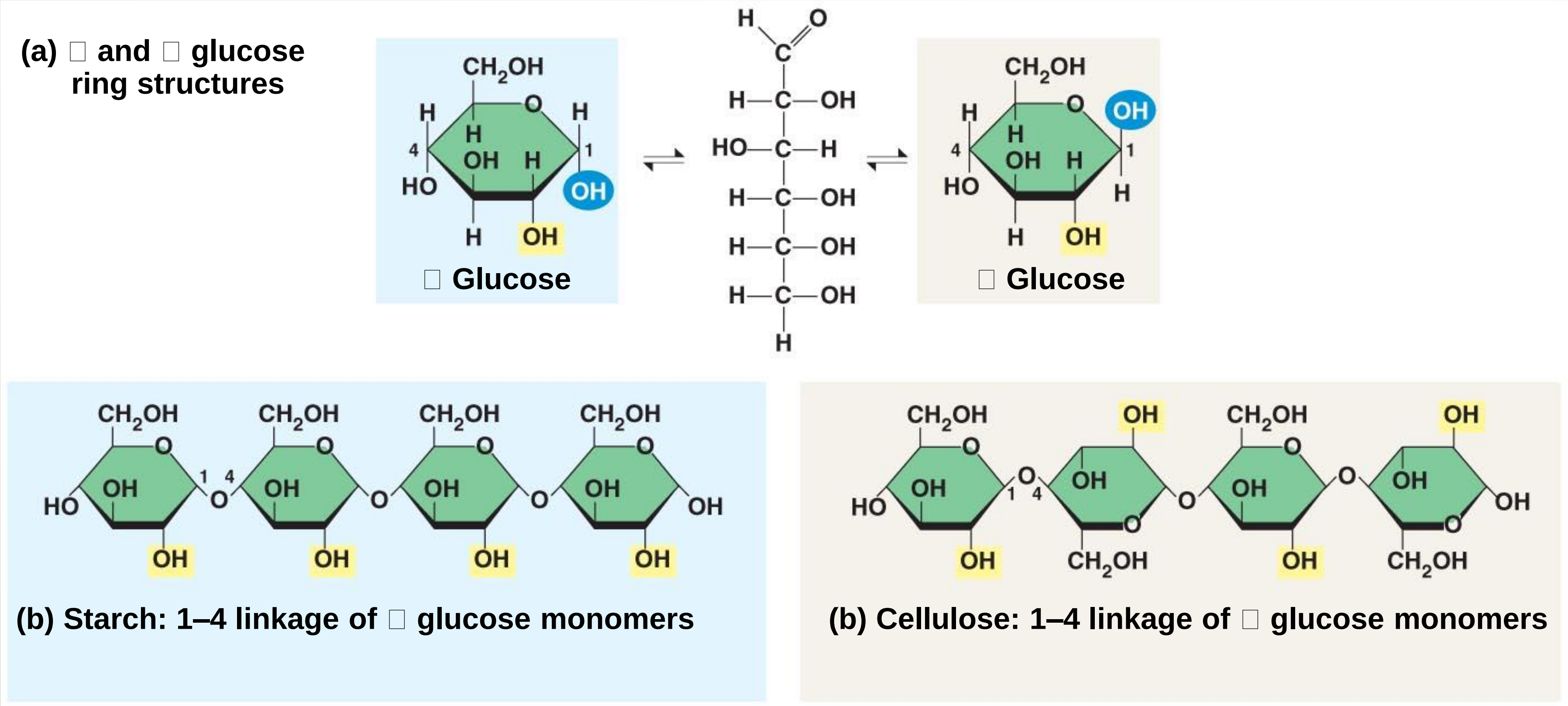
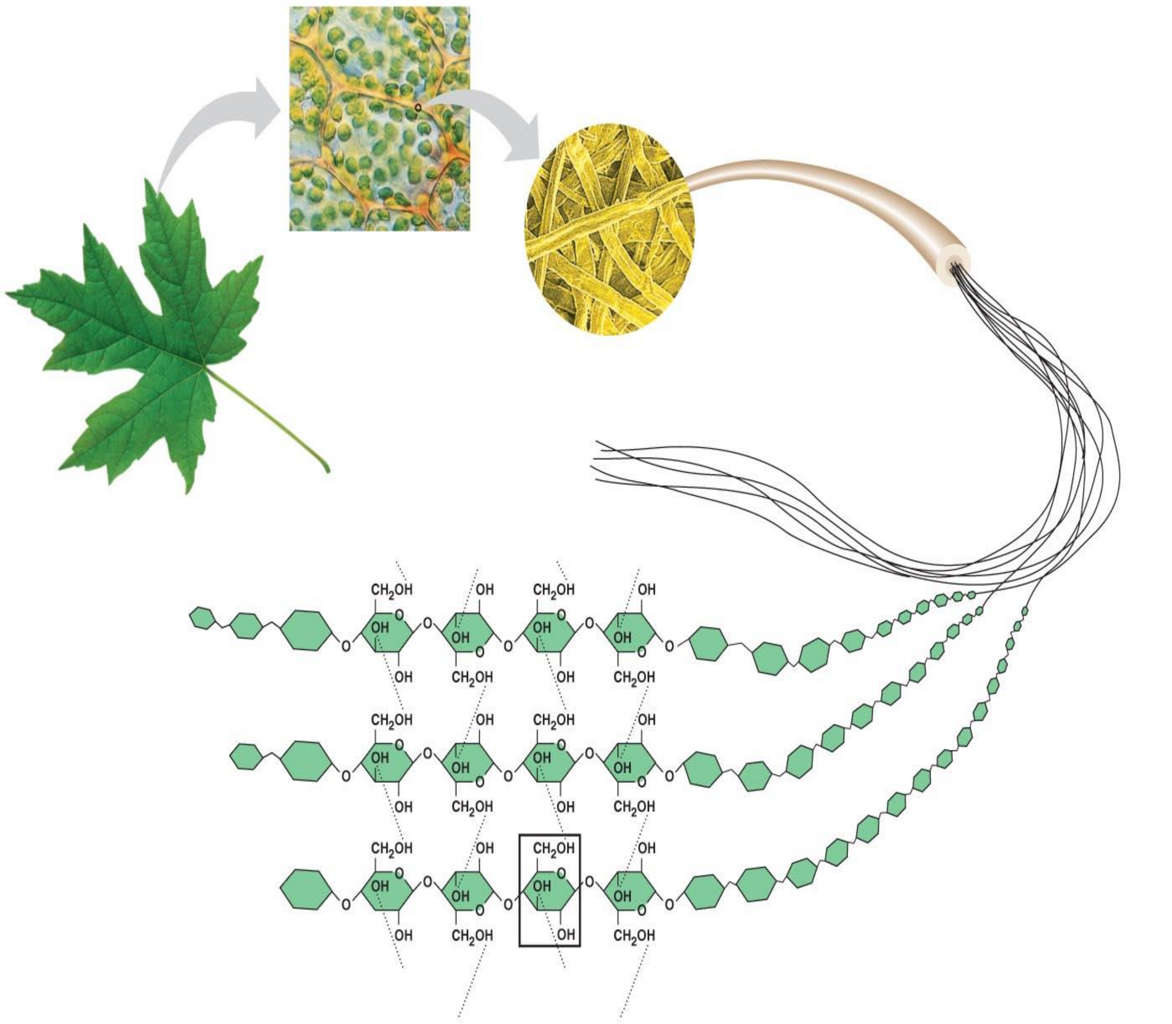

Chloroplast
Starch
1 µm
Amylose
Amylopectin
(a) Starch: a plant polysaccharide
Mitochondria
Glycogen granules
0.5 µm
Glycogen
(b) Glycogen: an animal polysaccharide

Fig. 5-7


(a) □ and □ glucose ring structures
□ Glucose
□ Glucose
(b) Starch: 1–4 linkage of □ glucose monomers
(b) Cellulose: 1–4 linkage of □ glucose monomers

- Polymers with α glucose are helical
- Polymers with β 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

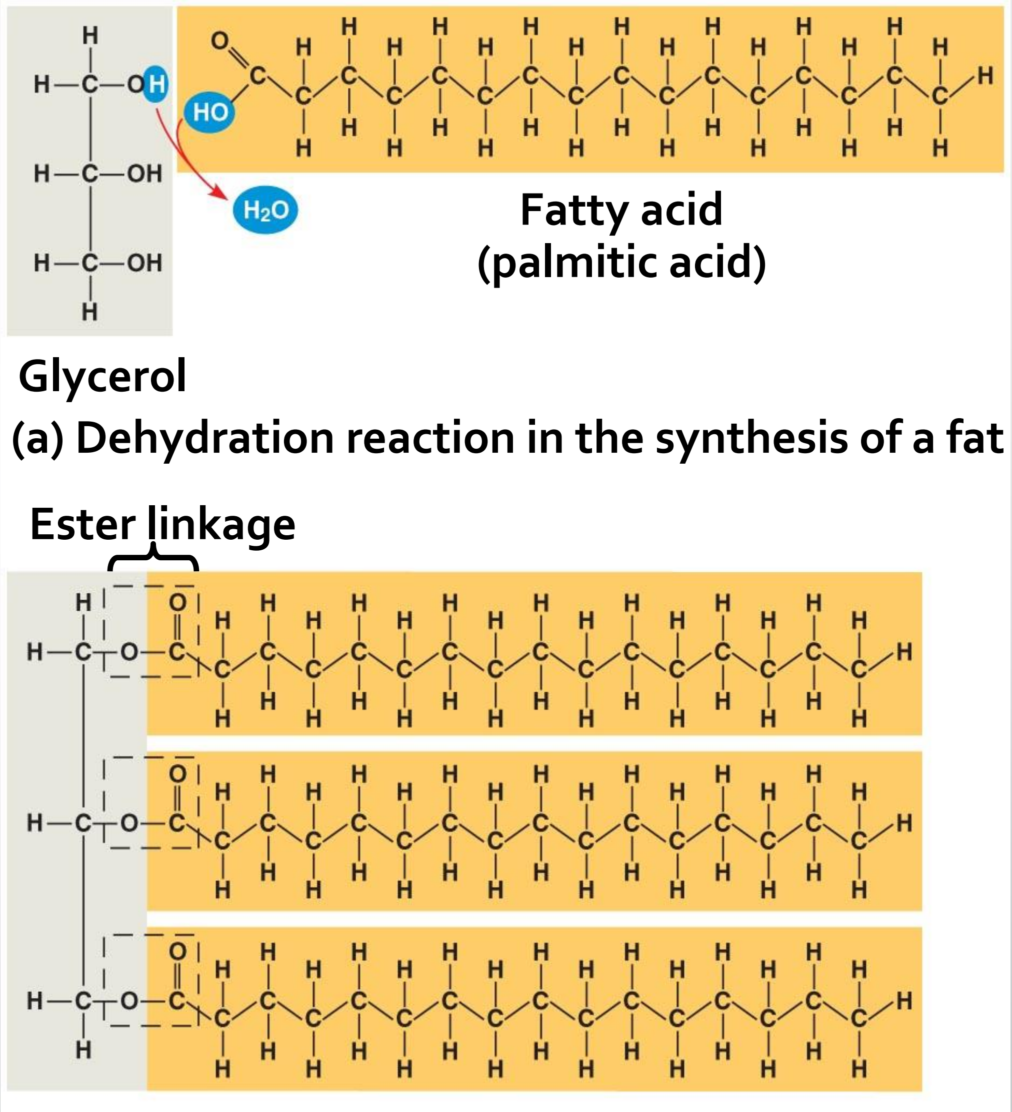


Lipids

- **Lipids** are the one class of large biological molecules that ….
- The unifying feature of lipids is having little or no affinity for water; therefore we say that they are ____________________, and they have many _______________ covalent bonds
- Most important to biology are fats, phospholipids, and steroids

Fats

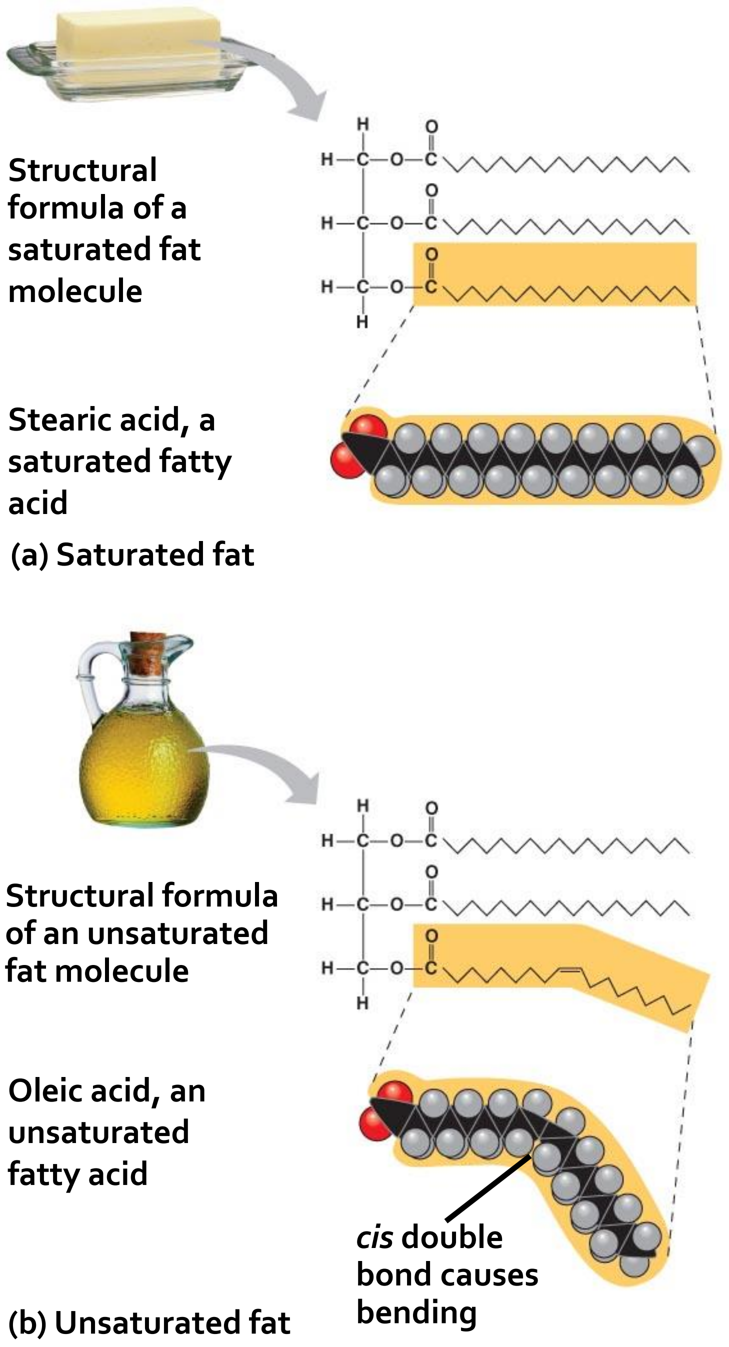
- **Fats** are constructed from two types of smaller molecules: glycerol and fatty acids
  - Glycerol is a three-carbon alcohol with a hydroxyl group attached to each carbon
  - A **fatty acid** consists of a carboxyl group attached to a long carbon skeleton
- Fatty acids vary in length (number of carbons)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



(a) Dehydration reaction in the synthesis of a fat

(b) Fat molecule (triacylglycerol)

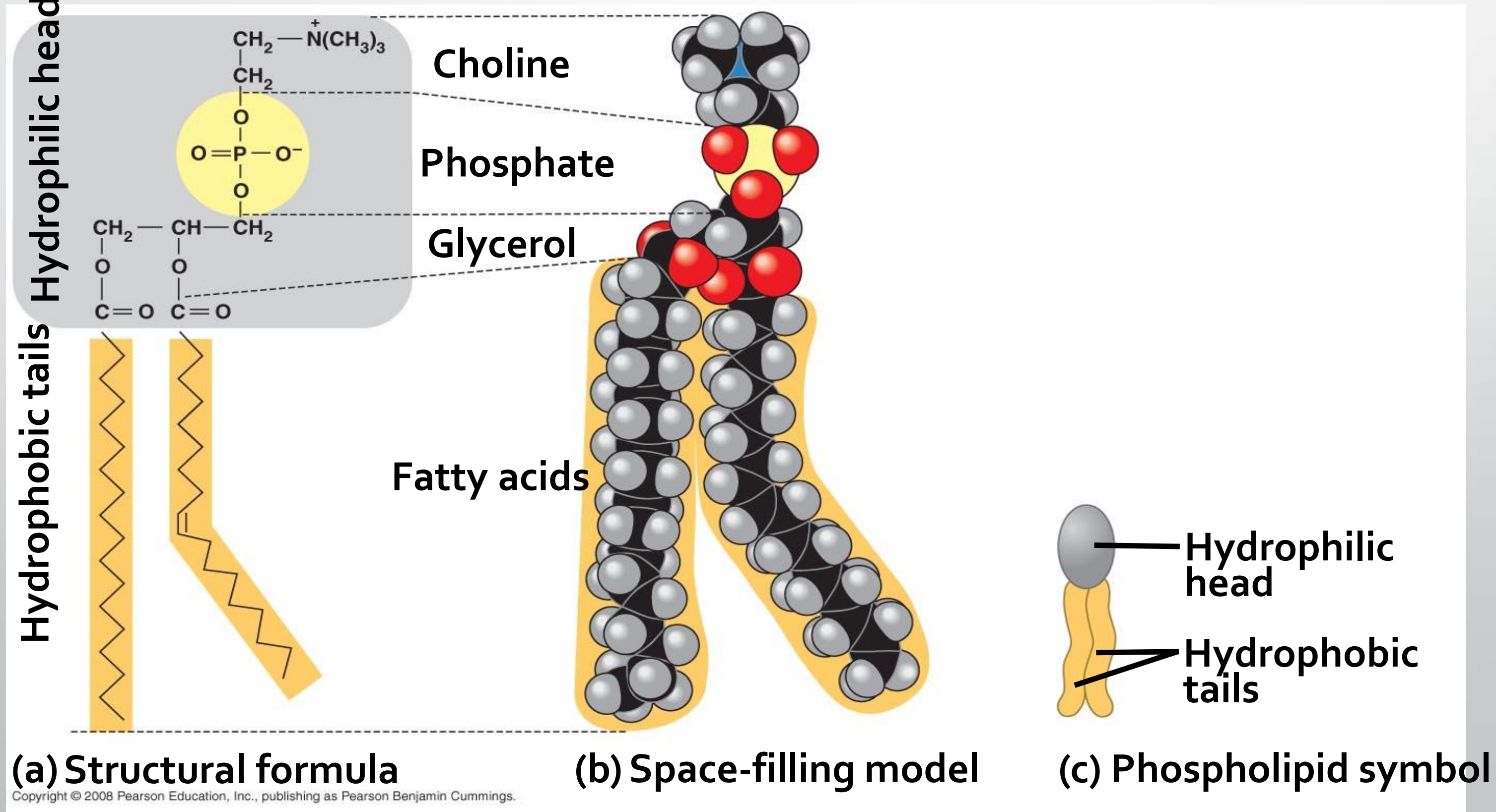
Fig. 5-12



Structural formula of a saturated fat molecule
Stearic acid, a saturated fatty acid
(a) Saturated fat
Structural formula of an unsaturated fat molecule
Oleic acid, an unsaturated fatty acid
cis double bond causes bending
(b) Unsaturated fat

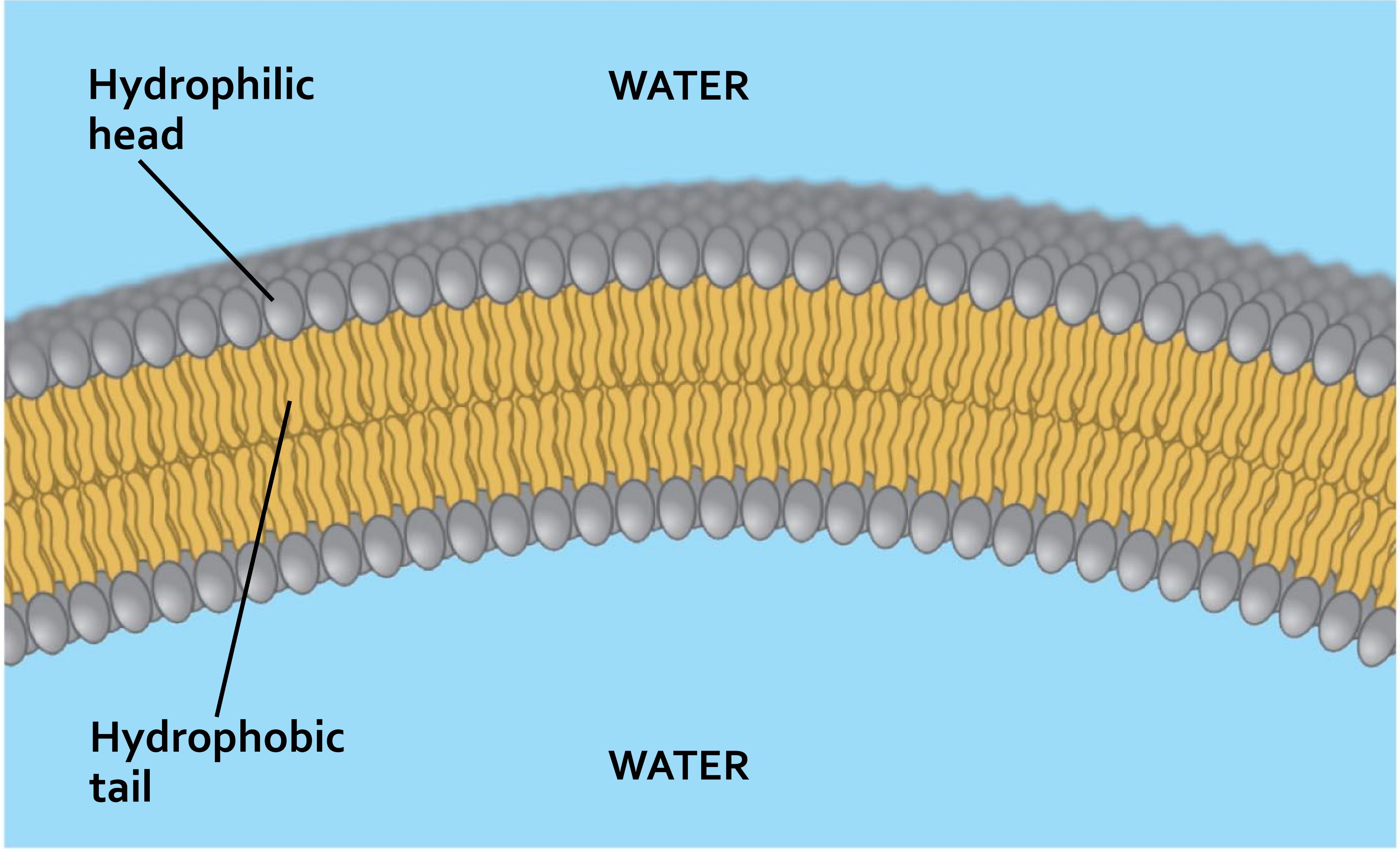
Phospholipids

- two fatty acids and a phosphate group are attached to glycerol
  - two fatty acid tails are hydrophobic, but the phosphate group and its attachments are hydrophilic



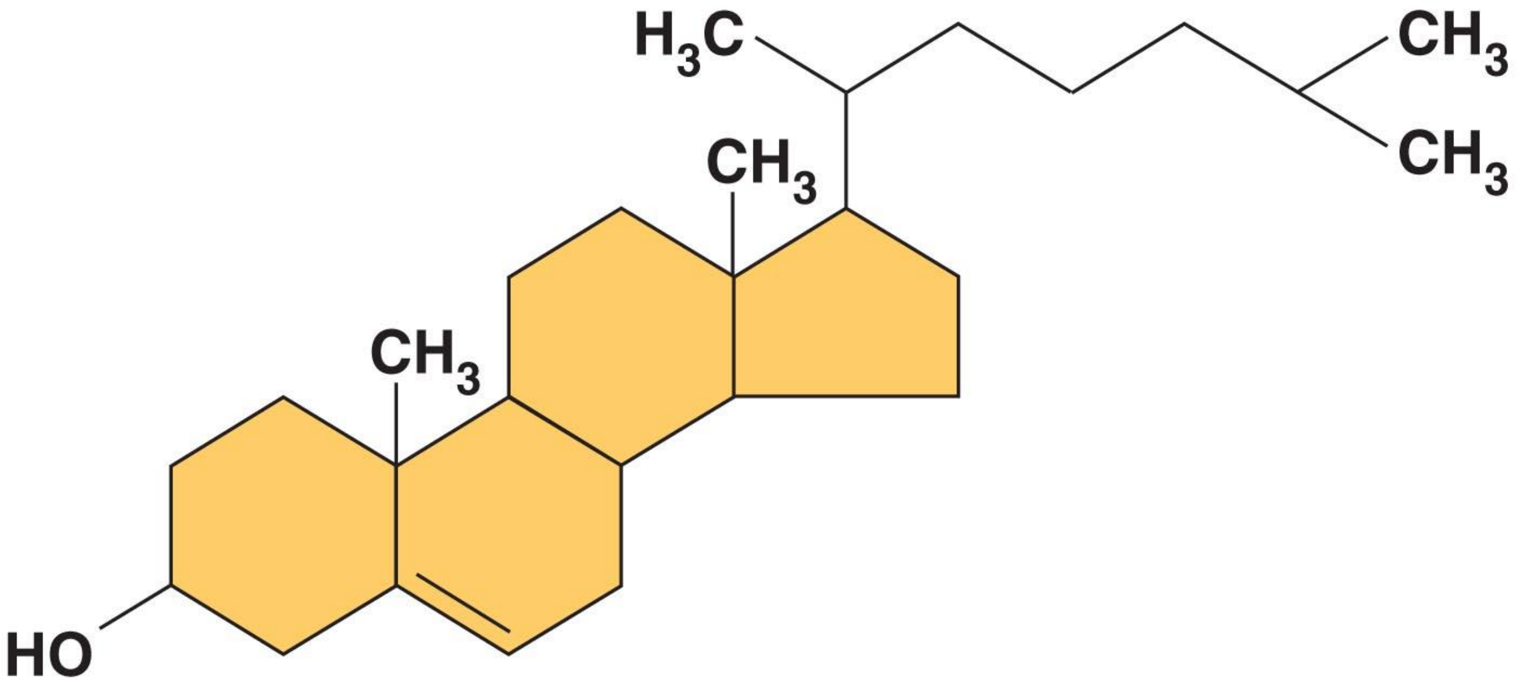
- What happens when phospholipids are exposed to water?

Fig. 5-14



Steroids

- lipids characterized by a carbon skeleton consisting of four fused rings
  - Example is **Cholesterol**, a component in animal cell membranes

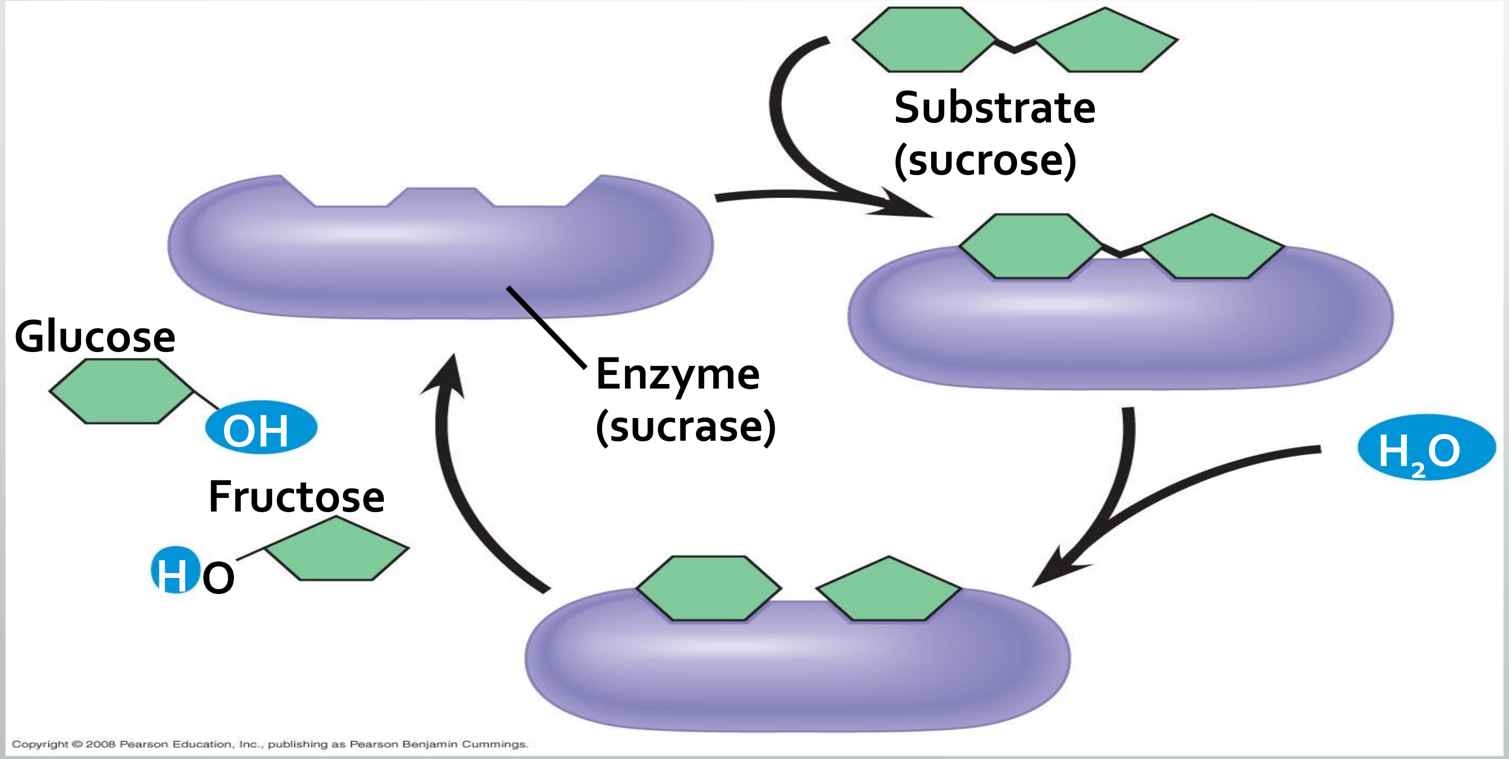


Proteins

- Majority of the dry mass of cells
- Protein functions include structural support, storage, transport, cellular communications, movement, assisting in chemical reactions, and defense against foreign substances

- **Enzymes** are a type of protein that acts as a **catalyst…**this mean that they…

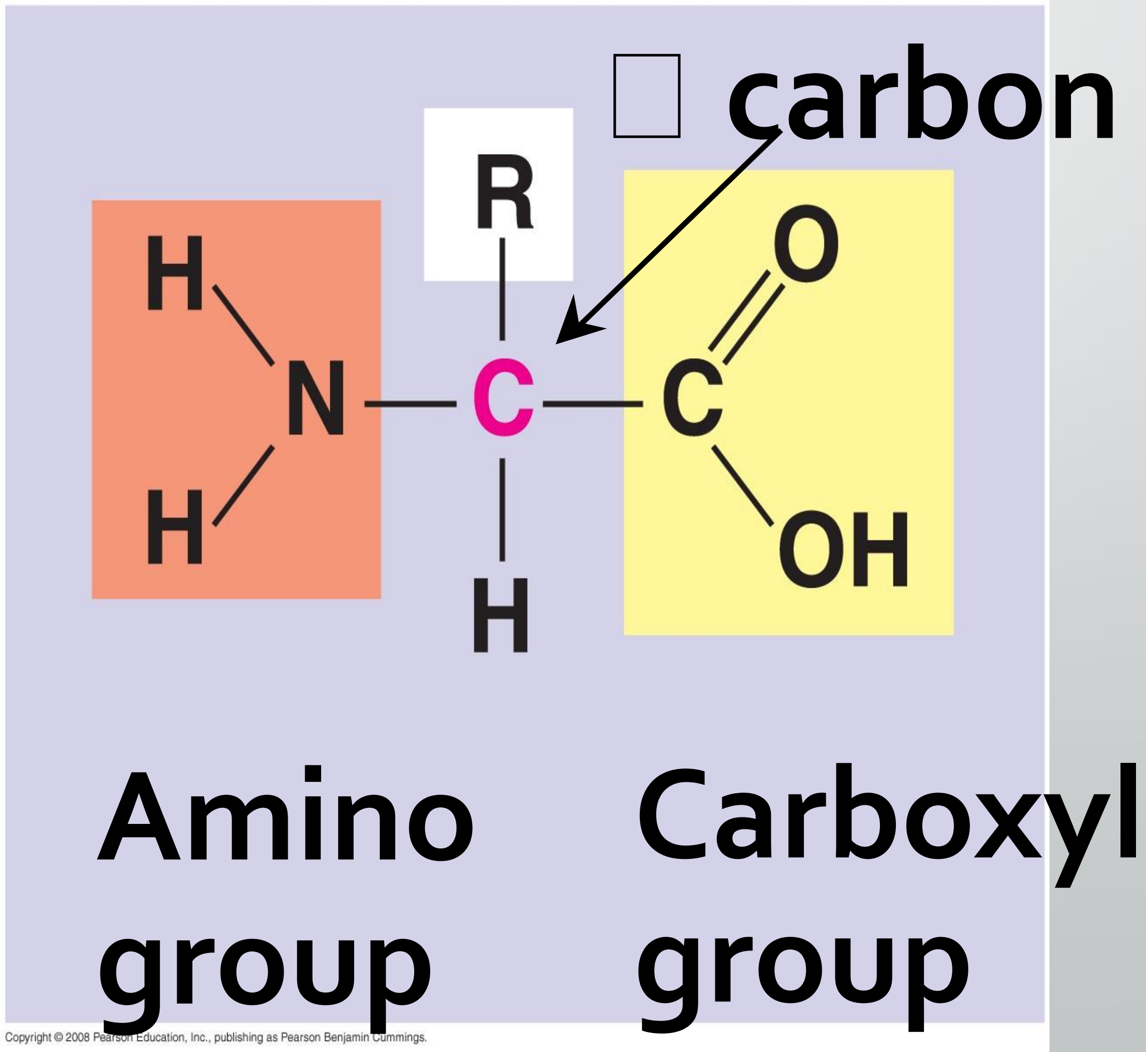
- Enzymes can perform their functions repeatedly, functioning as workhorses that carry out the processes of life



Polypeptides

- **Polypeptides** are polymers built from …

- A **protein** consists of one or more polypeptides
- **Amino acids** are organic molecules with carboxyl and amino groups
- Amino acids differ in their properties due to differing side chains, called R groups



Nonpolar

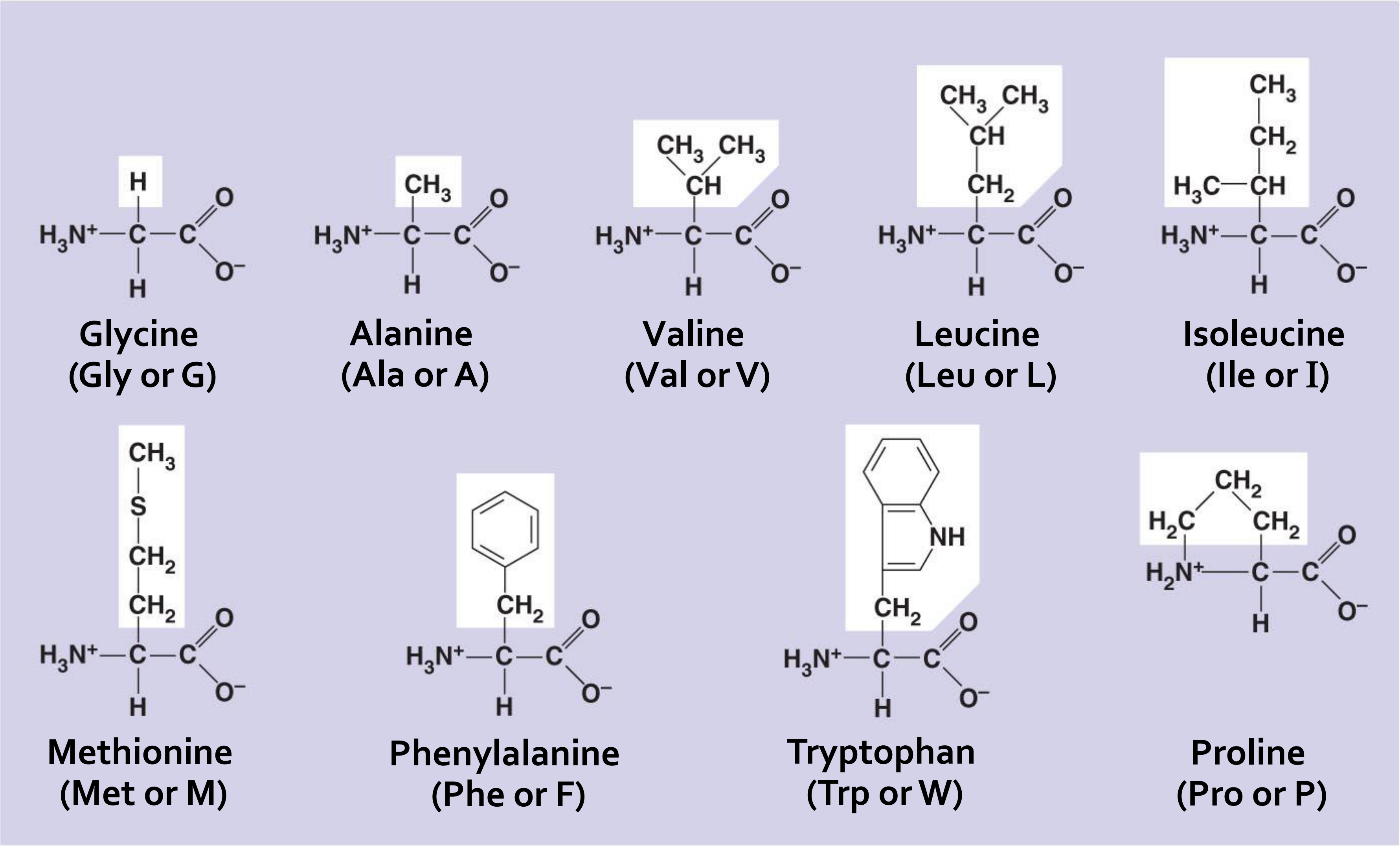
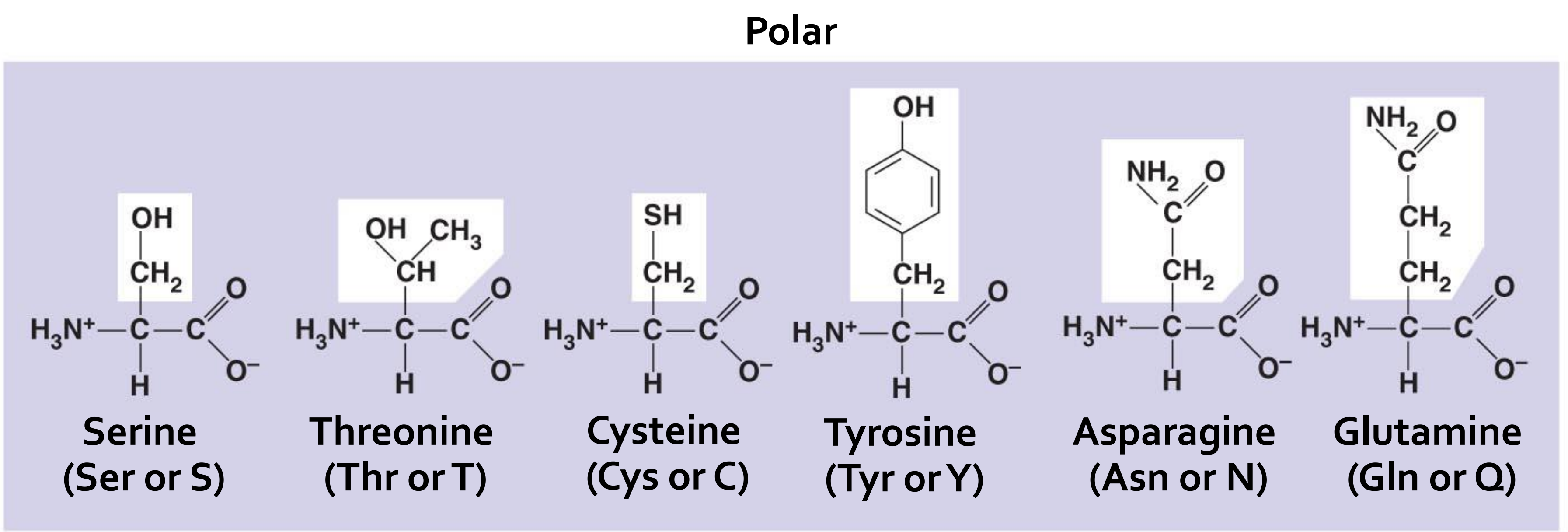
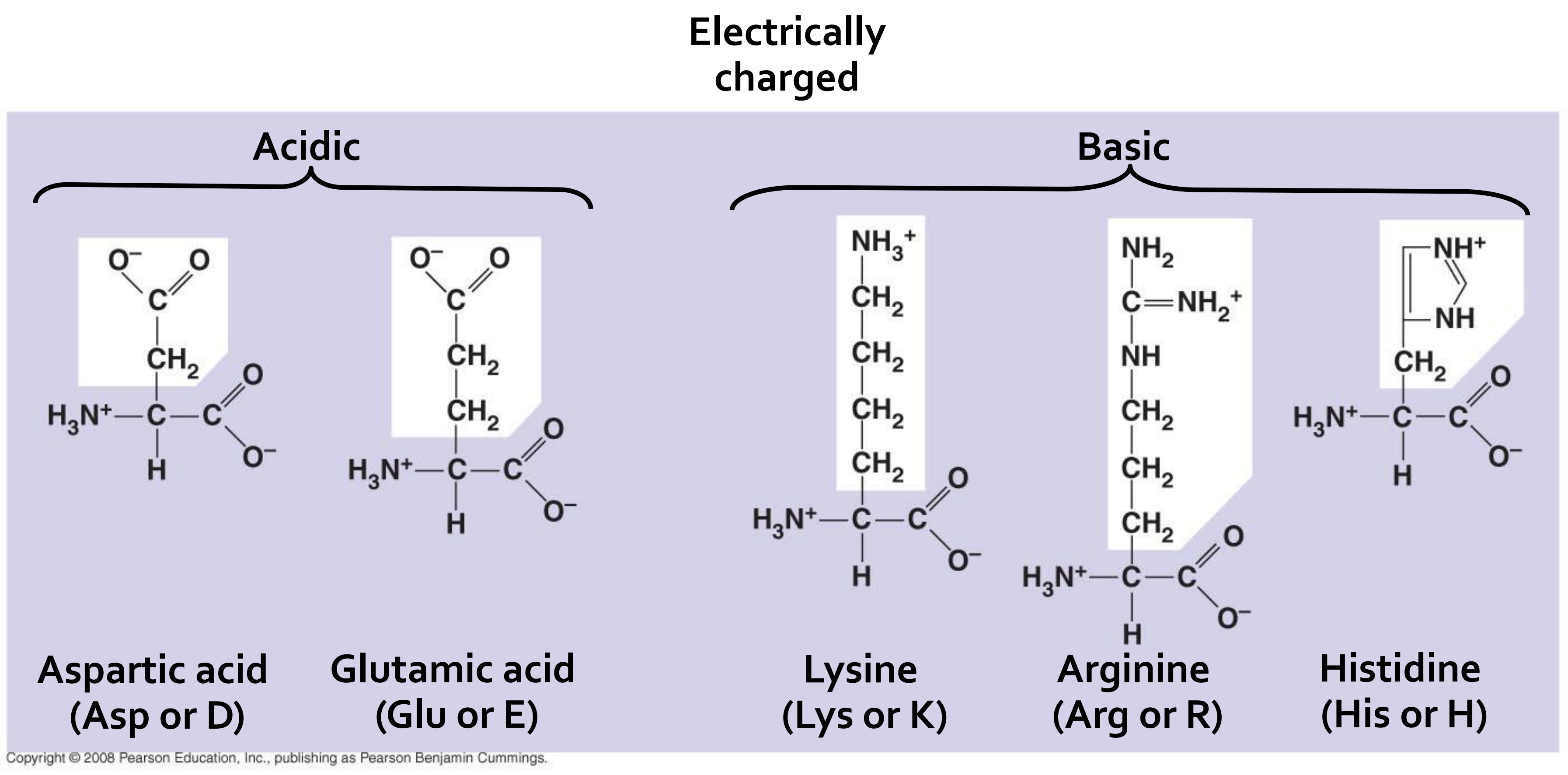

Glycine
(Gly or G)
Alanine
(Ala or A)
Valine
(Val or V)
Leucine
(Leu or L)
Isoleucine
(Ile or I)
Methionine
(Met or M)
Phenylalanine
(Phe or F)
Tryptophan
(Trp or W)
Proline
(Pro or P)

Fig. 5-17b



Polar
OH
CH2
H3N+
C
C
O
O–
H
Serine
(Ser or S)
OH
CH3
CH
Threonine
(Thr or T)
SH
Cysteine
(Cys or C)
Tyrosine
(Tyr or Y)
NH2
Asparagine
(Asn or N)
Glutamine
(Gln or Q)

Fig. 5-17c


Electrically charged
Acidic
Basic
O⁻ O C CH2 H3N+ C C O O⁻ H
NH3+ CH2 CH2 CH2 CH2
NH2 C NH2+ NH CH2 CH2 CH2
NH+ NH CH2
Aspartic acid (Asp or D)
Glutamic acid (Glu or E)
Lysine (Lys or K)
Arginine (Arg or R)
Histidine (His or H)
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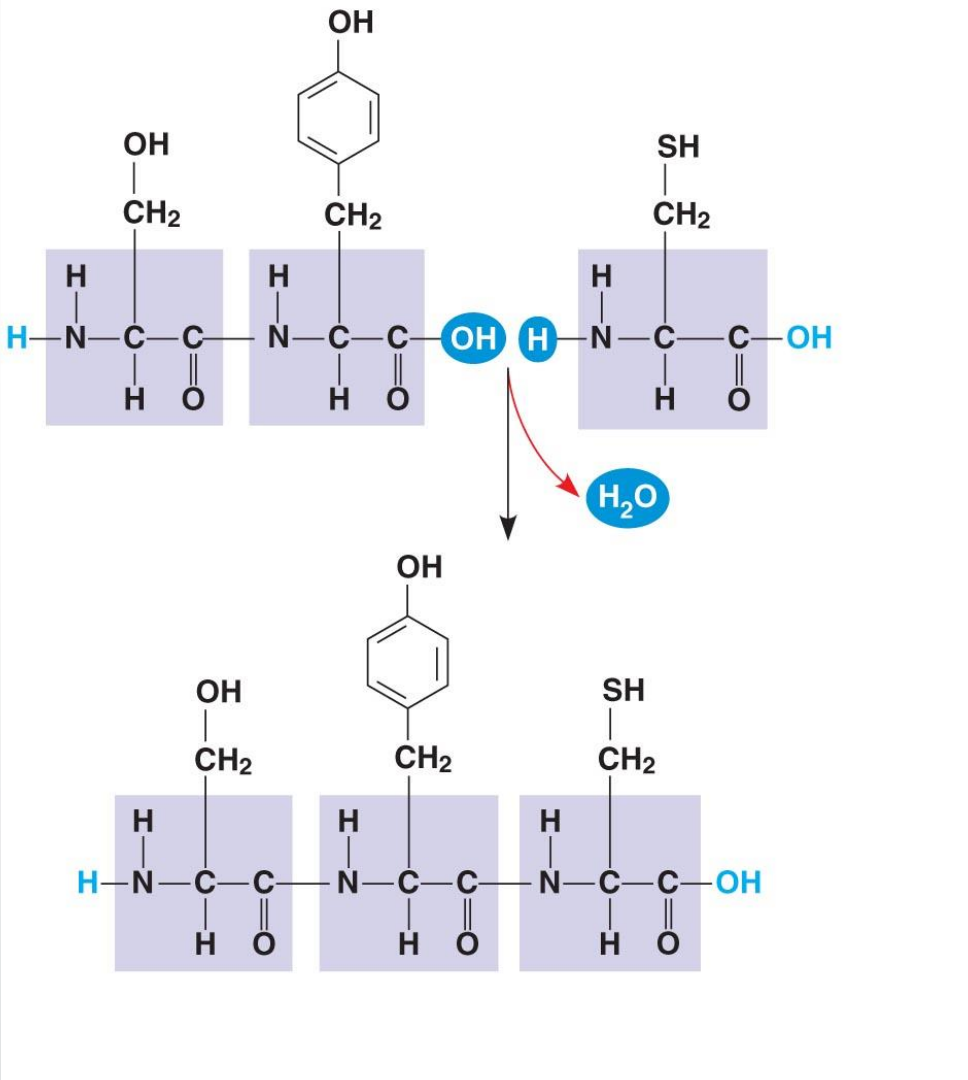
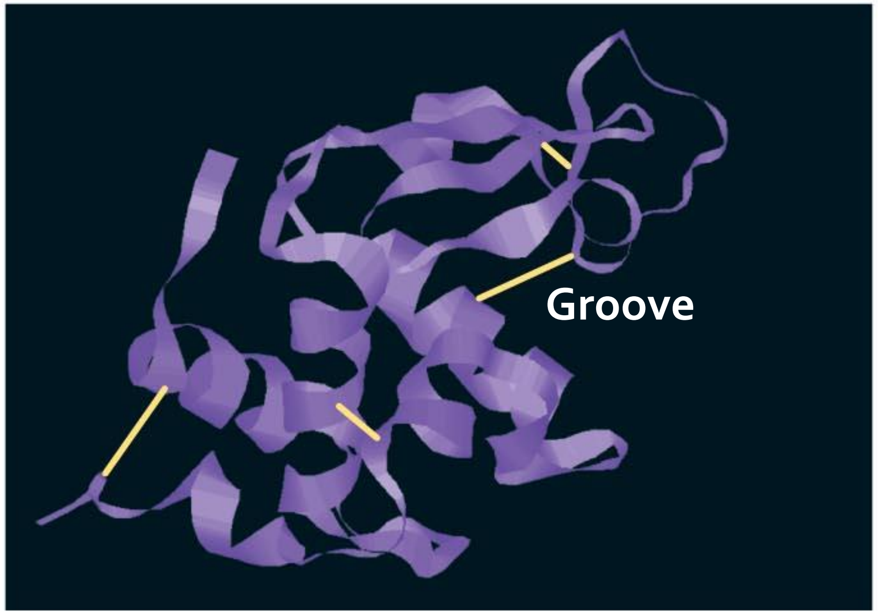
Amino Acid Polymers

- Amino acids are linked by **peptide bonds**
  - polypeptides are polymers 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 (determined by the genetic information present in genes

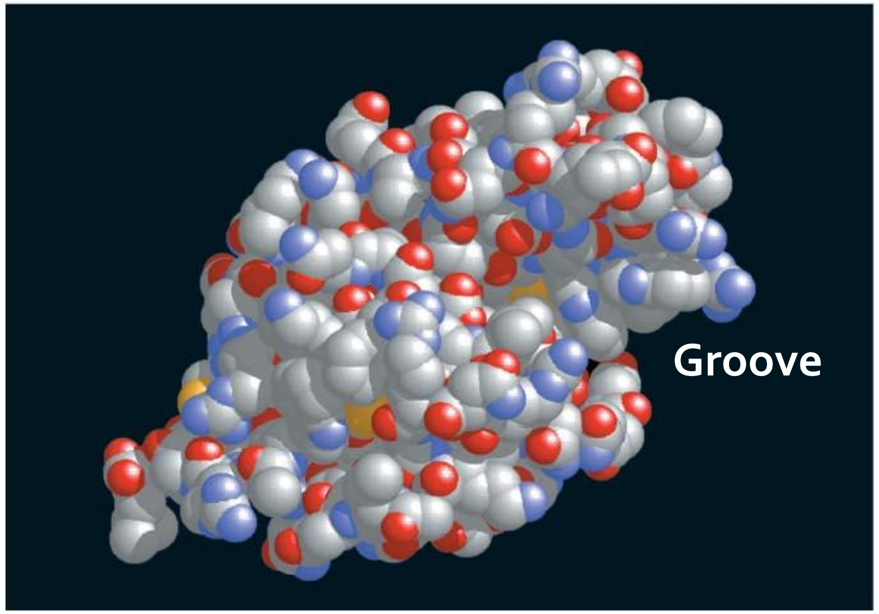


Protein Structure and Function

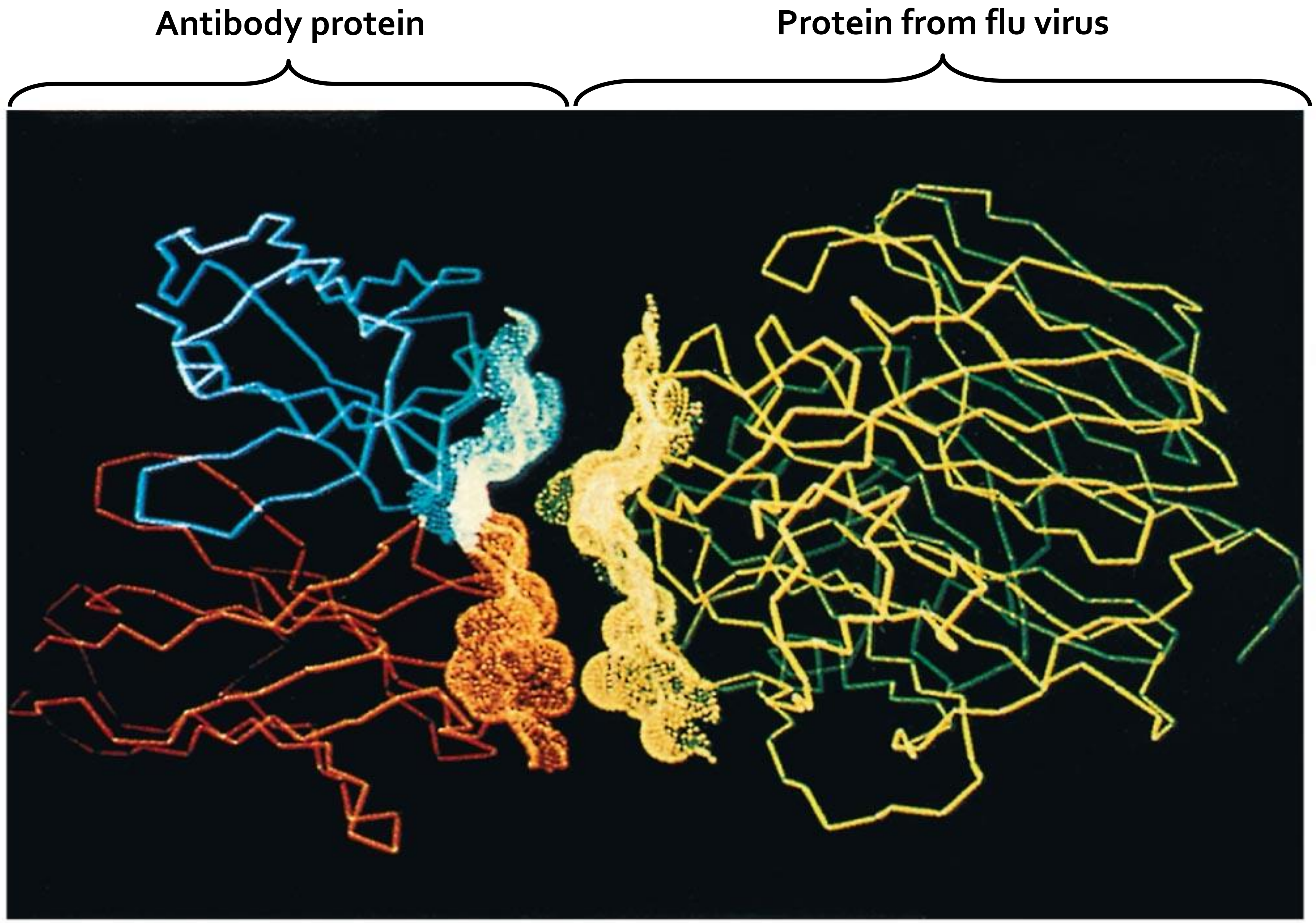
- A functional protein consists of one or more polypeptides twisted, folded, and coiled into a unique shape
- The sequence of amino acids determines a protein's three-dimensional structure
- Remember…



(a) A ribbon model of lysozyme

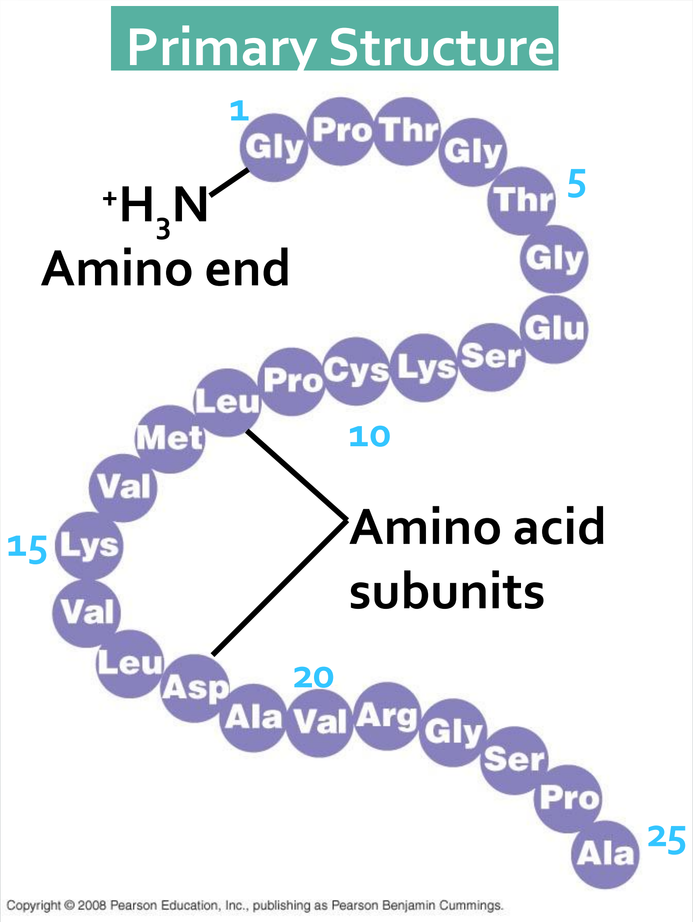


(b) A space-filling model of lysozyme


Antibody protein
Protein from flu virus

Four levels of Protein Structure

- **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 (DNA)



- **secondary structure** results from hydrogen bonds between amino acids in the polypeptide backbone
- Typical secondary structures are a coil called an α **helix** and a folded structure called a β **pleated sheet**

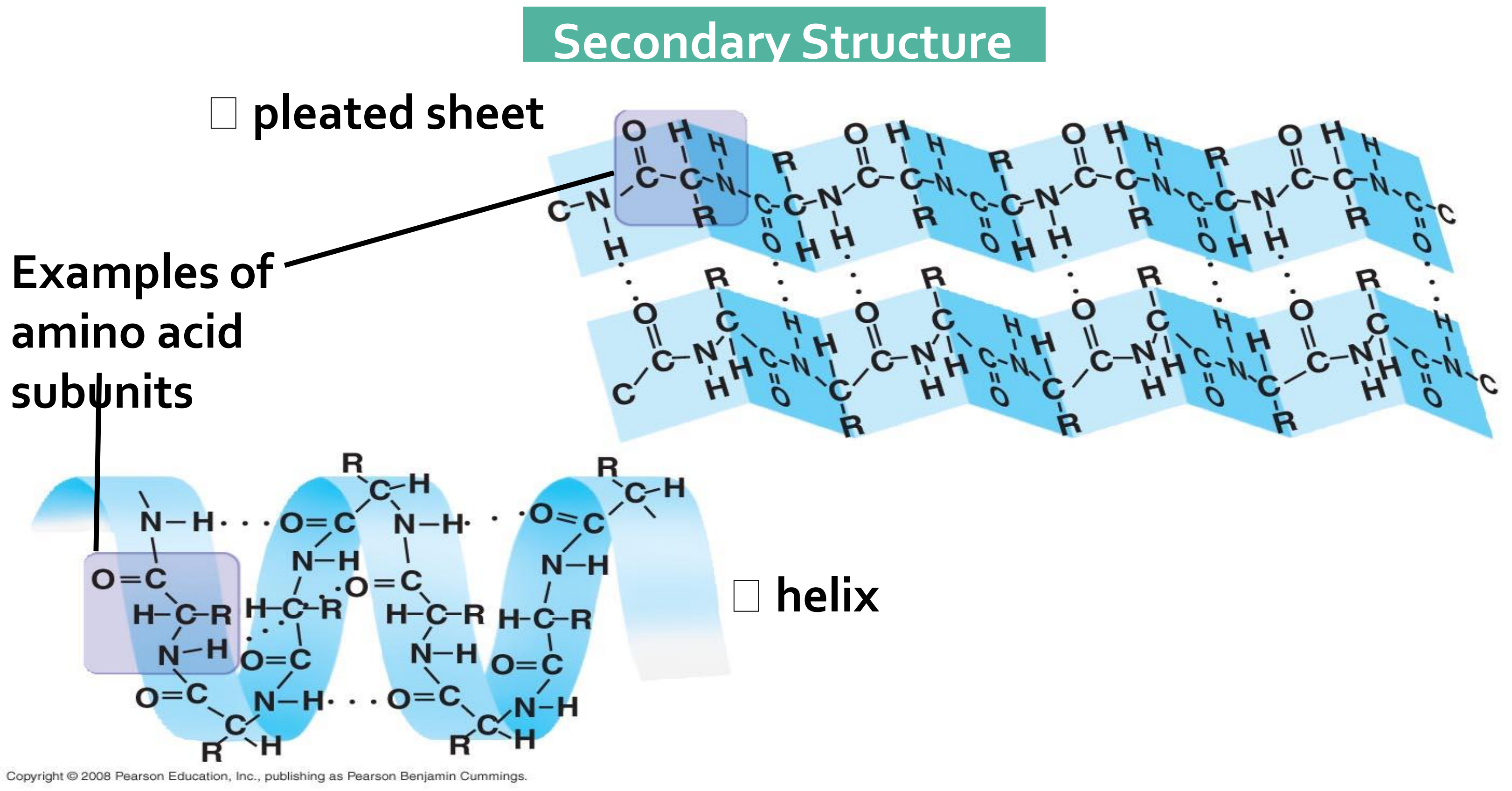
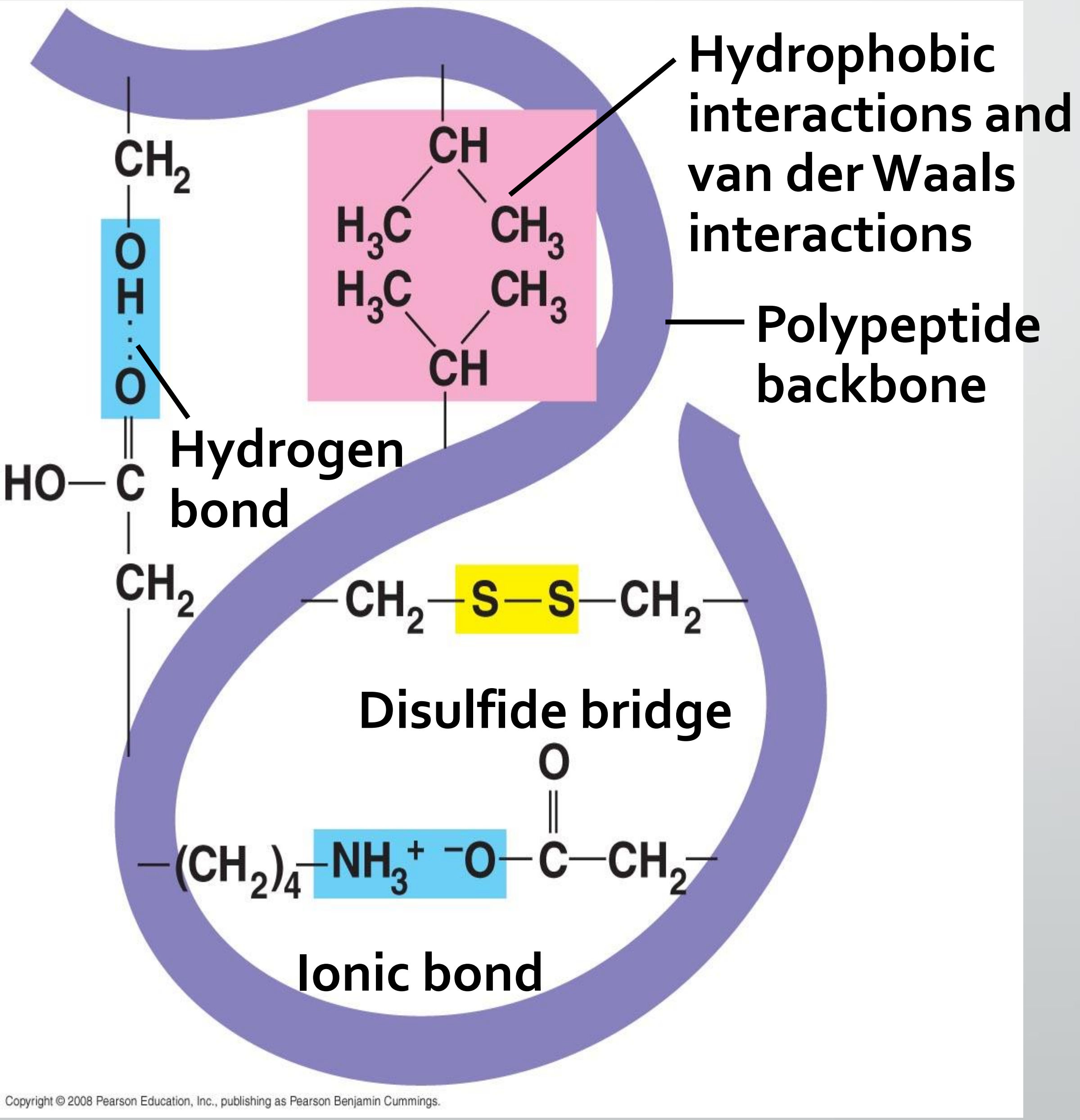


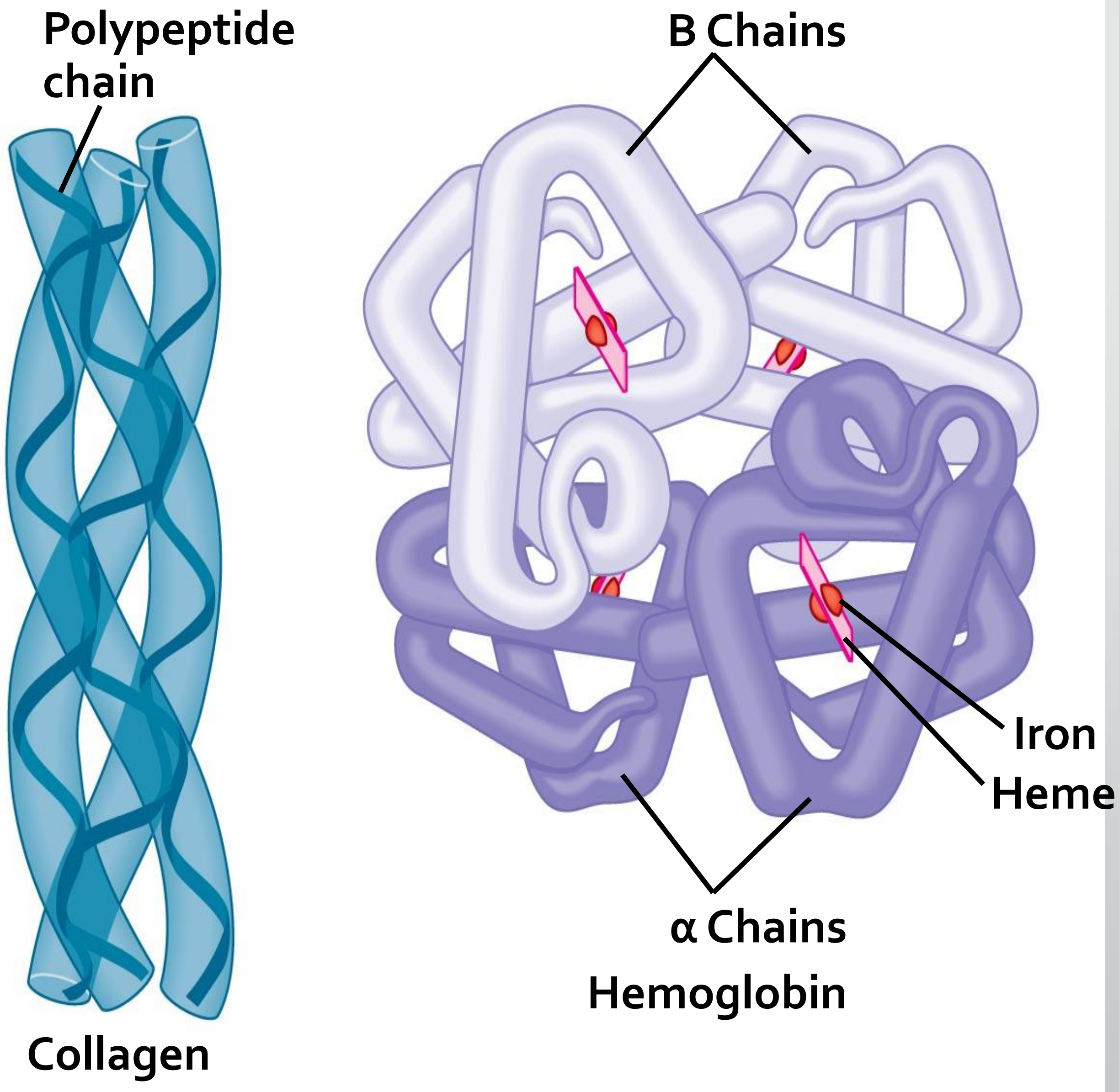
Fig. 5-21d


Abdominal glands of the spider secrete silk fibers made of a structural protein containing β-pleated sheets.
The radiating strands, made of dry silk fibers, maintain the shape of the web.
The spiral strands (capture strands) are elastic, stretching in response to wind, rain, and the touch of insects.

- **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

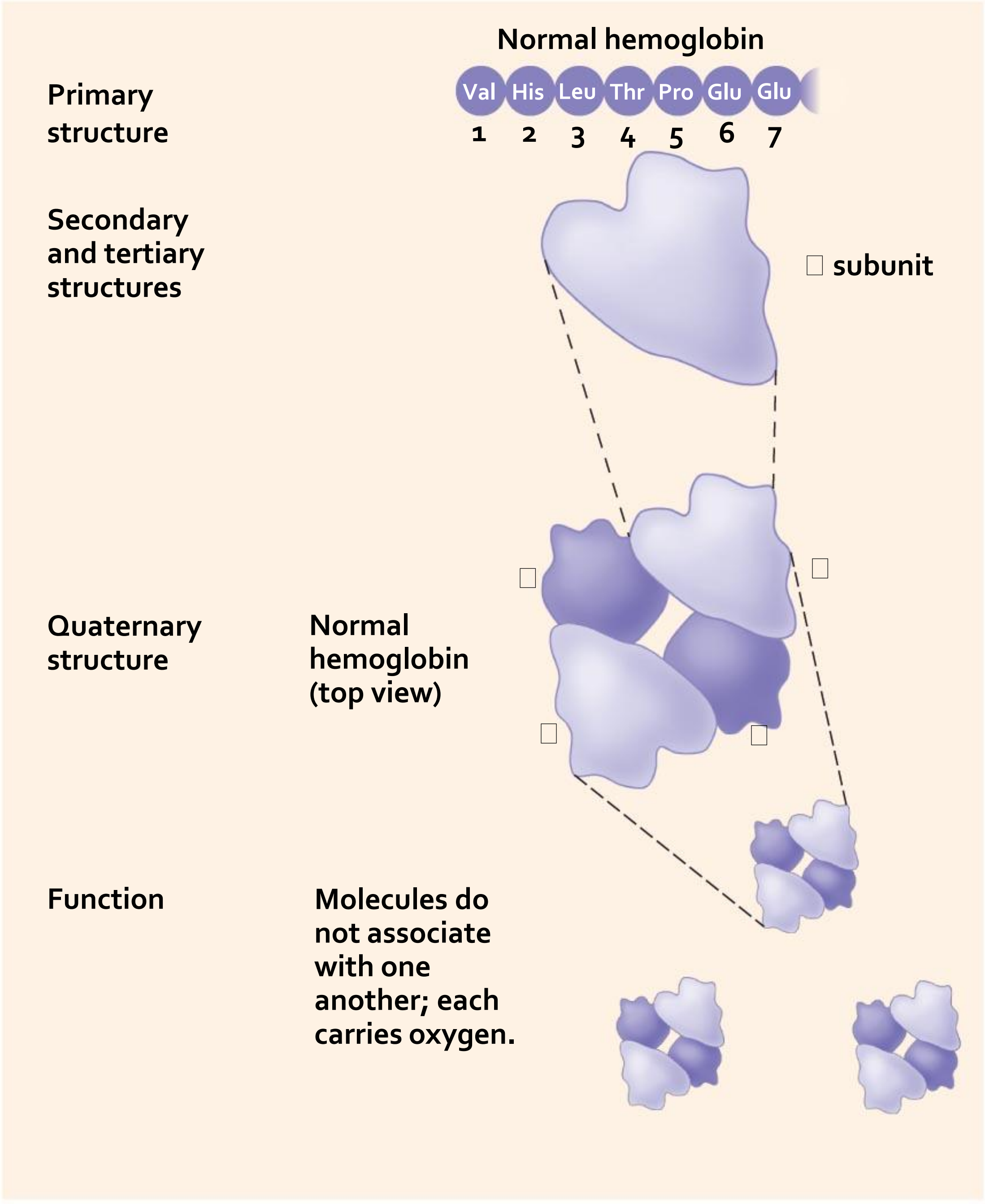


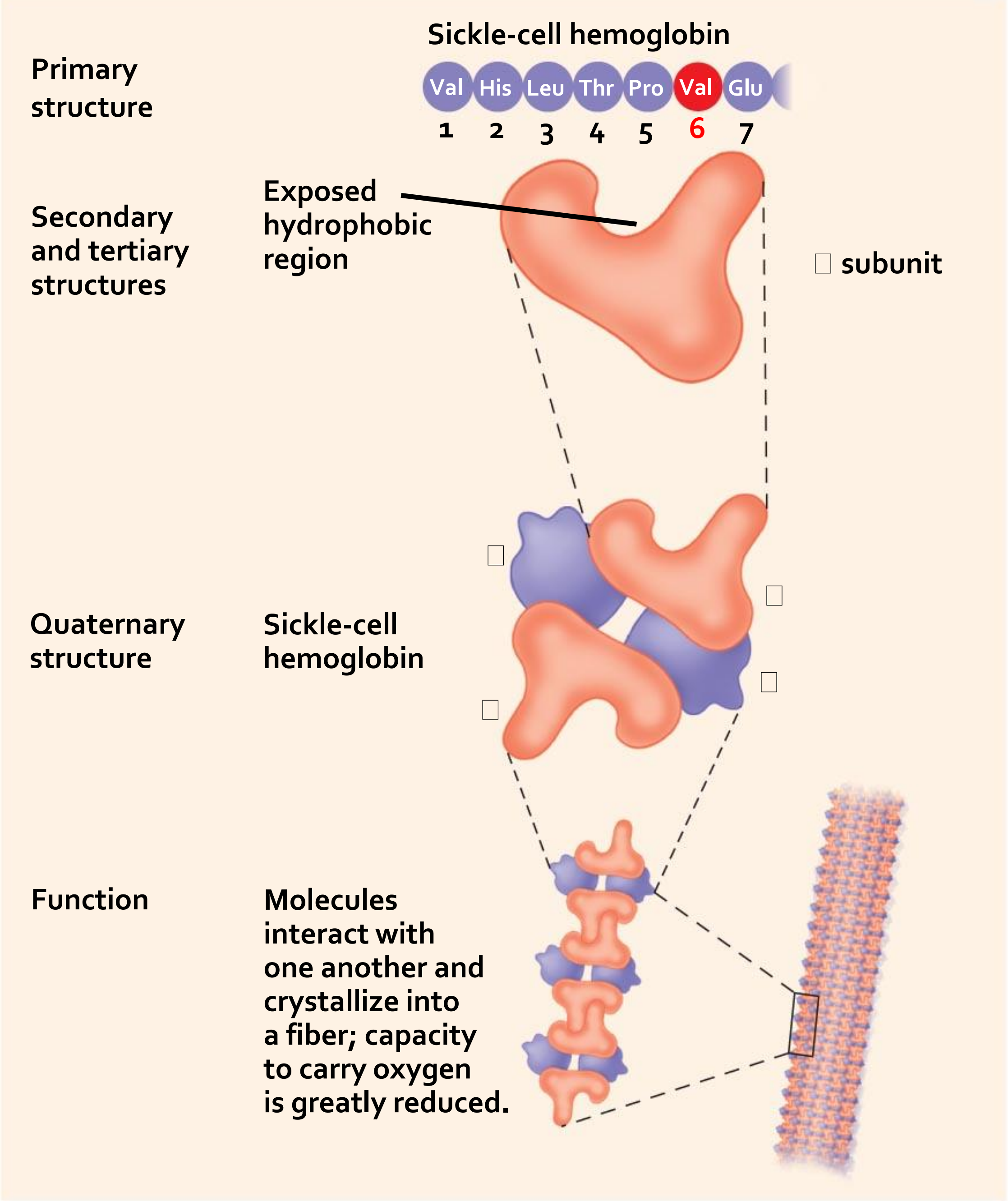
- **Quaternary structure** results when two or more polypeptide chains form one macromolecule
  - Collagen is a fibrous protein consisting of three polypeptides coiled like a rope
  - Hemoglobin is a globular protein consisting of four polypeptides: two alpha and two beta chains



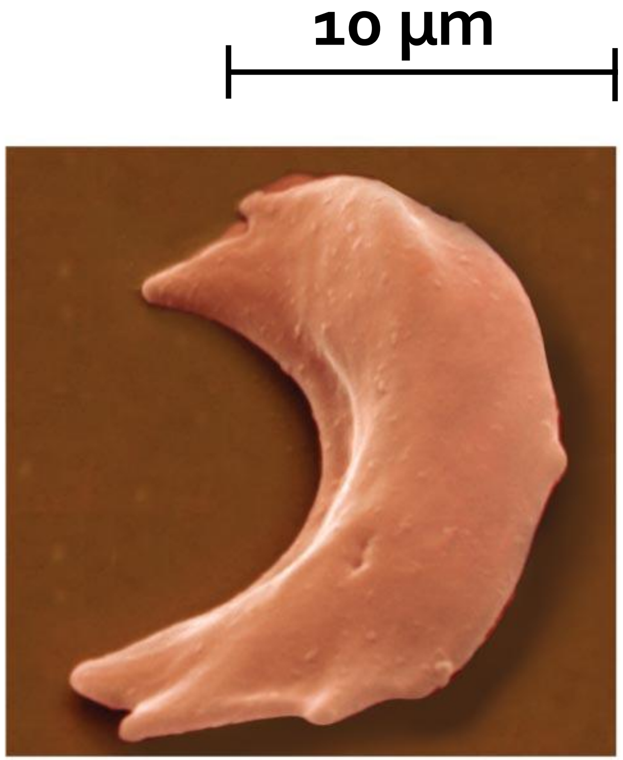
Sickle-Cell Disease: A Change in Primary Structure

- 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


Normal hemoglobin
Primary structure
Val His Leu Thr Pro Glu Glu
1 2 3 4 5 6 7
Secondary and tertiary structures
subunit
Quaternary structure
Normal hemoglobin (top view)
Function
Molecules do not associate with one another; each carries oxygen.


Sickle-cell hemoglobin
Primary structure
Val His Leu Thr Pro Val Glu
1 2 3 4 5 6 7
Secondary and tertiary structures
Exposed hydrophobic region
□ subunit
Quaternary structure
Sickle-cell hemoglobin
□
□
□
□
Function
Molecules interact with one another and crystallize into a fiber; capacity to carry oxygen is greatly reduced.

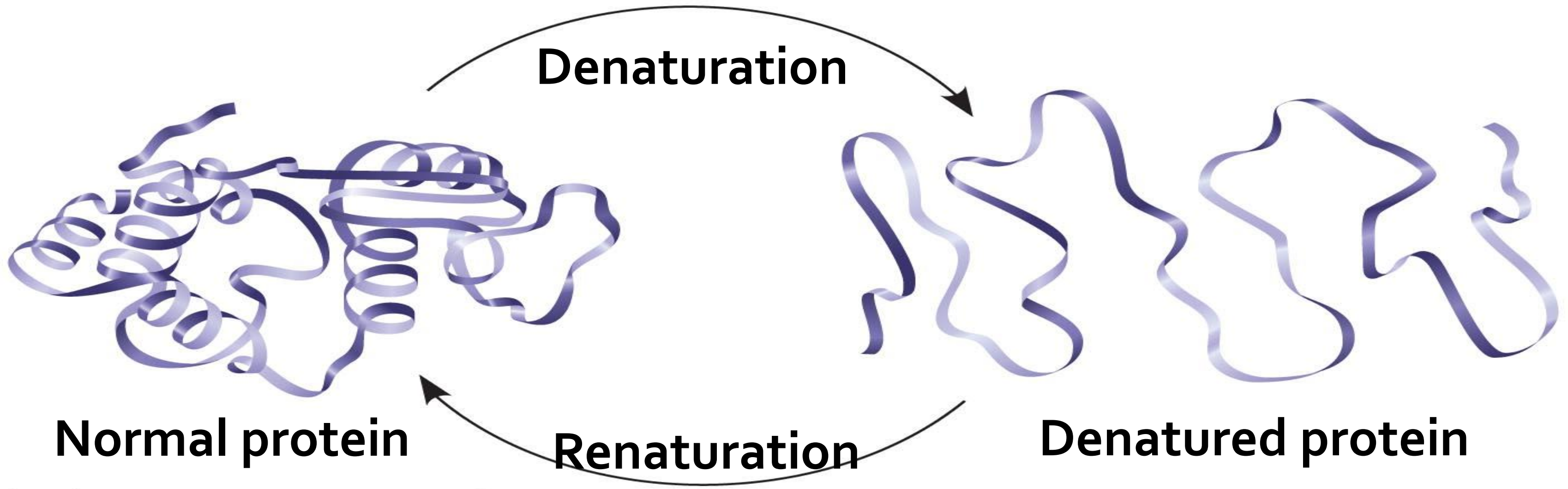
Normal red blood cells are full of individual hemoglobin molecules, each carrying oxygen.



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

What Determines Protein Structure?

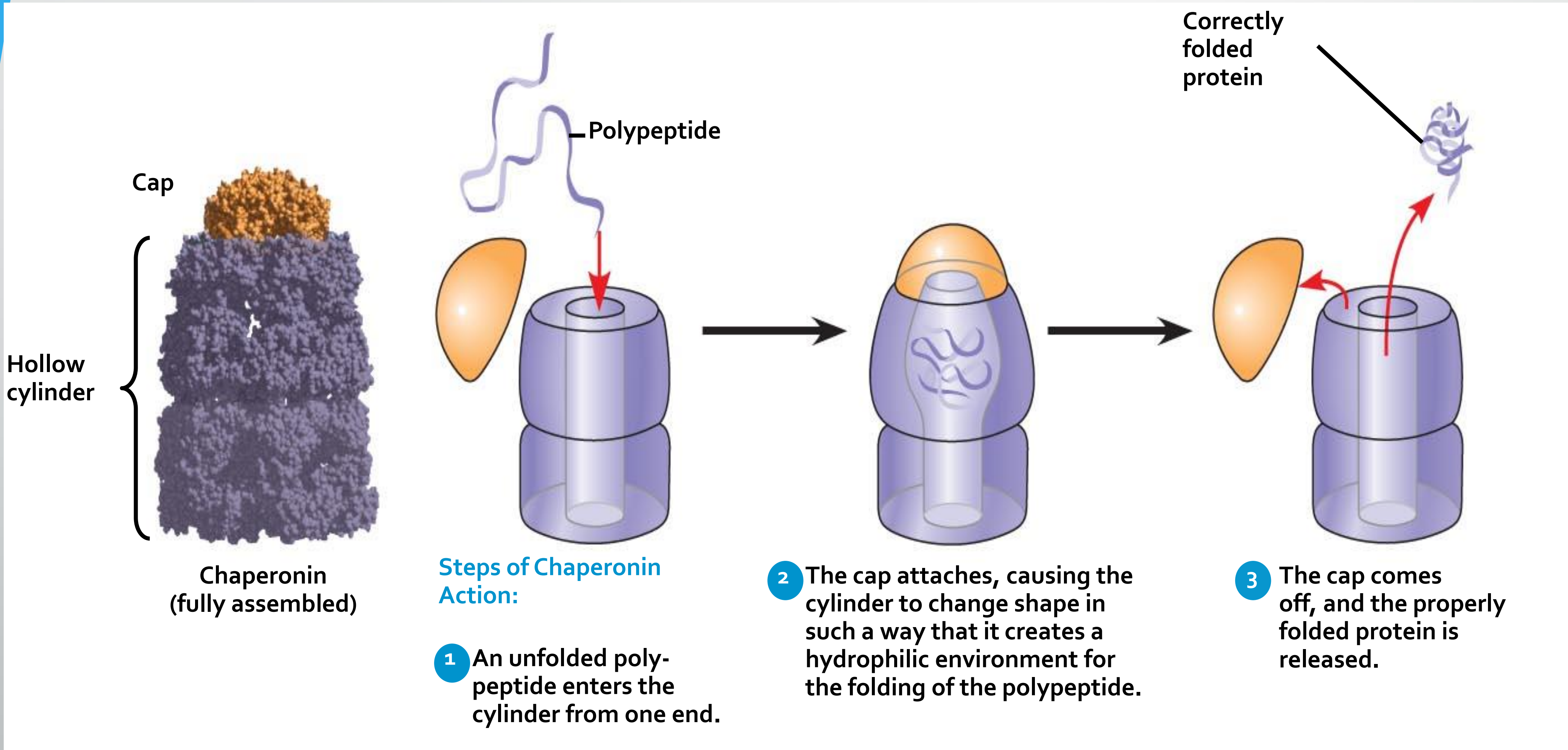
- In addition to primary structure, physical and chemical conditions can affect structure
  - Alterations in pH, salt concentration, temperature, or other environmental factors can cause a protein to unravel
  - This loss of a protein's native structure is called **denaturation**
- A denatured protein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



Protein Folding in the Cell

- It is hard to predict a protein's structure from its primary structure
- Most proteins probably go through several states on their way to a stable structure
- **Chaperonins** are protein molecules that assist the proper folding of other proteins

Fig. 5-24


Cap
Hollow cylinder
Chaperonin (fully assembled)
Polypeptide
Correctly folded protein
Steps of Chaperonin Action:
1 An unfolded poly-peptide 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.

- 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 uses computer programs to predict protein structure from amino acid sequences

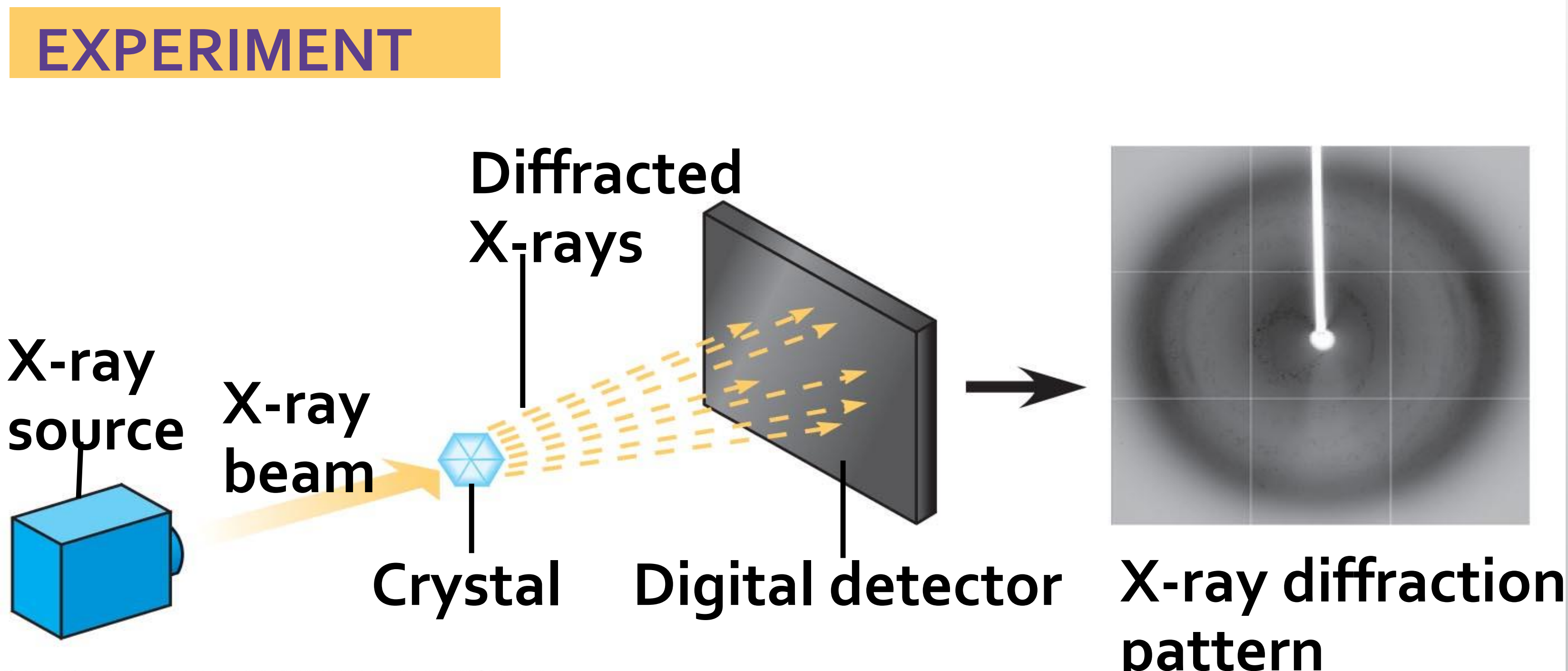
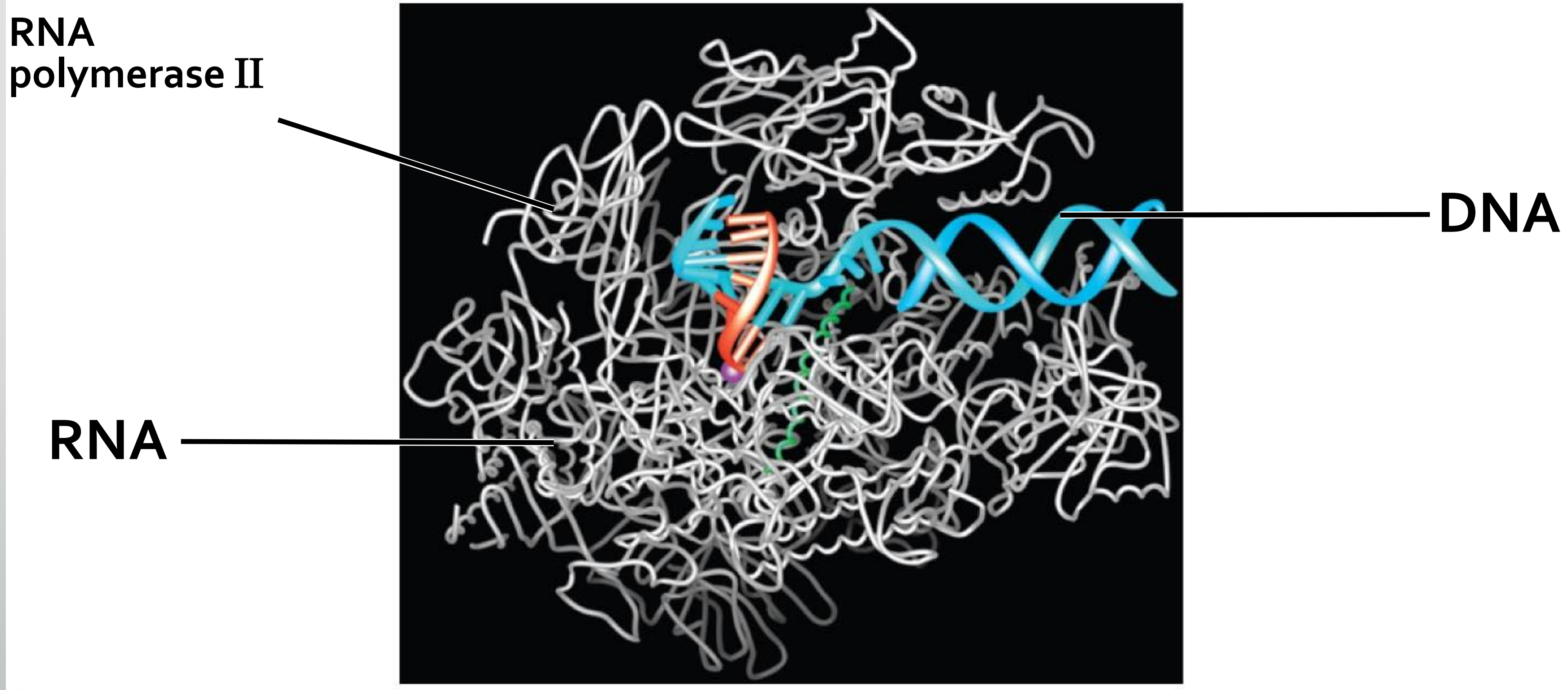


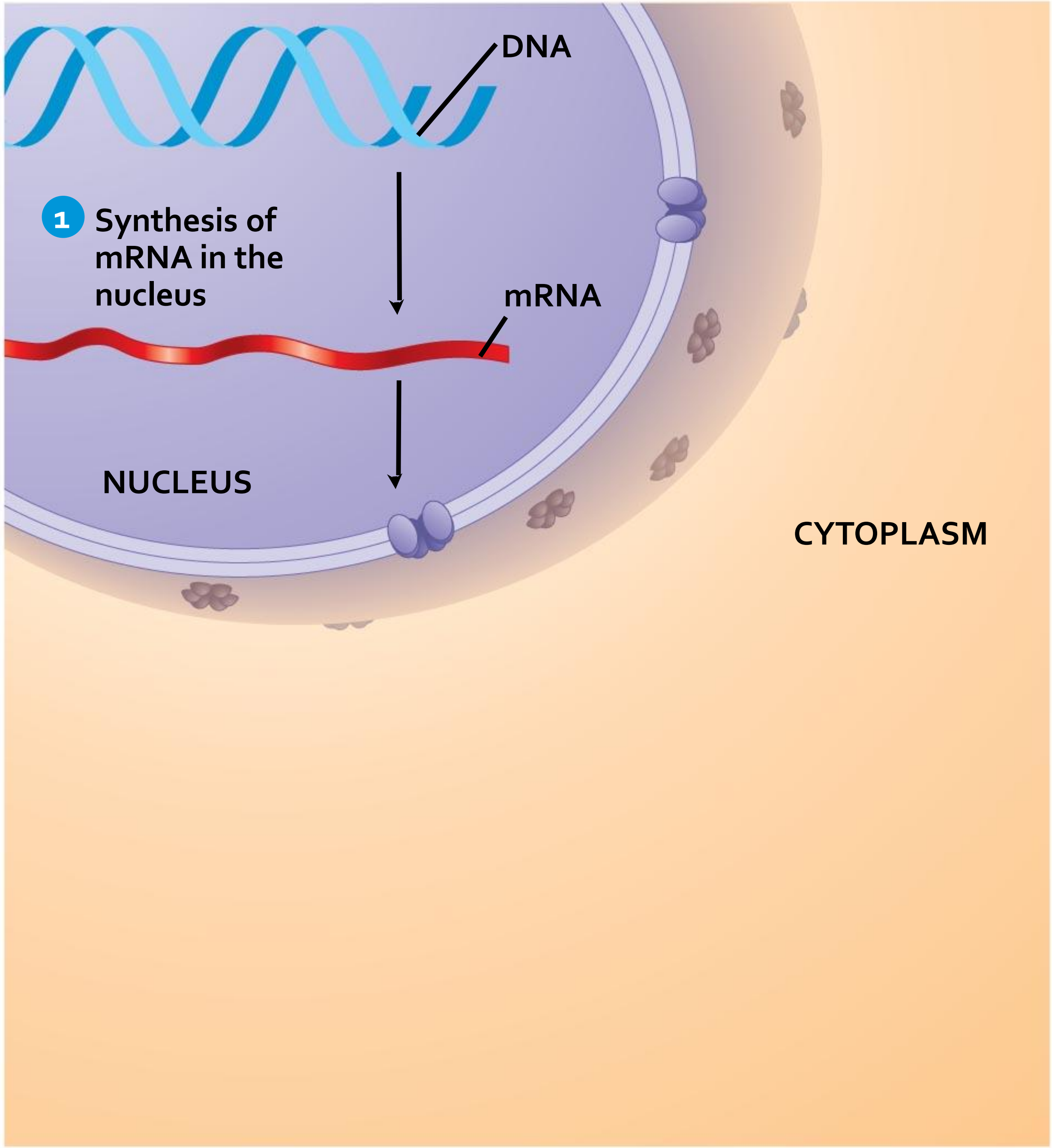
Fig. 5-25b

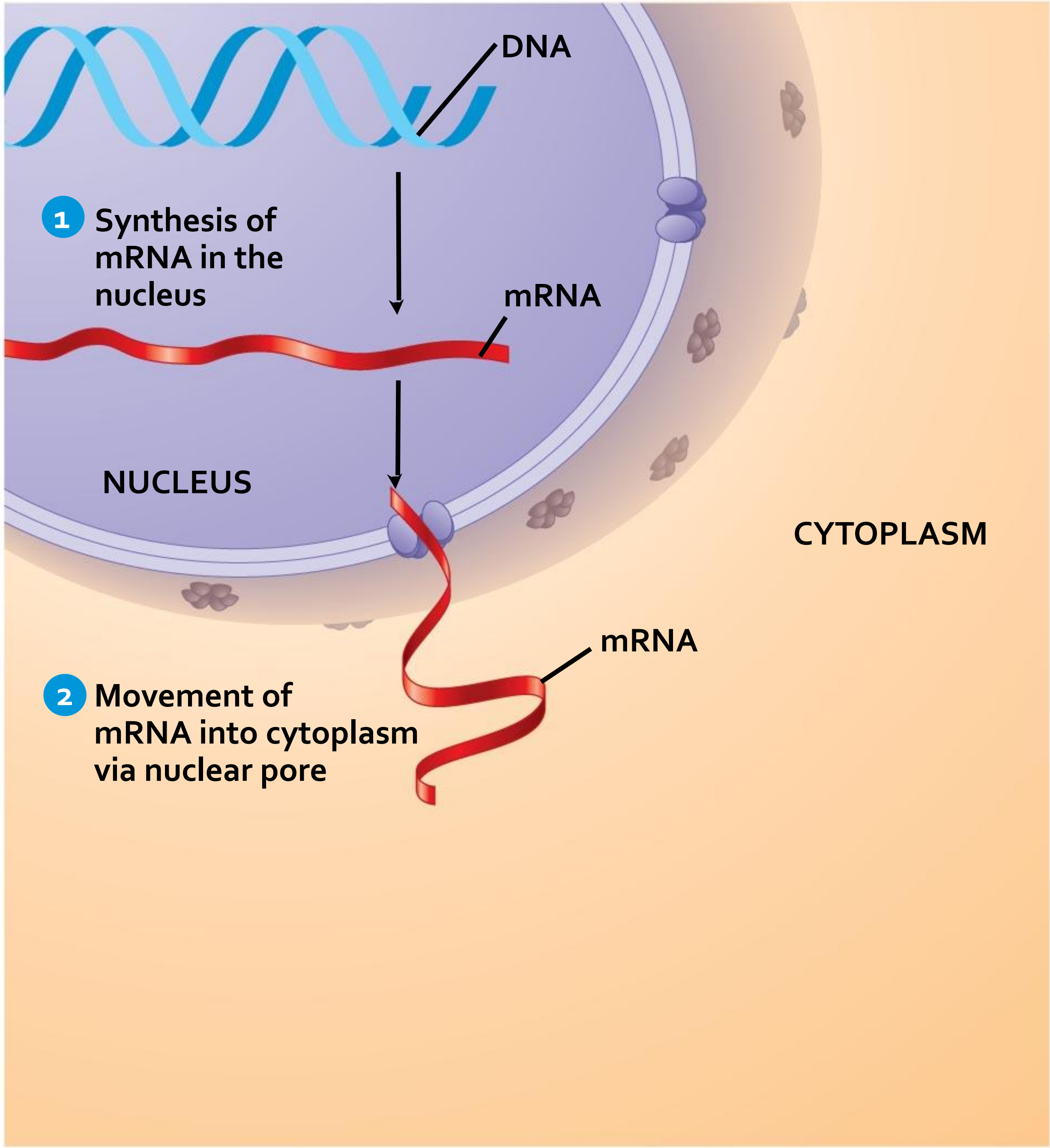
RESULTS

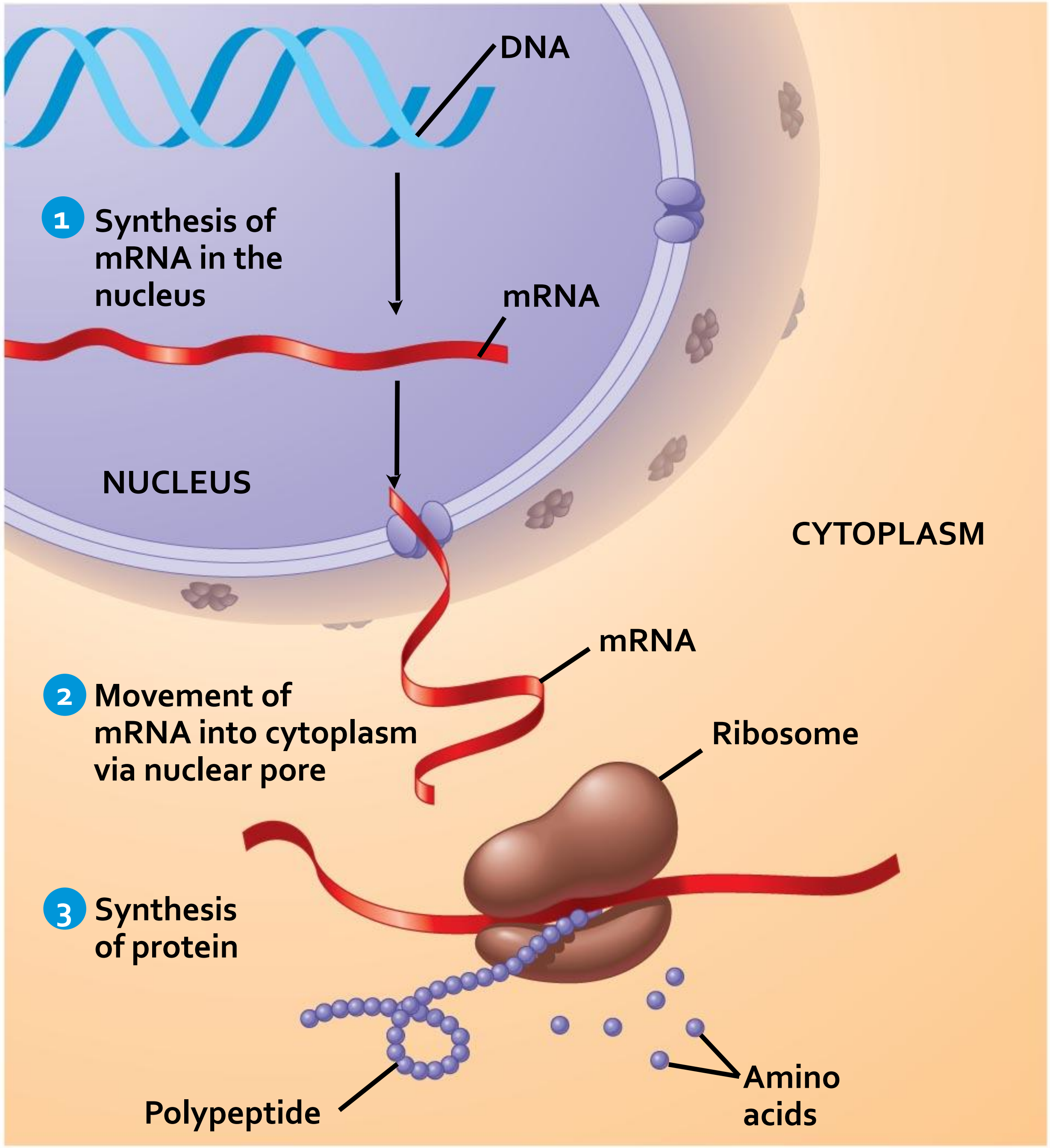


Nucleic acids

- The amino acid sequences of polypeptides are programmed in **genes**
  - Genes are made of DNA, a **nucleic acid**
- 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


DNA
1 Synthesis of mRNA in the nucleus
mRNA
NUCLEUS
CYTOPLASM

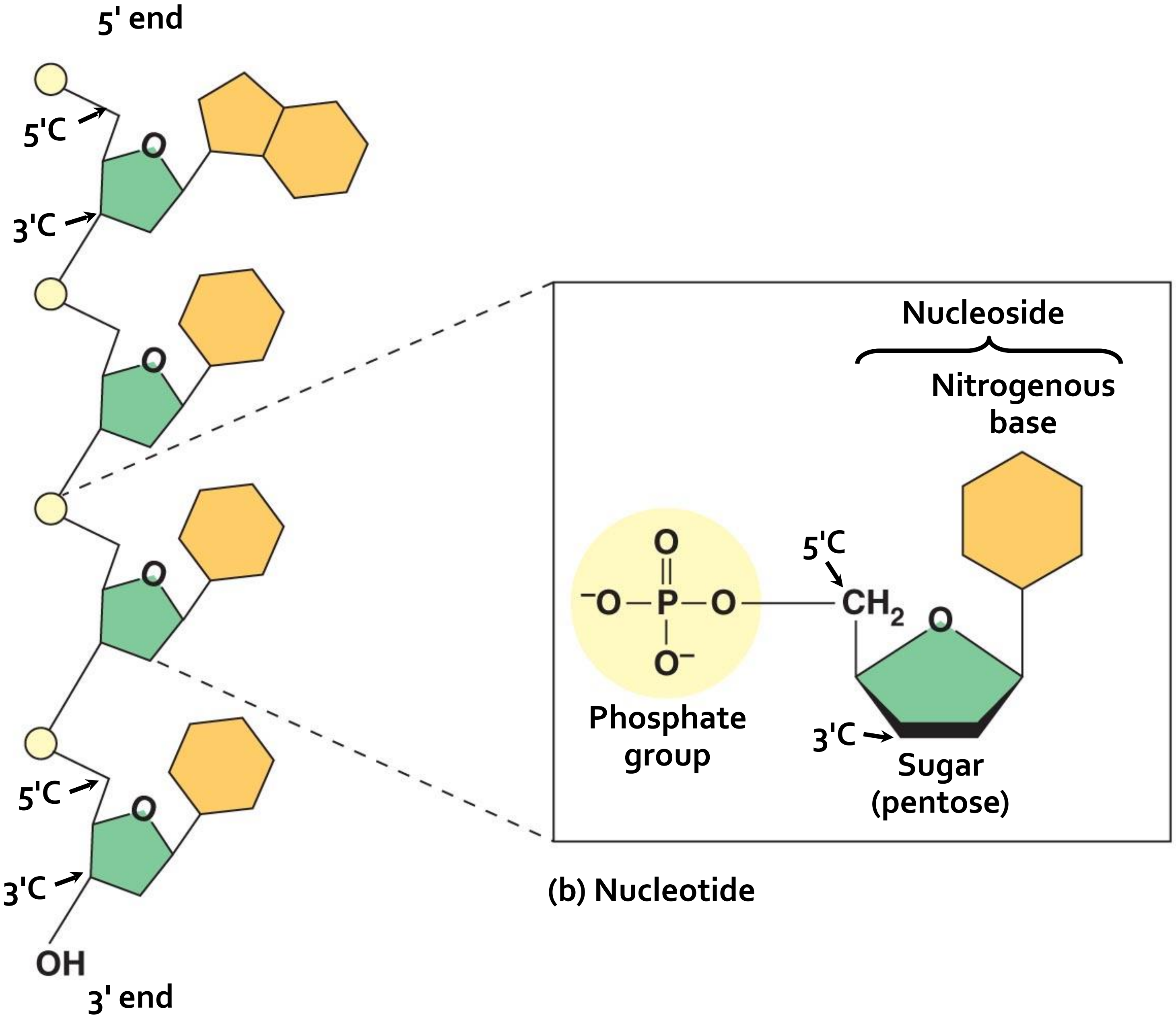

DNA
1 Synthesis of mRNA in the nucleus
mRNA
NUCLEUS
CYTOPLASM
mRNA
2 Movement of mRNA into cytoplasm via nuclear pore


DNA
1 Synthesis of mRNA in the nucleus
mRNA
NUCLEUS
CYTOPLASM
mRNA
2 Movement of mRNA into cytoplasm via nuclear pore
Ribosome
3 Synthesis of protein
Polypeptide
Amino acids

The Structure of Nucleic Acids

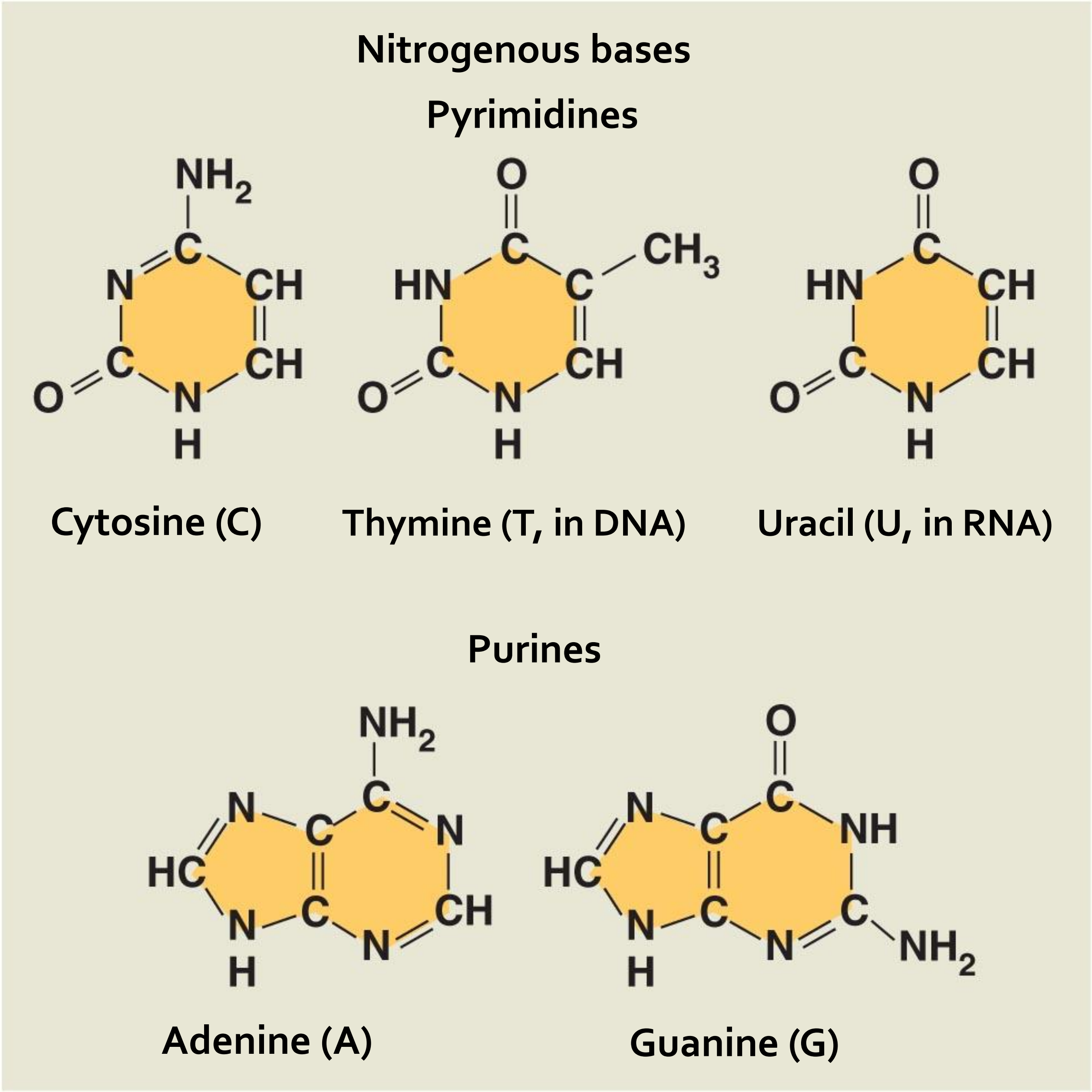
- Nucleic acids are polymers called **polynucleotides**
  - Each polynucleotide is made of monomers called **nucleotides**
  - Each nucleotide consists of…

1.
2.
3.

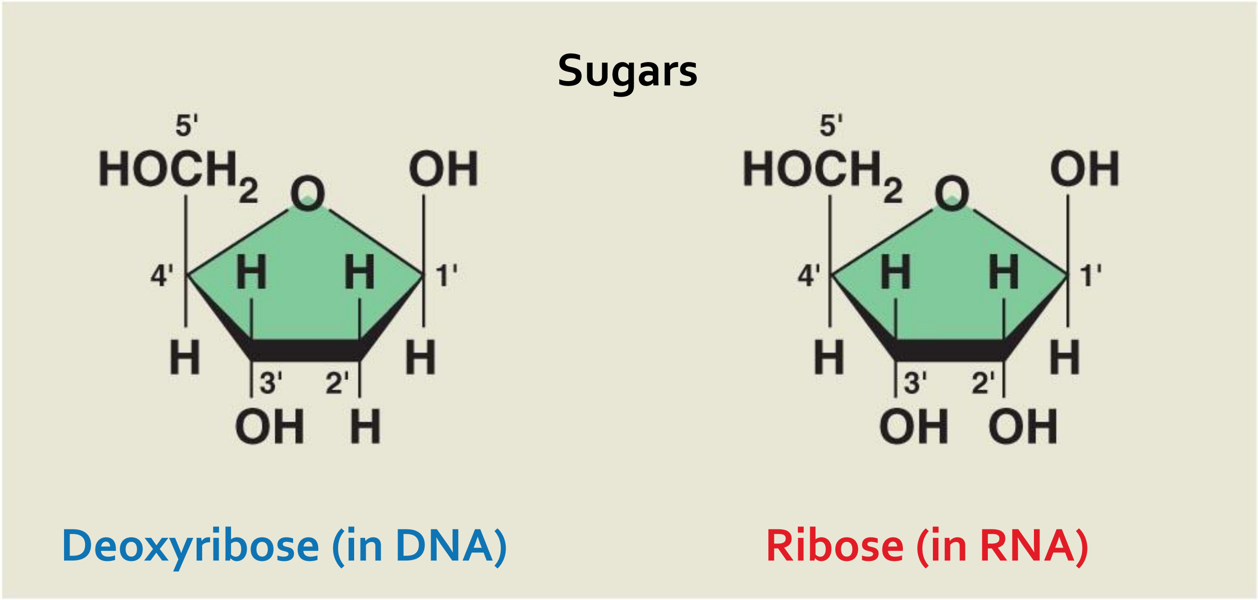


(a) Polynucleotide, or nucleic acid

(b) Nucleotide



(c) Nucleoside components: nitrogenous bases



(c) Nucleoside components: sugars

Nucleotide Monomers

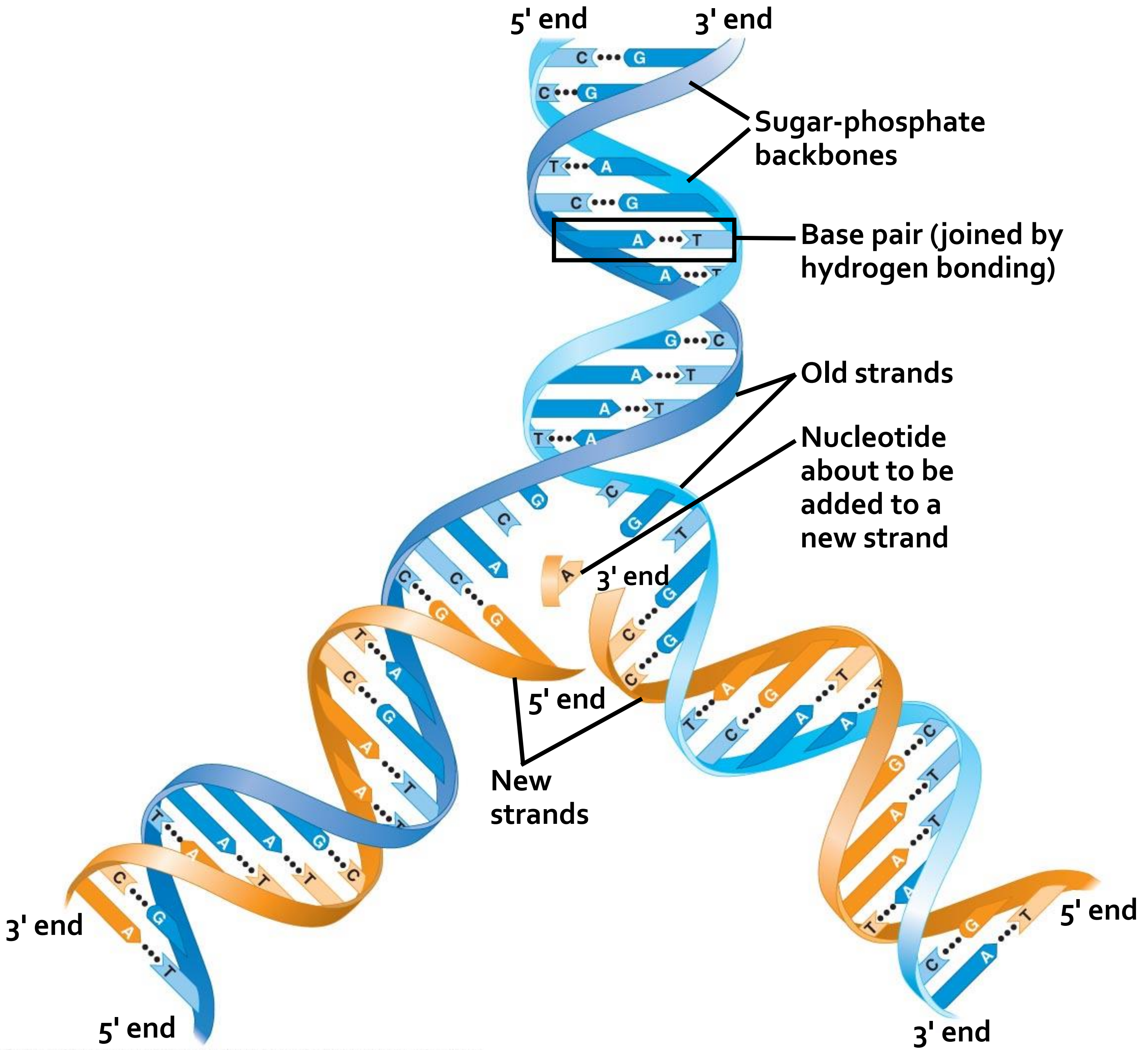
- Nucleoside = nitrogenous base + sugar
- There are two families of nitrogenous bases:
  - **Pyrimidines** (cytosine, thymine, and uracil) have a single six-membered ring
  - **Purines** (adenine and guanine) have a six-membered ring fused to a five-membered ring
- In DNA, the sugar is **deoxyribose**;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

Nucleotide Polymers

- Nucleotide polymers are linked together to build a polynucleotide
  - 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
  - creates a sugar-phosphate backbone with nitrogenous bases as appendages
- The sequence of bases along a DNA or mRNA polymer is unique for each gene

The DNA Double Helix

- A DNA molecule has two polynucleotides spiraling around an imaginary axis, forming a **double helix**
- In the DNA double helix, the two backbones run in opposite $5' \rightarrow 3'$ directions from each other, an arrangement referred to as **antiparallel**
- The nitrogenous bases in DNA pair up and form hydrogen bonds: adenine (A) always with thymine (T), and guanine (G) always with cytosine (C)


5' end
3' end
Sugar-phosphate backbones
Base pair (joined by hydrogen bonding)
Old strands
Nucleotide about to be added to a new strand
3' end
5' end
New strands
3' end
5' end
5' end
3' end

DNA and Proteins as Tape Measures of Evolution

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

Fig. 5-UN2a

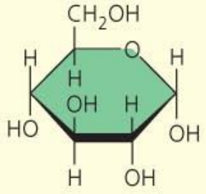
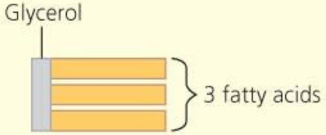
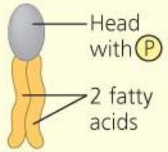
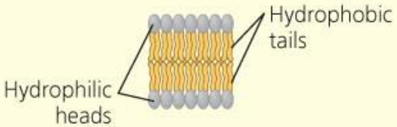
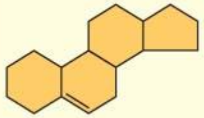
Large Biological Molecules	Components	Examples	Functions
Concept 5.2 **Carbohydrates** serve as fuel and building material	 Monosaccharide monomer	Monosaccharides: glucose, fructose	Fuel; carbon sources that can be converted to other molecules or combined into polymers
		Disaccharides: lactose, sucrose	
		Polysaccharides: • Cellulose (plants) • Starch (plants) • Glycogen (animals) • Chitin (animals and fungi)	 • Strengthens plant cell walls • Stores glucose for energy • Stores glucose for energy • Strengthens exoskeletons and fungal cell walls
Concept 5.3 **Lipids** are a diverse group of hydrophobic molecules and are not macromolecules		Triacylglycerols (fats or oils): glycerol + 3 fatty acids	Important energy source 
		Phospholipids: phosphate group + 2 fatty acids	Lipid bilayers of membranes 
	 Steroid backbone	Steroids: four fused rings with attached chemical groups	• Component of cell membranes (cholesterol) • Signals that travel through the body (hormones)

Fig. 5-UN2b

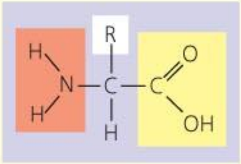
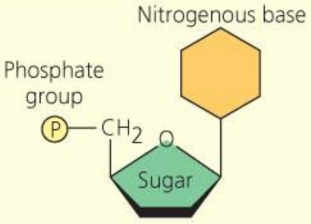
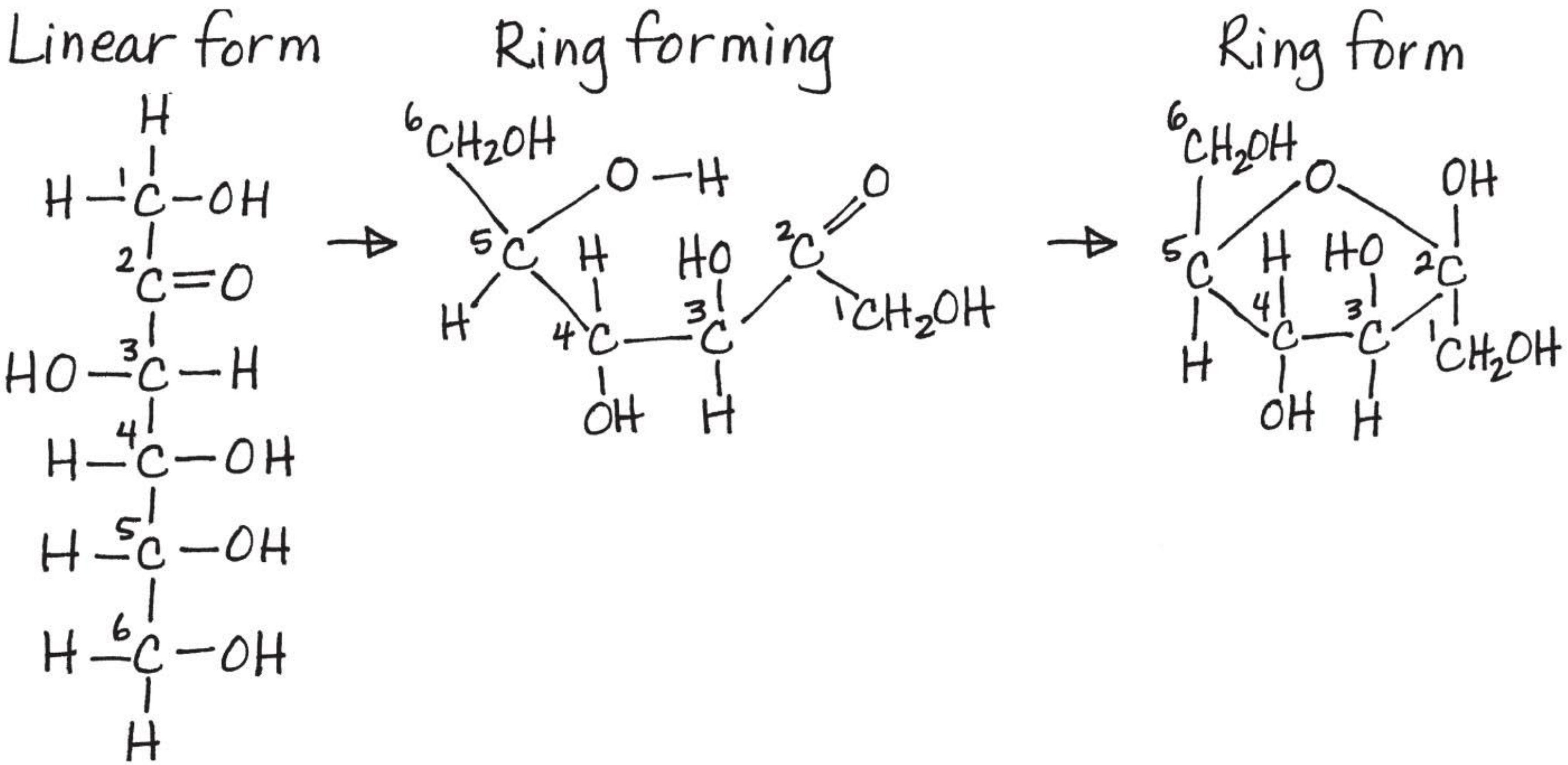
Large Biological Molecules	Components	Examples	Functions
Concept 5.4 **Proteins** have many structures, resulting in a wide range of functions	 Amino acid monomer (20 types)	• Enzymes • Structural proteins • Storage proteins • Transport proteins • Hormones • Receptor proteins • Motor proteins • Defensive proteins	• Catalyze chemical reactions • Provide structural support • Store amino acids • Transport substances • Coordinate organismal responses • Receive signals from outside cell • Function in cell movement • Protect against disease
Concept 5.5 Nucleic acids store and transmit hereditary information	 Nucleotide monomer	DNA:  • Sugar = deoxyribose • Nitrogenous bases = C, G, A, T • Usually double-stranded	Stores all hereditary information
		RNA:  • Sugar = ribose • Nitrogenous bases = C, G, A, U • Usually single-stranded	Carries protein-coding instructions from DNA to protein-synthesizing machinery

Fig. 5-UN4



Linear form
Ring forming
Ring form
H
H
C
OH
C
O
HO
C
H
H
C
OH
H
C
OH
H
C
OH
H
$^6CH_2OH$
O
H
C
H
H
HO
C
O
$^1CH_2OH$
C
C
OH
H
$^6CH_2OH$
O
OH
C
H
HO
C
C
C
C
$^1CH_2OH$
H
OH
H

Fig. 5-UN5

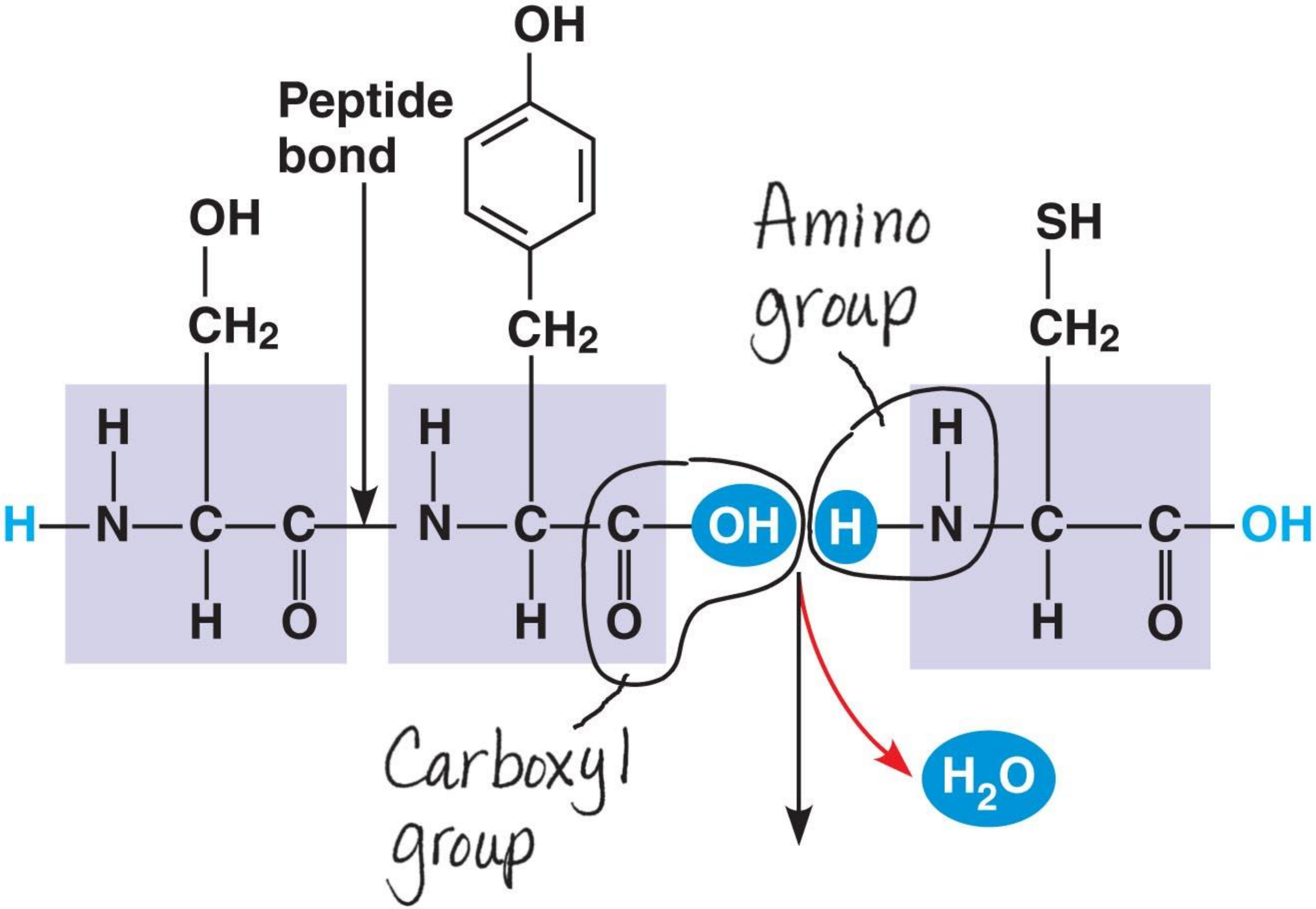


Fig. 5-UN6

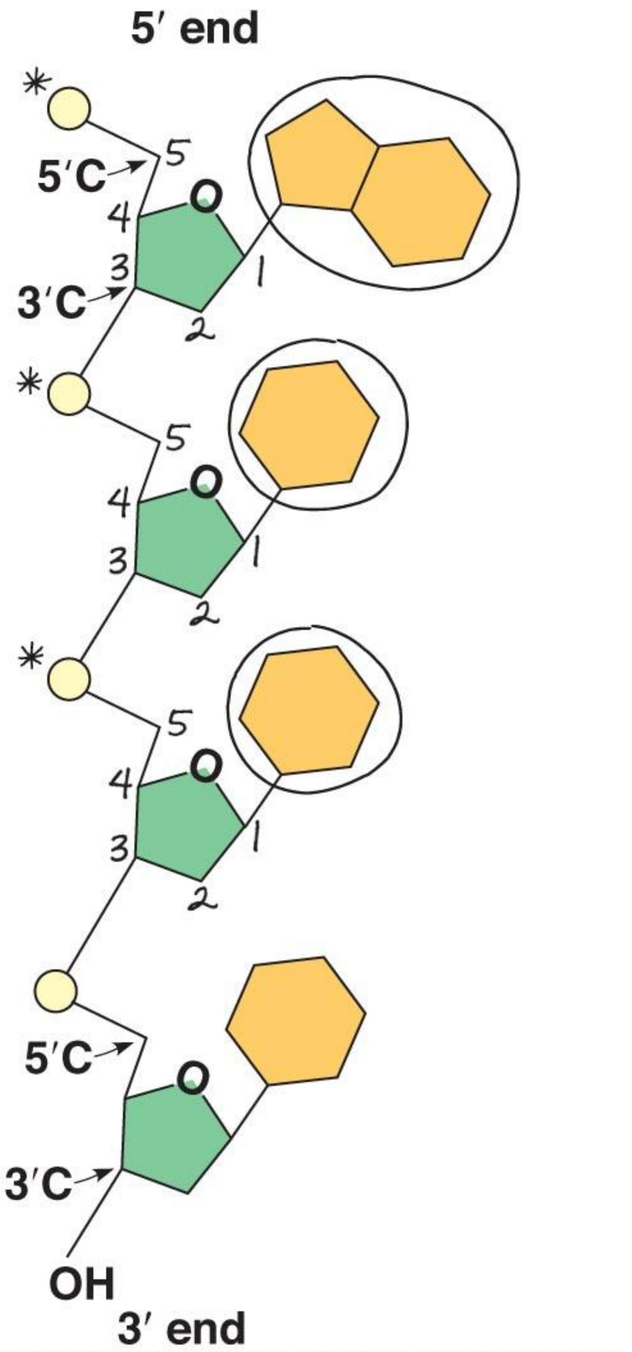


Fig. 5-UN7

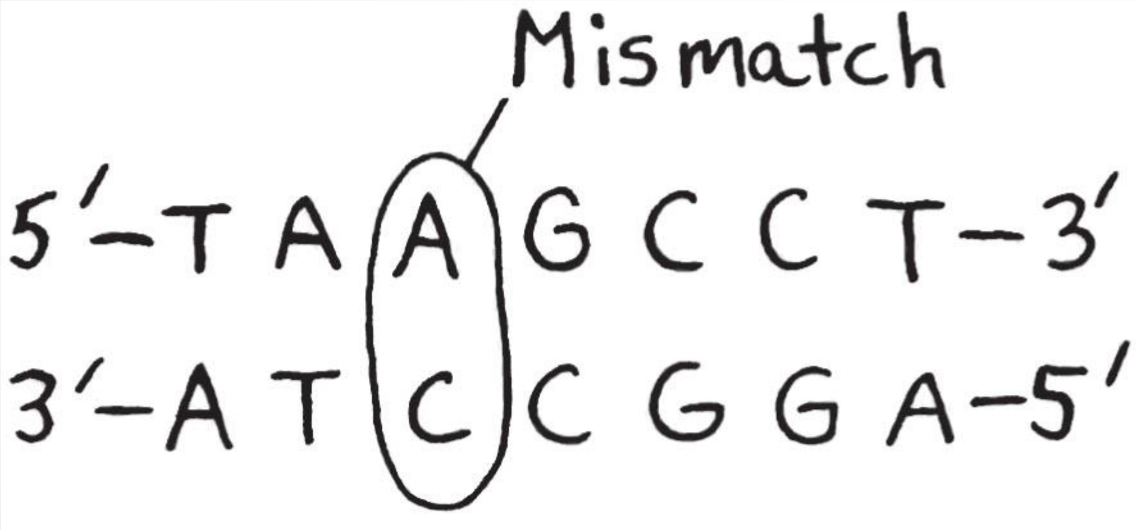


Fig. 5-UN8

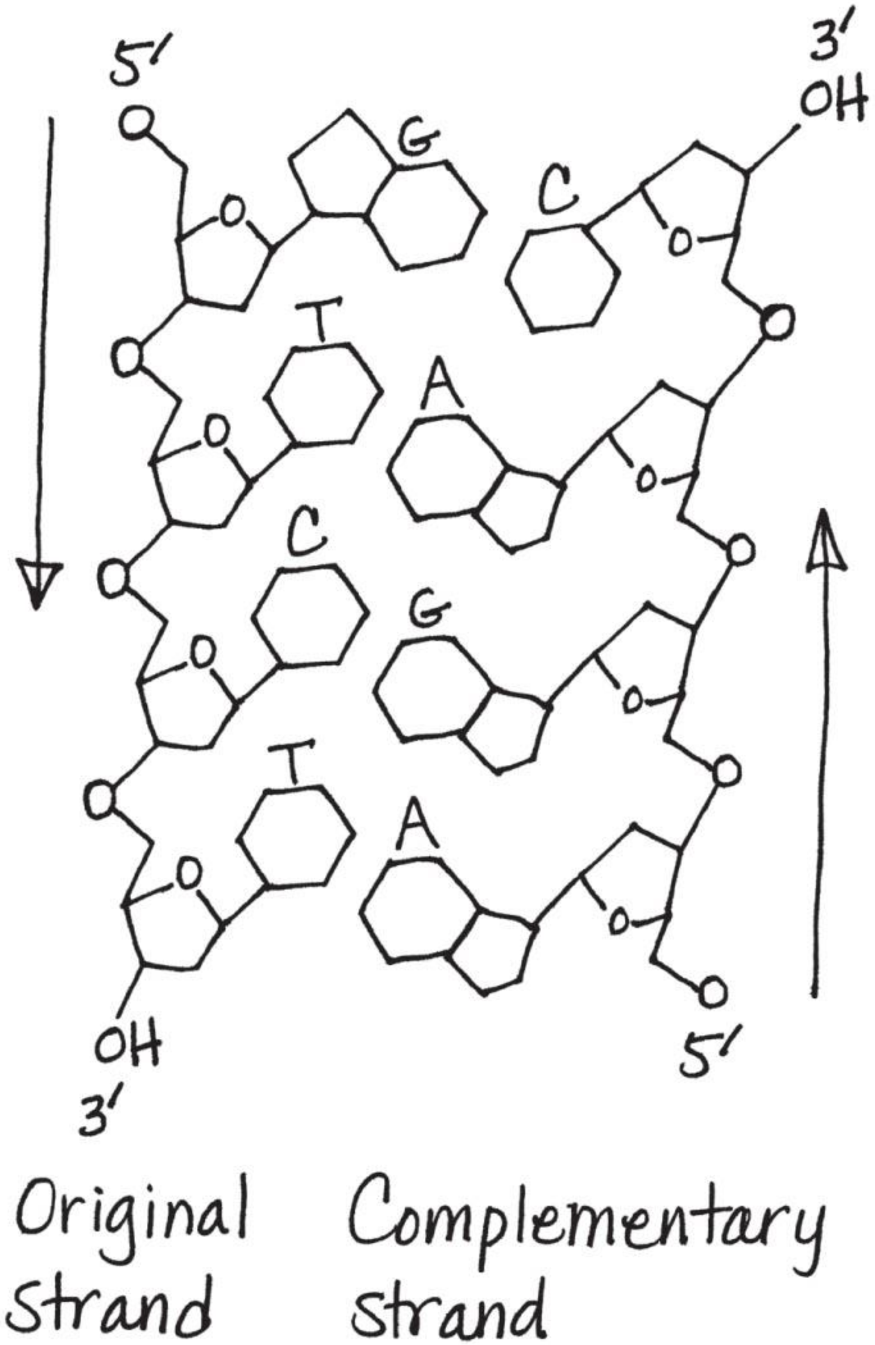
5′–T A A G C C T–3′

3′–A T T C G G A–5′

Fig. 5-UN9

	Monomers or components	Polymer or larger molecule	Type of linkage
Sugars	Monosaccharides	Polysaccharides	Glycosidic linkages
Lipids	Fatty acids	Triacylglycerols	Ester linkages
Proteins	Amino acids	Polypeptides	Peptide bonds
Nucleic acids	Nucleotides	Polynucleotides	Phosphodiester linkages

Fig. 5-UN10



You should now be able to:

1. List and describe the four major classes of molecules
2. Describe the formation of a glycosidic linkage and distinguish between monosaccharides, disaccharides, and polysaccharides
3. Distinguish between saturated and unsaturated fats and between *cis* and *trans* fat molecules
4. Describe the four levels of protein structure
5. Distinguish between the following pairs: pyrimidine and purine, nucleotide and nucleoside, ribose and deoxyribose, the 5′ end and 3′ end of a nucleotide