Chapter 5

The Structure and Function of Large Biological Molecules

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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Overview: The Molecules of Life

- All living things are made up of four classes of large biological molecules: *carbohydrates*, *lipids*, *proteins*, and *nucleic acids.*
- Within cells, small organic molecules are joined together to form larger molecules.
- ***Macromolecules*** are large molecules composed of thousands of covalently connected atoms.
- Molecular structure and function are inseparable.

Why do scientists study the structures of macromolecules?

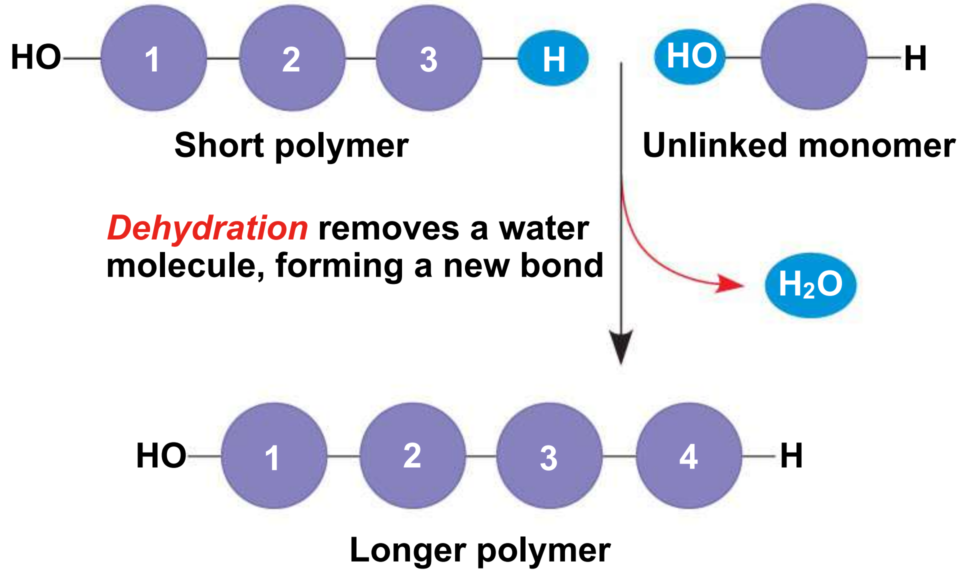
Macromolecules are polymers, built from monomers

- A ***polymer*** is a long chain-like 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*

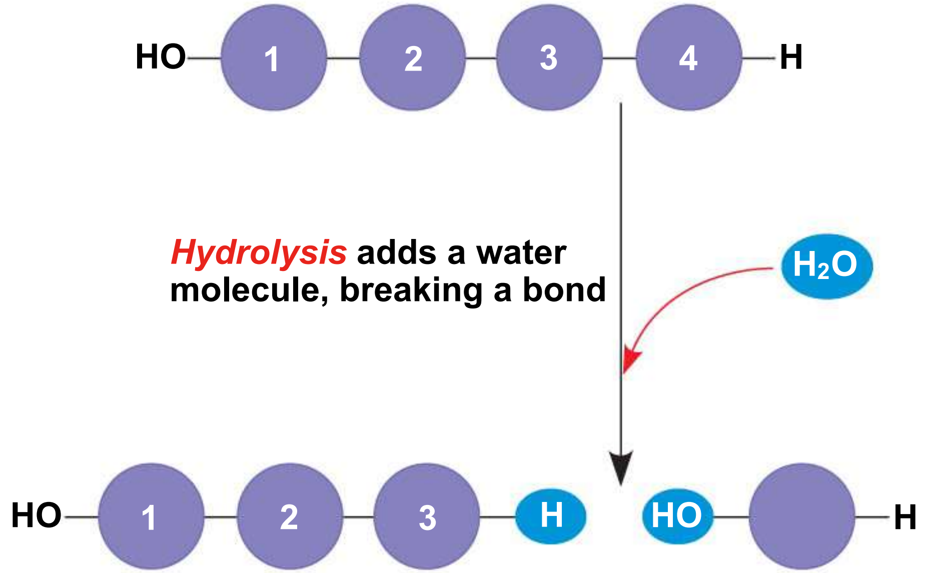
The Synthesis and Breakdown of Polymers

- A **condensation reaction** or more specifically a **dehydration reaction** occurs when two monomers bond together through the loss of a water molecule: ***dehydration synthesis = build by removing HOH.***
- **Enzymes** are organic catalysts = macromolecules that speed up chemical reactions.
- Polymers are disassembled to monomers by ***hydrolysis: breaking down by adding HOH.***

The synthesis and breakdown of polymers



(a) Dehydration reaction in the synthesis of a polymer



(b) Hydrolysis of a polymer

The Diversity of Polymers

- Each cell has thousands of different kinds of 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.*

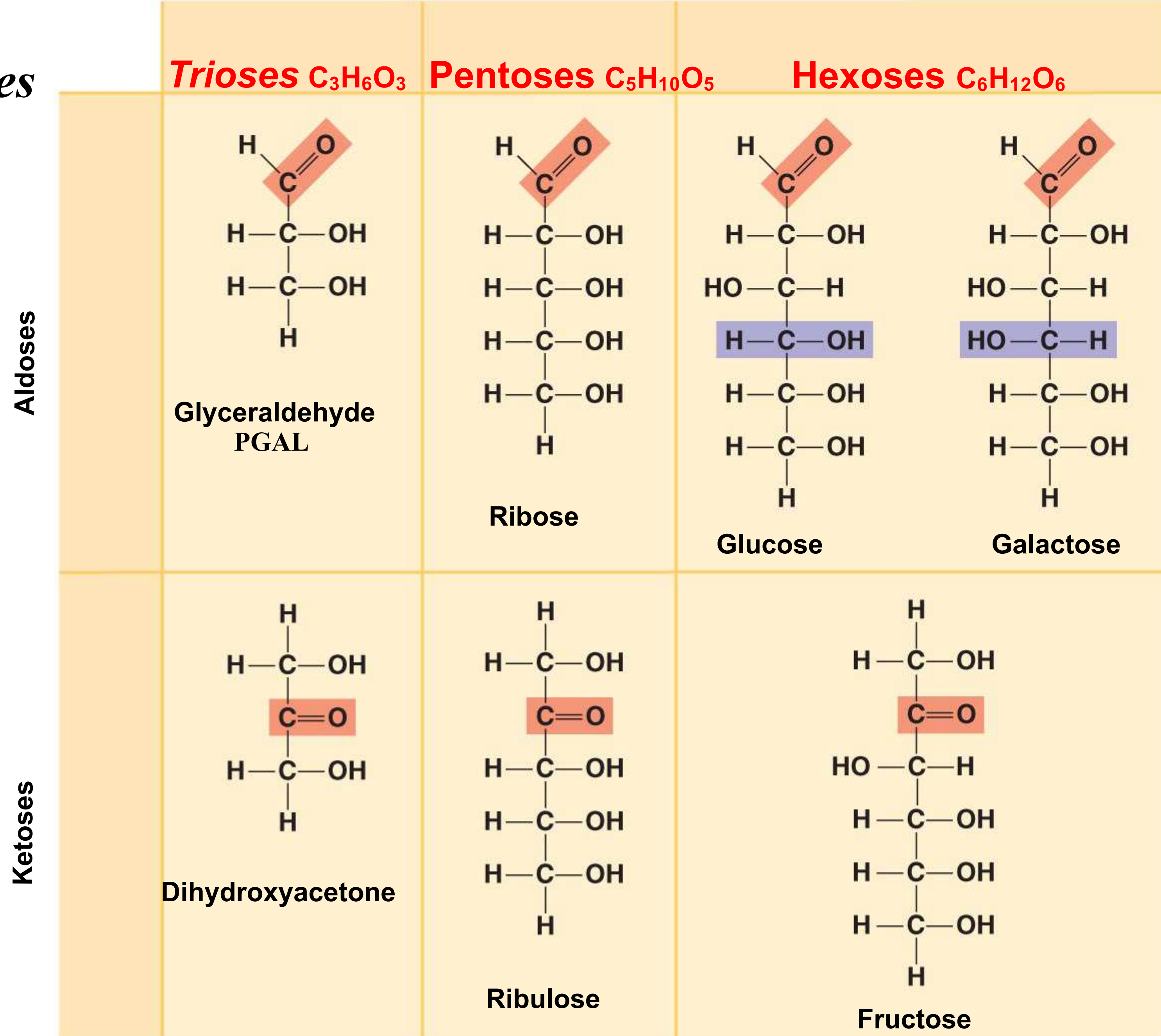
Carbohydrates serve as fuel and building material

- ***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

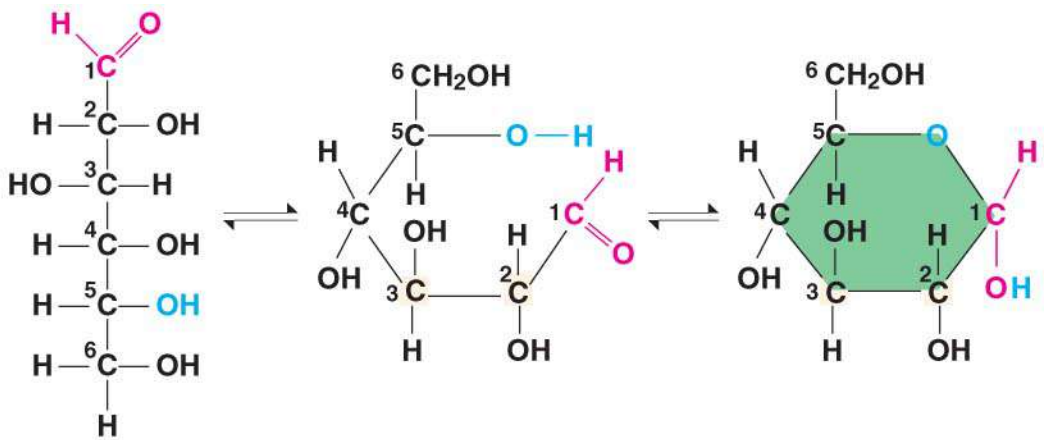
- ***Monosaccharides*** have molecular formulas that are usually multiples of ***CH_2O***
- Glucose ($C_6H_{12}O_6$) is the most common monosaccharide.
- Monosaccharides are classified by
  - The location of the carbonyl group (as aldose or ketose)
  - The number of carbons in the carbon skeleton.

Mono-saccharides

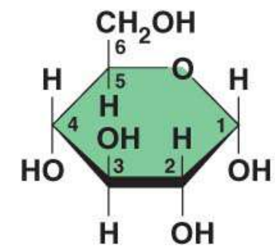


- Though often drawn as linear skeletons, in aqueous solutions many sugars form rings.
- Monosaccharides serve as a major fuel for cells and as raw material for building molecules.

Linear and ring forms of ***glucose***



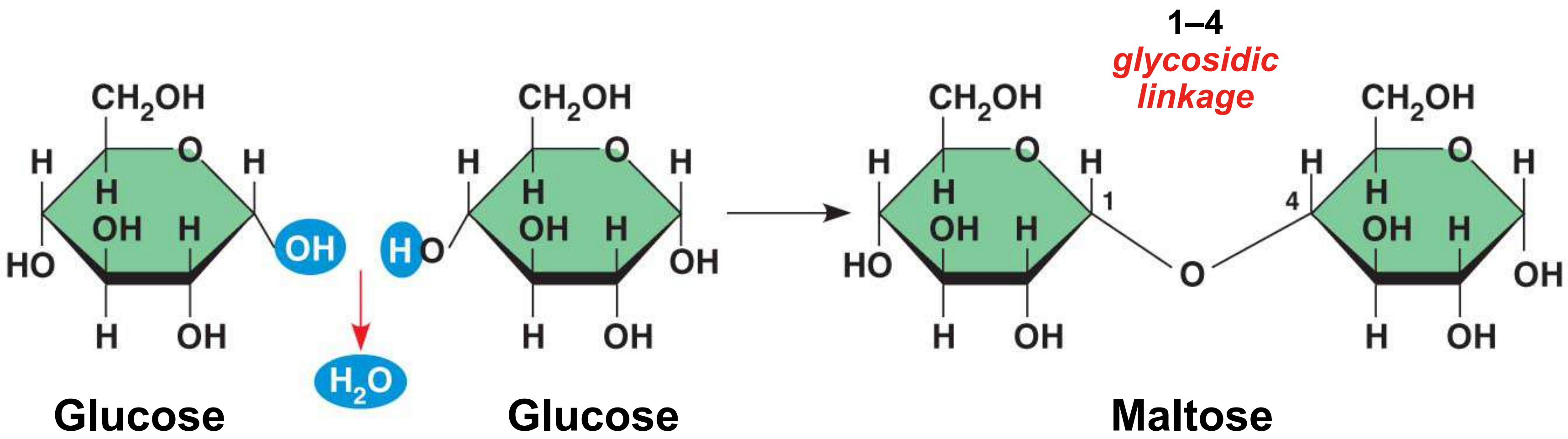
Linear and ring forms



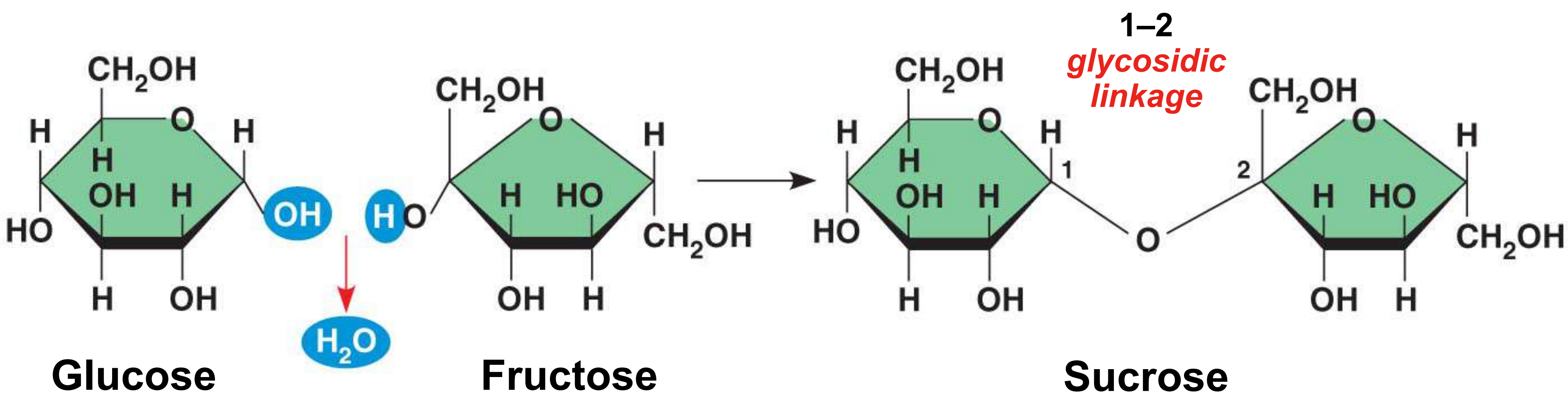
Abbreviated ring structure

- A **disaccharide** is formed when a dehydration reaction joins two monosaccharides by removing HOH to form a covalent bond.
- This covalent bond is called a ***glycosidic linkage.***
- The condensation or dehydration synthesis reaction: $C_6H_{12}O_6 + C_6H_{12}O_6 = C_{12}H_{22}O_{11}$

Examples of disaccharide synthesis



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



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

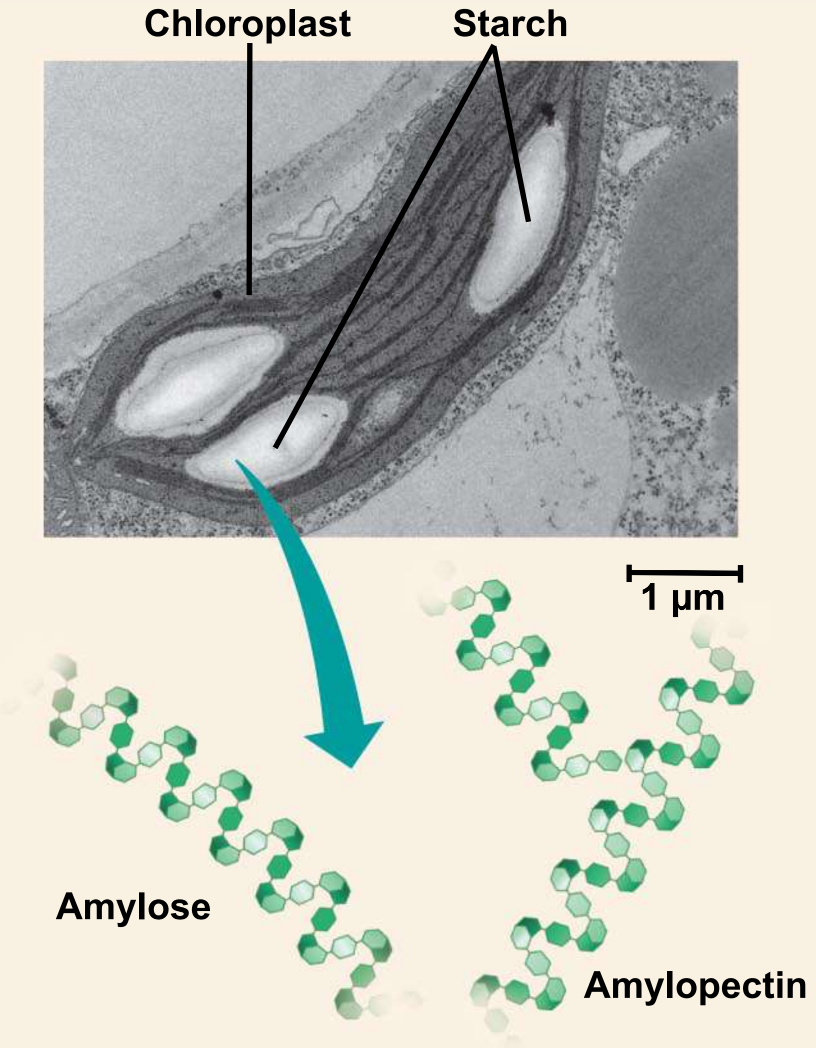
Polysaccharides

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

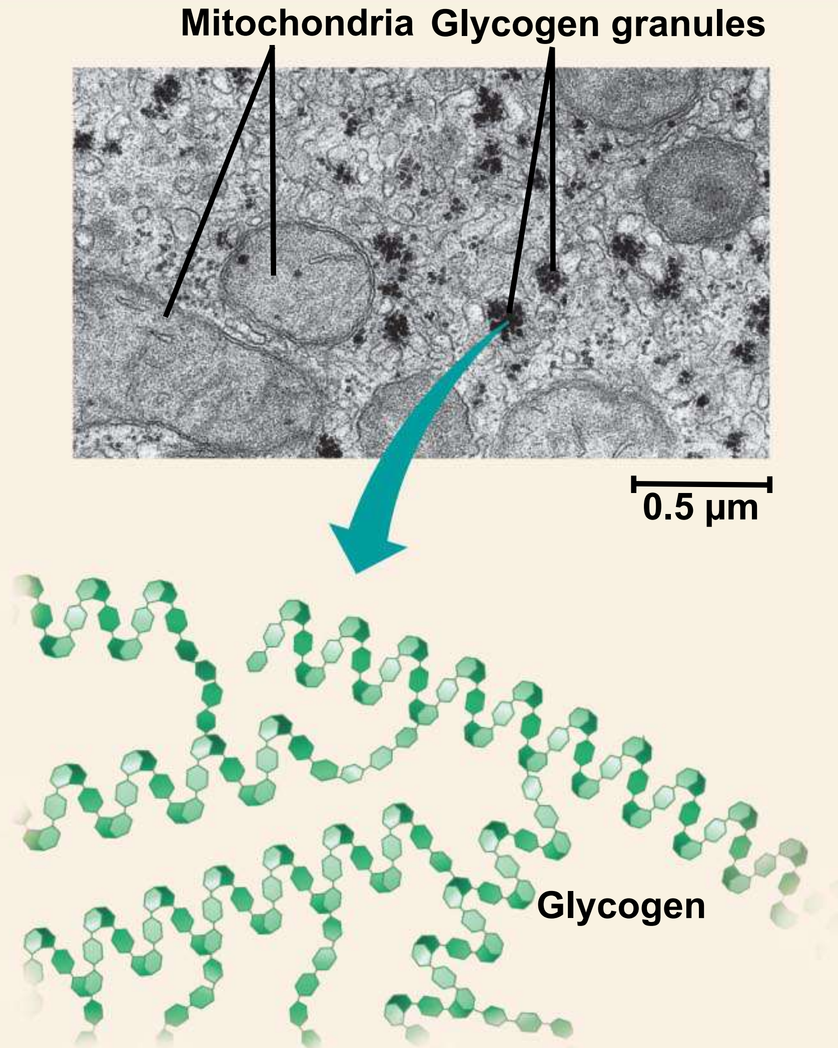
Storage Polysaccharides

- ***Starch*** is a ***plant storage*** polysaccharide. Starch is made of glucose monomers.
- Plants store surplus starch as granules within chloroplasts and other plastids.
- ***Glycogen*** is an ***animal storage*** polysaccharide. Glycogen is found in the liver and muscles.

Storage polysaccharides of plants and animals



(a) *Starch: a plant polysaccharide*



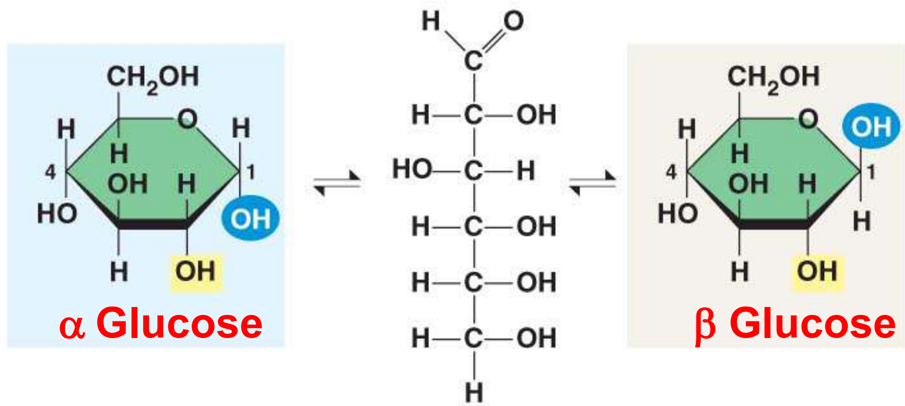
(b) *Glycogen: an animal polysaccharide*

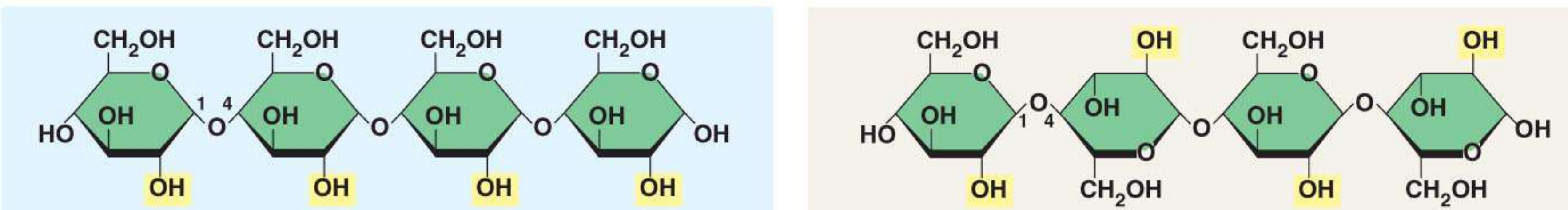
Structural Polysaccharides

- The *polysaccharide* ***cellulose*** is a major component of *plant cell walls.*
- Like starch, cellulose is a polymer of glucose, but the glycosidic linkages differ.
- The difference is based on two ring forms for glucose: alpha (α) and beta (β)

Polysaccharides: Starch and cellulose structures

(a) α and β glucose ring structures



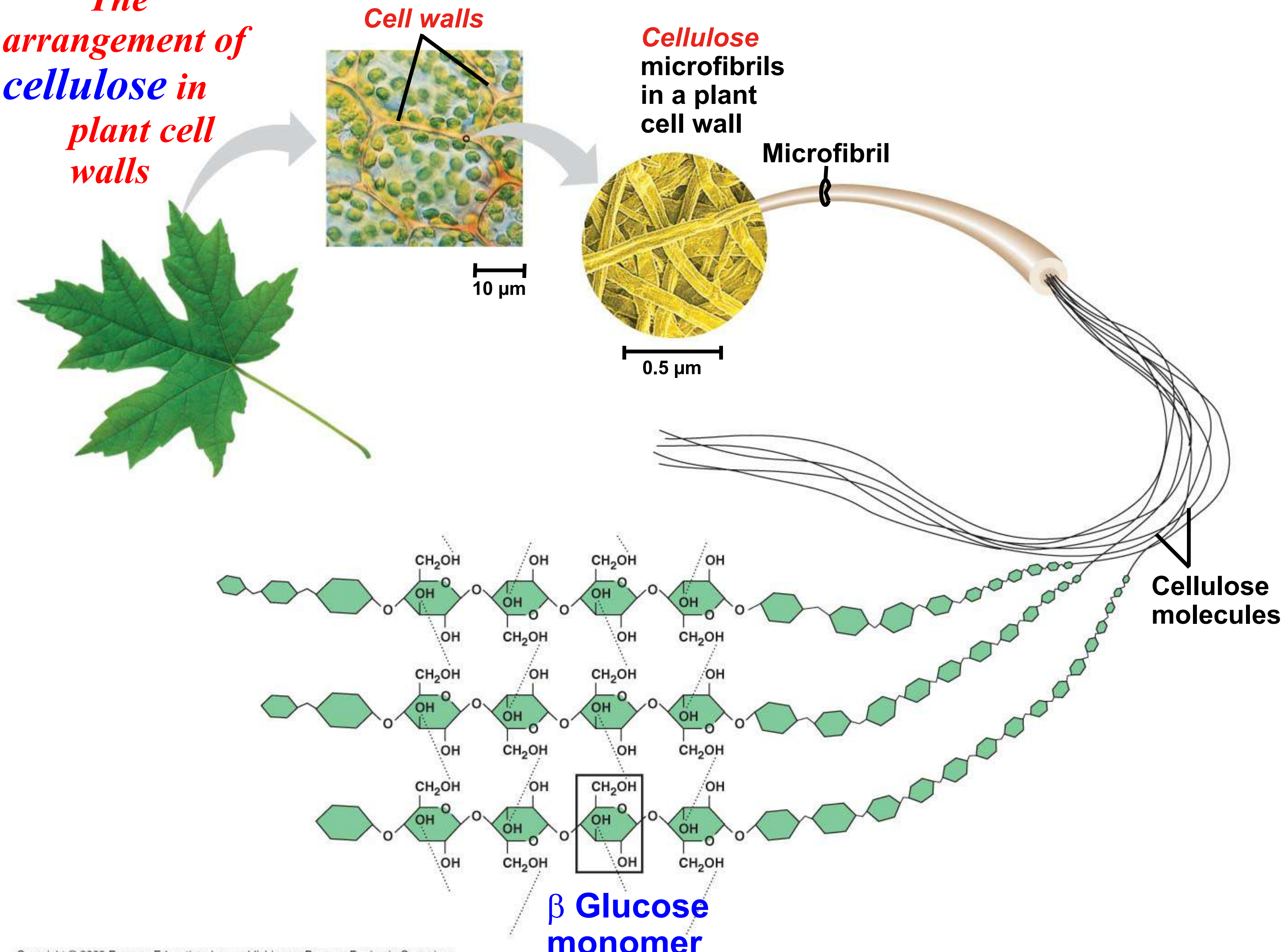


(b) **Starch**: 1–4 linkage of α glucose monomers

(b) **Cellulose**: 1–4 linkage of β 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.

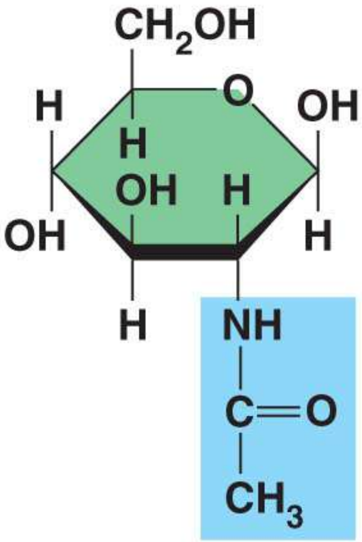
The arrangement of cellulose in plant cell walls



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

- ***Chitin***, another *structural polysaccharide*, is found in the *exoskeleton* of arthropods.
- Chitin also provides structural support for the *cell walls of fungi.*
- *Unlike starch and glycogen, chitin is a polysaccharide with nitrogen (N) in each sugar monomer.*

Chitin = a structural polysaccharide



(a) The structure of the *chitin monomer.*

(b) Chitin forms the *exoskeleton* of arthropods.

(c) Chitin is used to make a strong and flexible surgical thread.

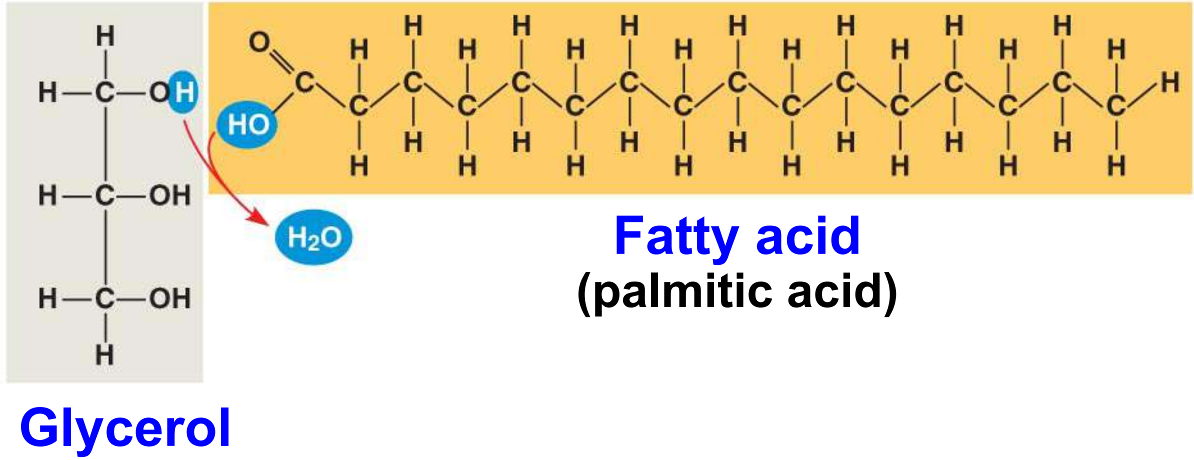
Lipids **are a diverse group of *hydrophobic* molecules**

- ***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.

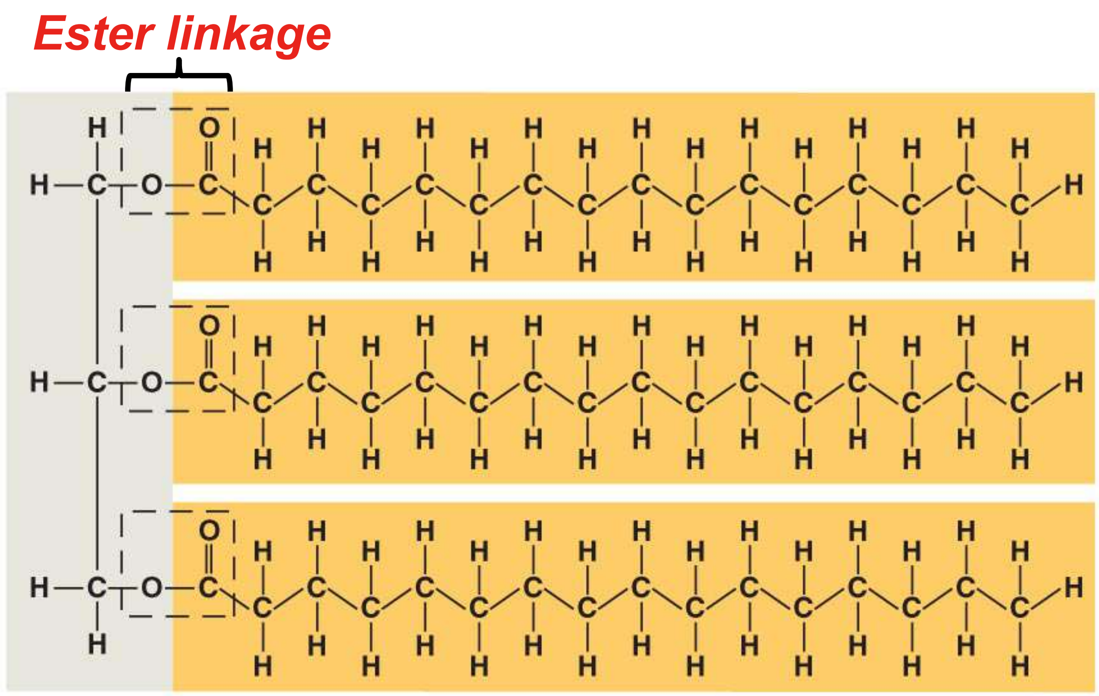
Fats

- ***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 hydrocarbon chain*.
- This fatty acid hydrocarbon can be either *saturated or unsaturated*.

The Synthesis and Structure of a fat = triacylglycerol



(a) Dehydration reaction in the synthesis of a fat

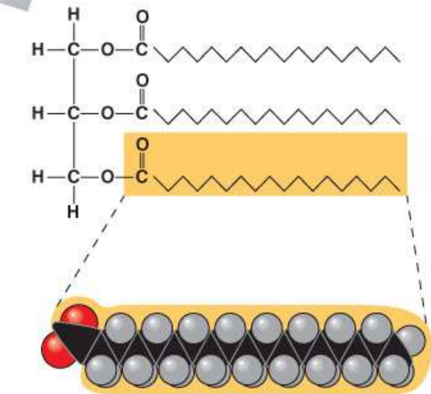


(b) Fat molecule (*Triglyceride*)

- 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 (covalent bond), creating a **triacylglycerol**, or triglyceride.

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

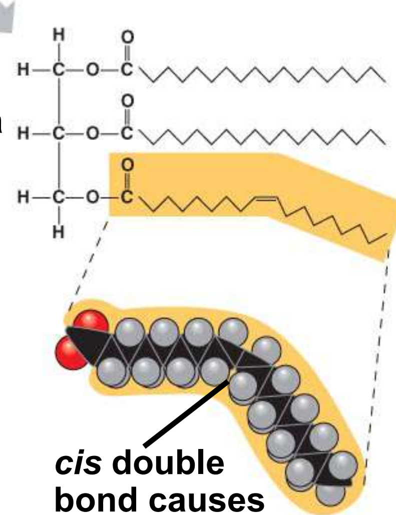
Examples of Saturated and Unsaturated Fats and Fatty acids



Structural formula of a *saturated fat* molecule

Stearic acid, a saturated fatty acid

(a) **Saturated fat**



Structural formula of an *unsaturated* fat molecule. The *chain bends*

Oleic acid, an unsaturated fatty acid

cis double bond causes **bending**

(b) **Unsaturated fat**

- 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.

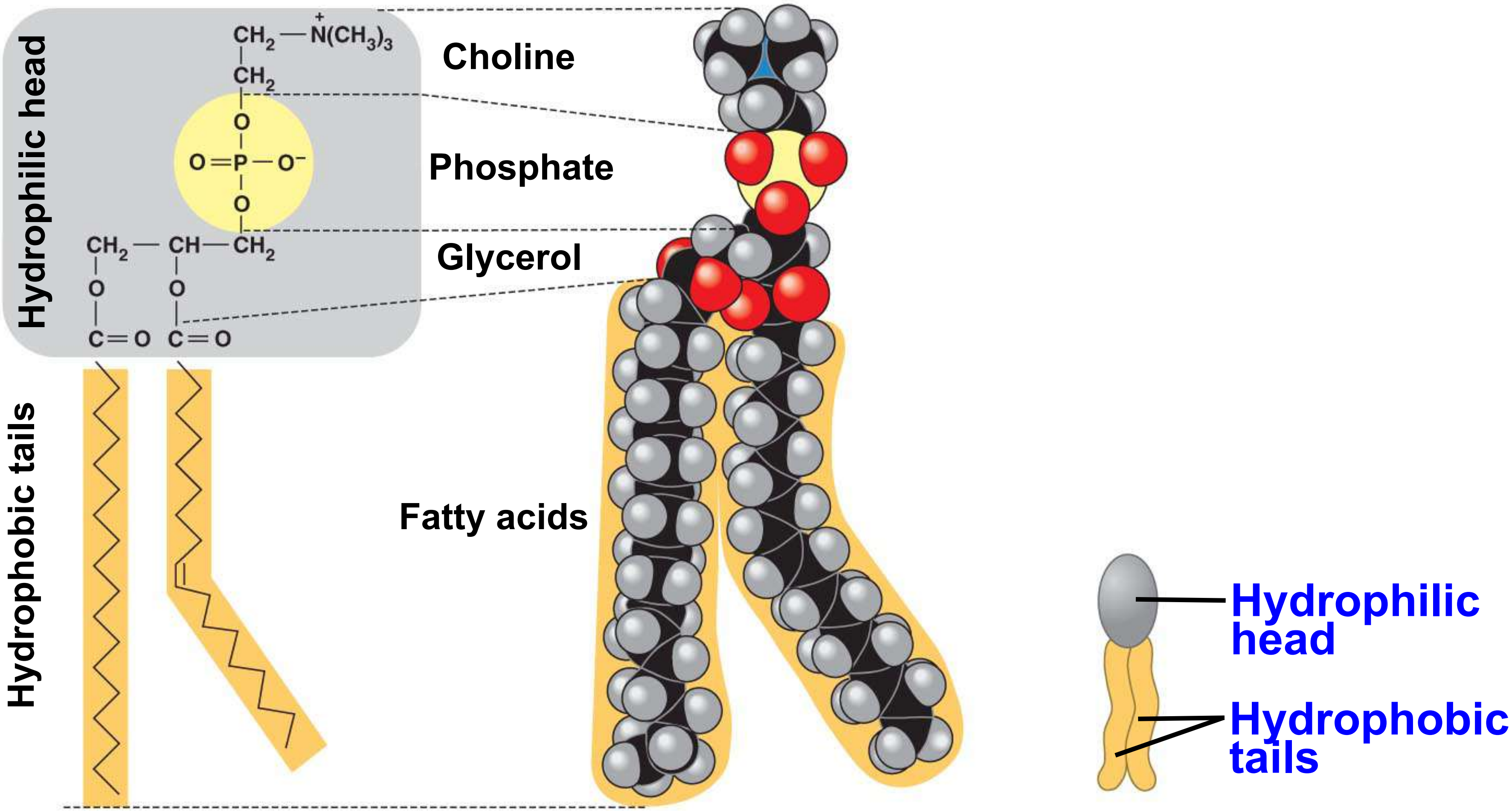
- A diet rich in saturated fats may contribute to cardiovascular disease through plaque deposits.
- ***Hydrogenation*** is the process of converting *unsaturated fats to saturated fats by adding hydrogen.*
- Hydrogenating vegetable oils also creates unsaturated fats with *trans* double bonds = *trans fats.*
- *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 fat in adipose cells.
- Adipose tissue also cushions vital organs and insulates the body.

Phospholipids -- Membranes

- 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.
- A phospholipid is an *amphipathic* molecule: hydrophillic head and hydrophobic tails.

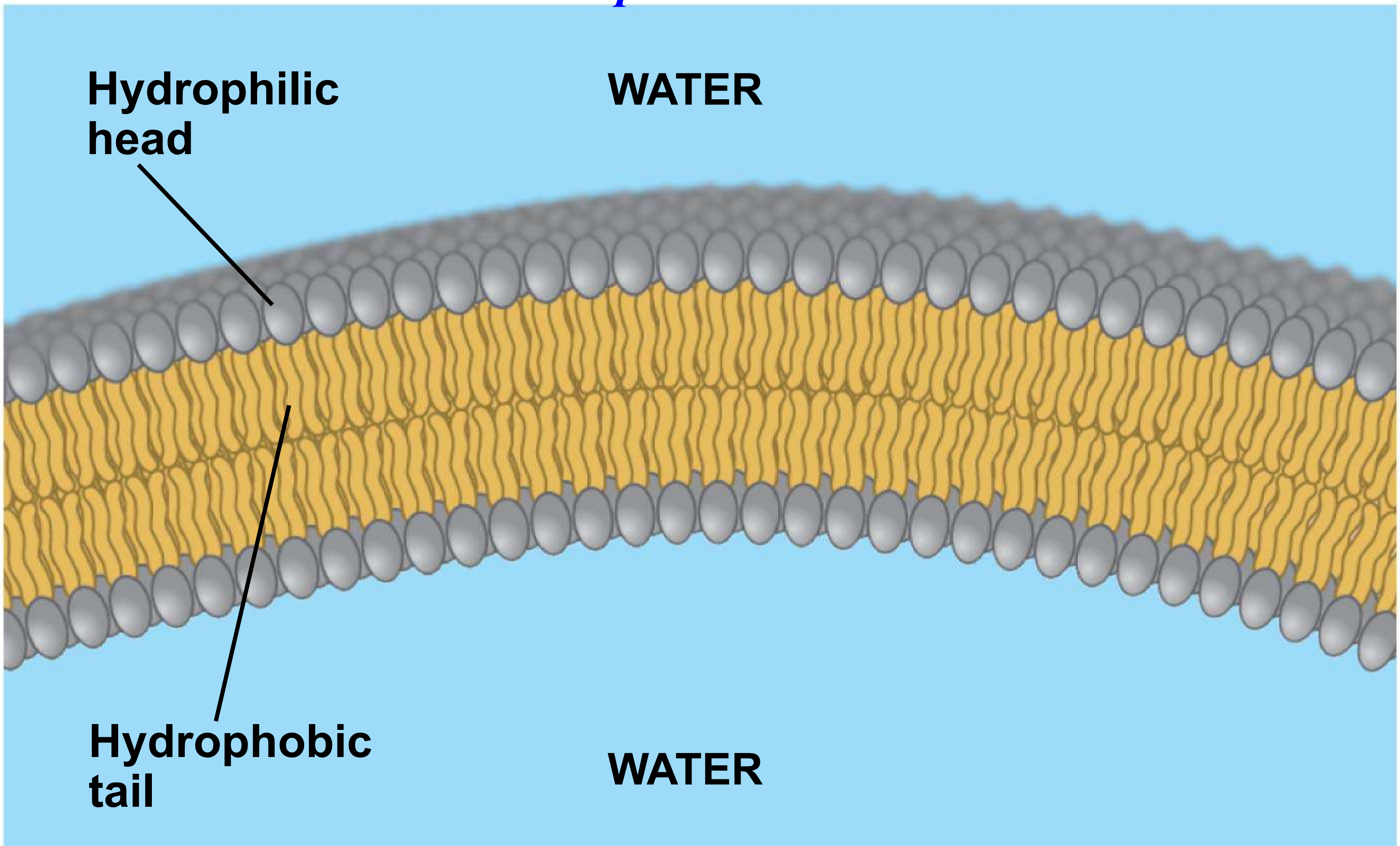
The structure of a ***phospholipid*** **amphipathic**



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

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

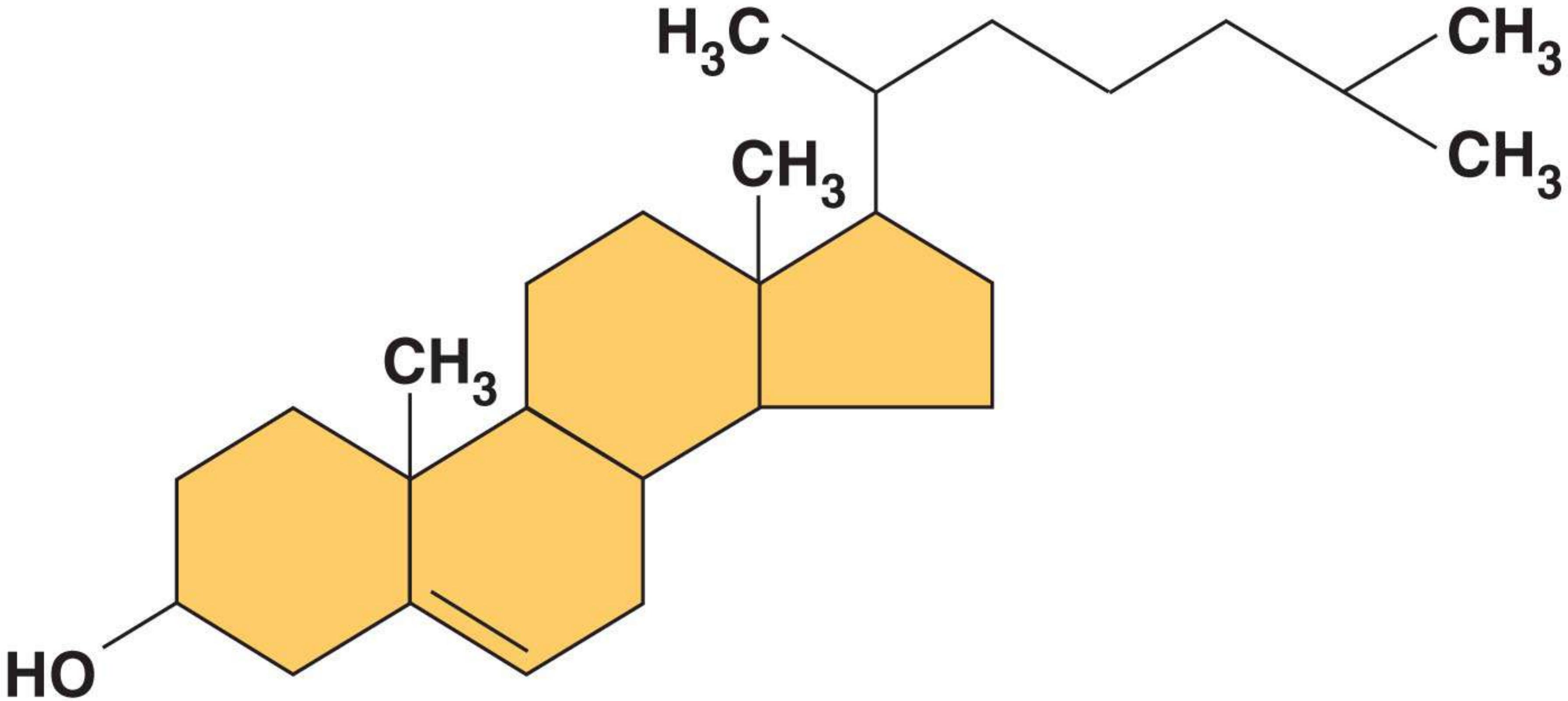
Bilayer structure formed by self-assembly of phospholipids into a membrane in an aqueous environment



Steroids = Lipids with 4 fused rings …

- ***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.

Cholesterol = a steroid, lipid



Proteins have many 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, defense against foreign substances, and organic catalysts (enzymes).
- Proteins are *polymers* called *polypeptides*.
- *Amino acids* are the *monomers* used to build *proteins*.

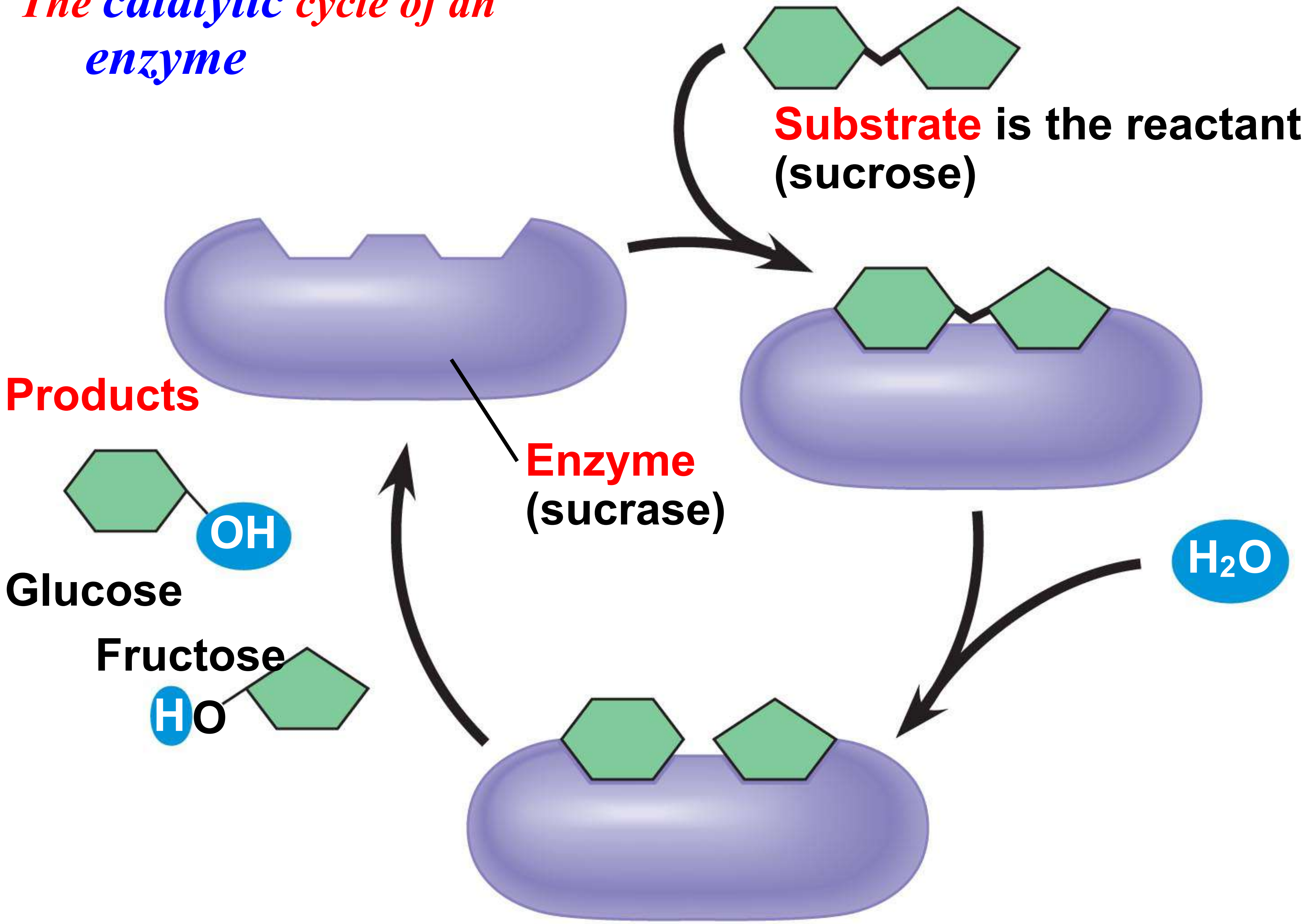
Proteins

Table 5.1 An Overview of Protein Functions

Type of Protein	Function	Examples
Enzymatic proteins	Selective acceleration of chemical reactions	Digestive enzymes
Structural proteins	Support	Silk fibers; collagen and elastin in animal connective tissues; keratin in hair, horns, feathers, and other skin appendages
Storage proteins	Storage of amino acids	Ovalbumin in egg white; casein, the protein of milk; storage proteins in plant seeds
Transport proteins	Transport of other substances	Hemoglobin, transport proteins
Hormonal proteins	Coordination of an organism's activities	Insulin, a hormone secreted by the pancreas
Receptor proteins	Response of cell to chemical stimuli	Receptors in nerve cell membranes
Contractile and motor proteins	Movement	Actin and myosin in muscles, proteins in cilia and flagella
Defensive proteins	Protection against disease	Antibodies combat bacteria and viruses.

- ***Enzymes*** are LARGE proteins that act as *catalysts* to *speed up* the rate of chemical reactions in cells.
- Enzymes are *specific*. They must have a *shape-match* with molecules in the chemical reaction.
- Enzymes can perform their functions repeatedly, working constantly to carry out the processes of life.

The catalytic cycle of an enzyme



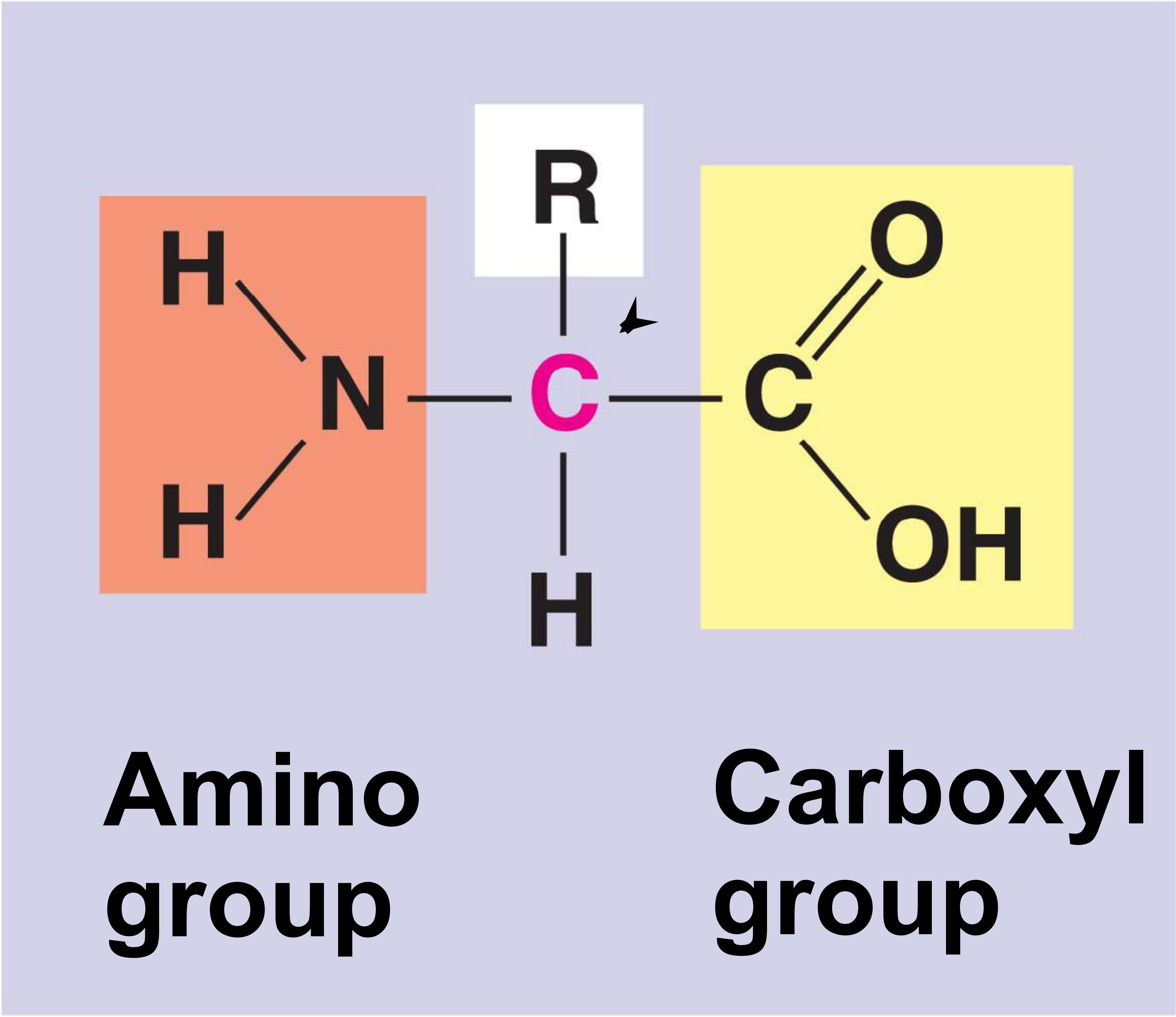
Proteins = Polypeptides

- ***Polypeptides*** are polymers built from a set of 20 amino acids (monomers).
- The ***sequence*** *of amino acids* determines a protein's 3D three-dimensional structure.
- A protein's structure determines its function.
- A wide ***variety*** of proteins can be made from a few monomers by varying the amino acid sequence.

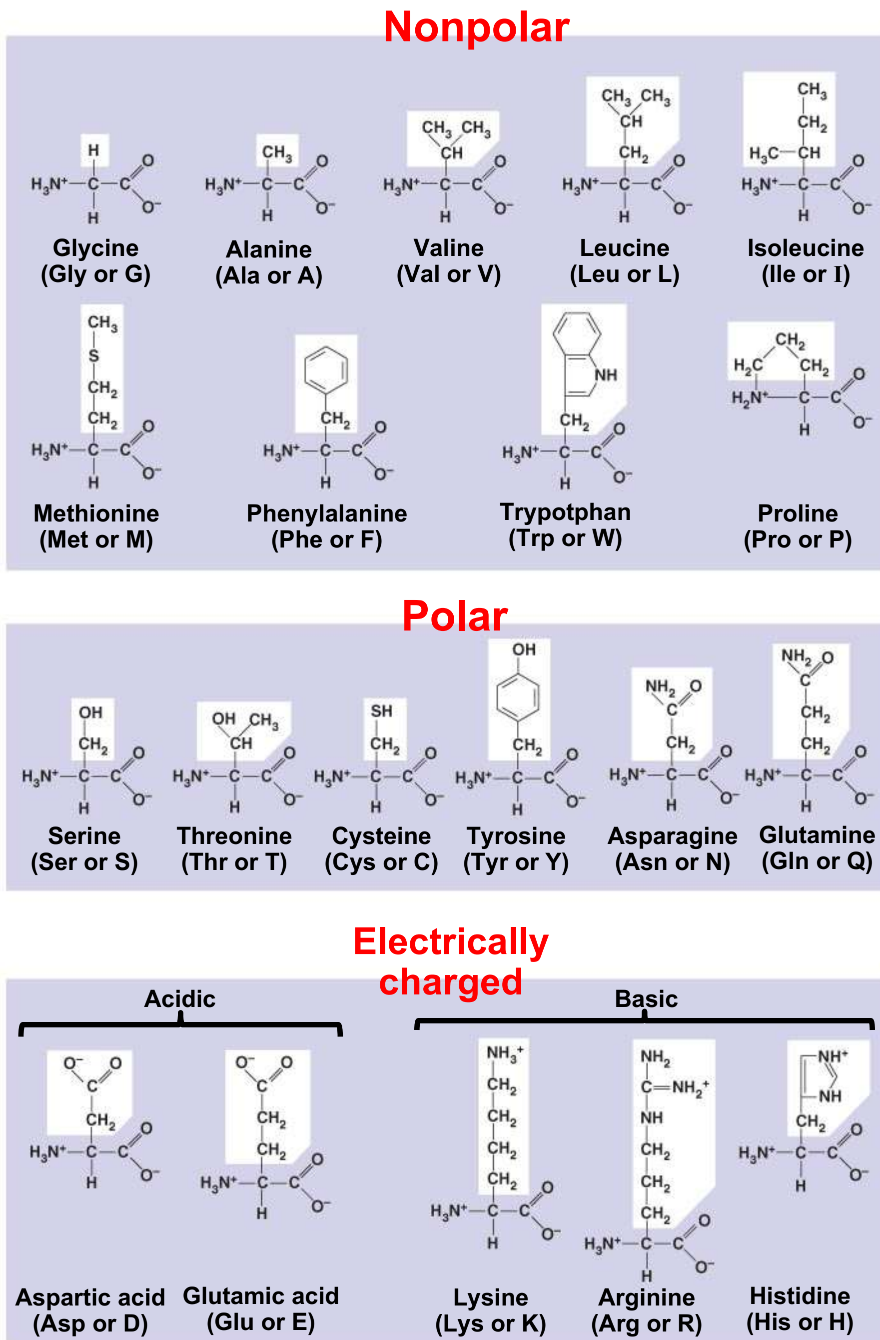
Proteins - Amino Acid Monomers

- ***Amino acids*** are organic molecules with carboxyl and amino groups attached to a central carbon.
- Amino acids differ in their properties due to *variable side chains*, called R groups. The R group is also attached to the central carbon.
- There are 20 different amino acids because there are 20 different side chains.

Amino Acid



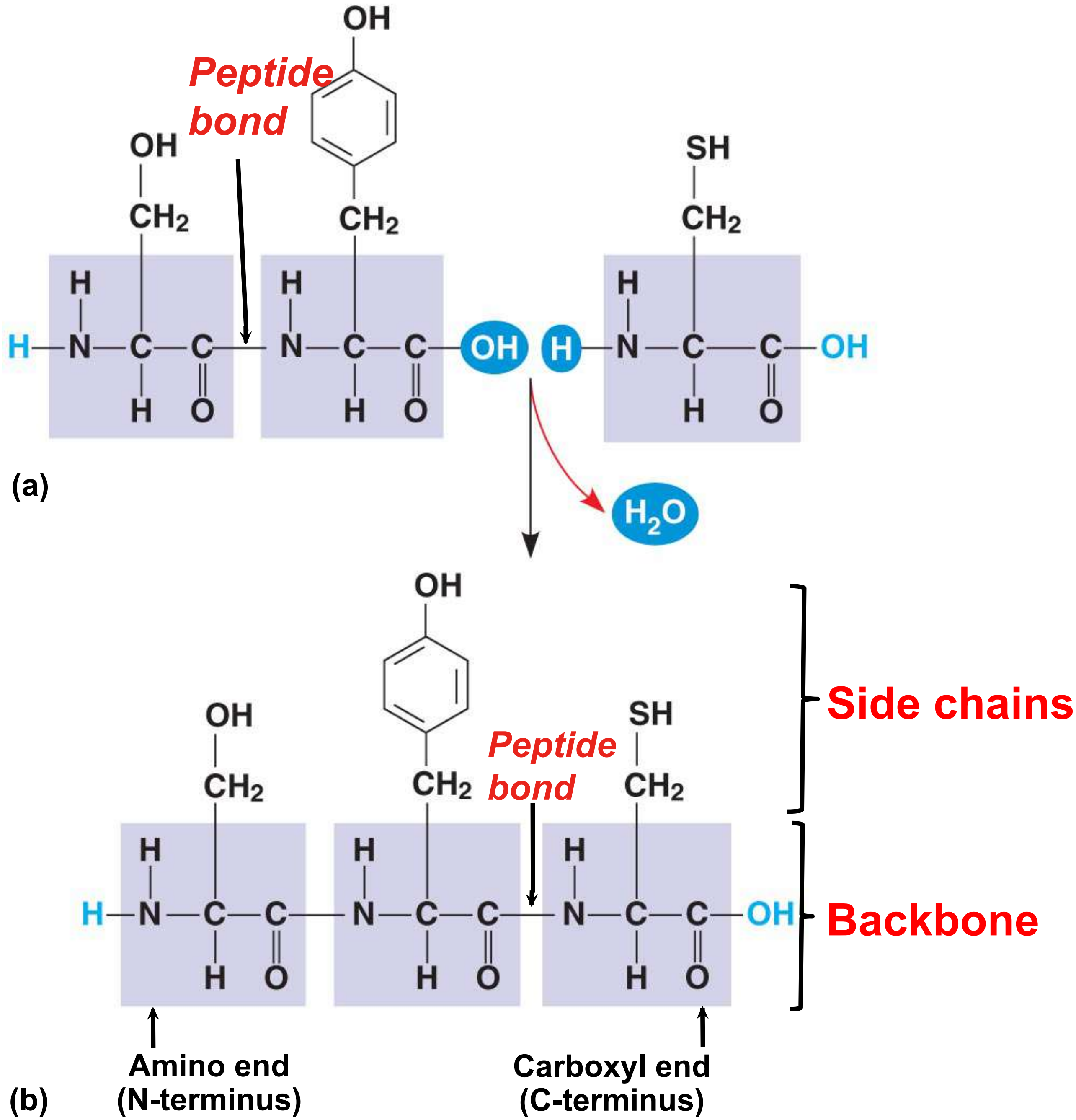
The 20 amino acids of proteins



Amino Acid Polymers

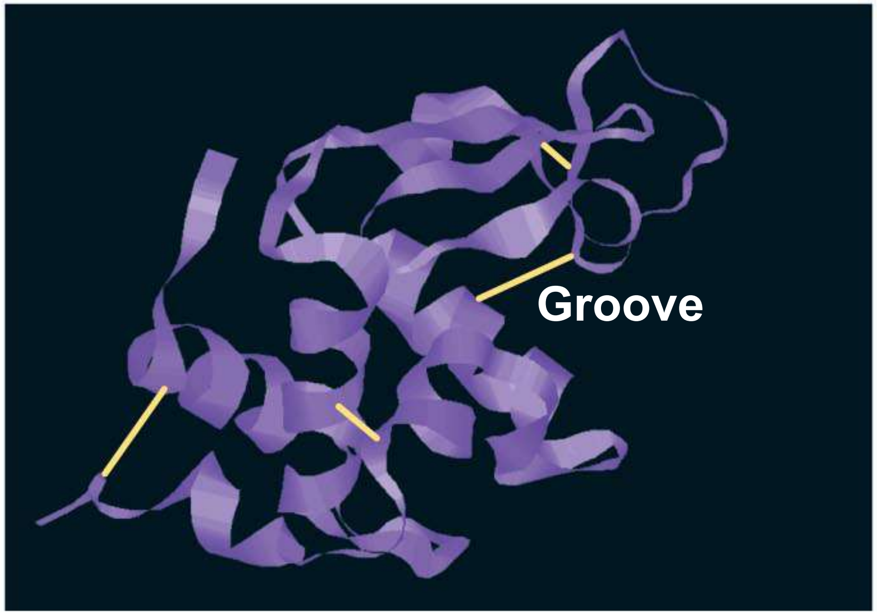
- *Amino acids are linked* by covalent bonds called ***peptide bonds***   ***C - N***
- A polypeptide is a polymer of amino acids.
- Polypeptides range in length from a few to more than a thousand monomers.
- Each polypeptide has a unique linear sequence of amino acids.

Making a polypeptide chain

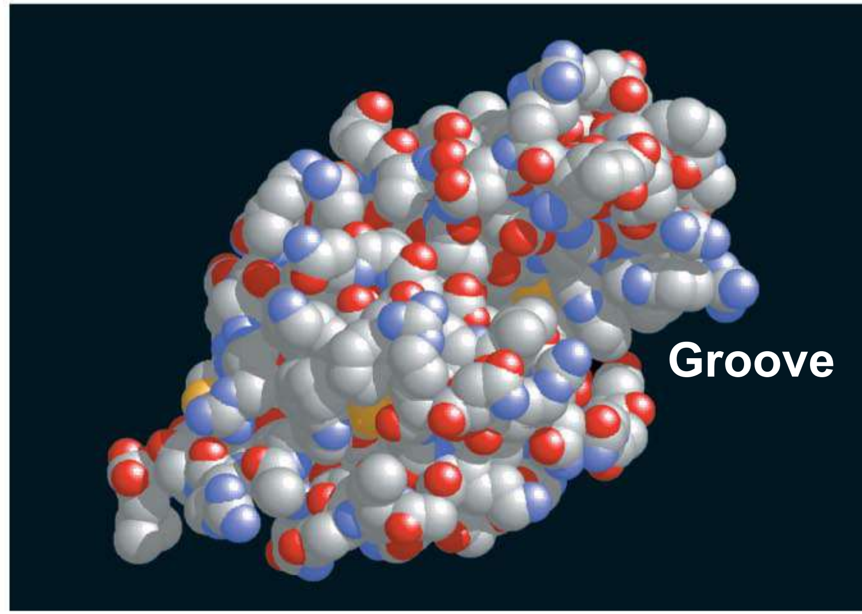


- The *sequence of amino acids* determines a protein's three-dimensional structure.
- *A protein's structure determines its function*.
- A ***functional protein*** consists of one or more polypeptides twisted, folded, and coiled into a *unique shape*.

A protein folds into a specific Shape / Structure so it can perform its Function

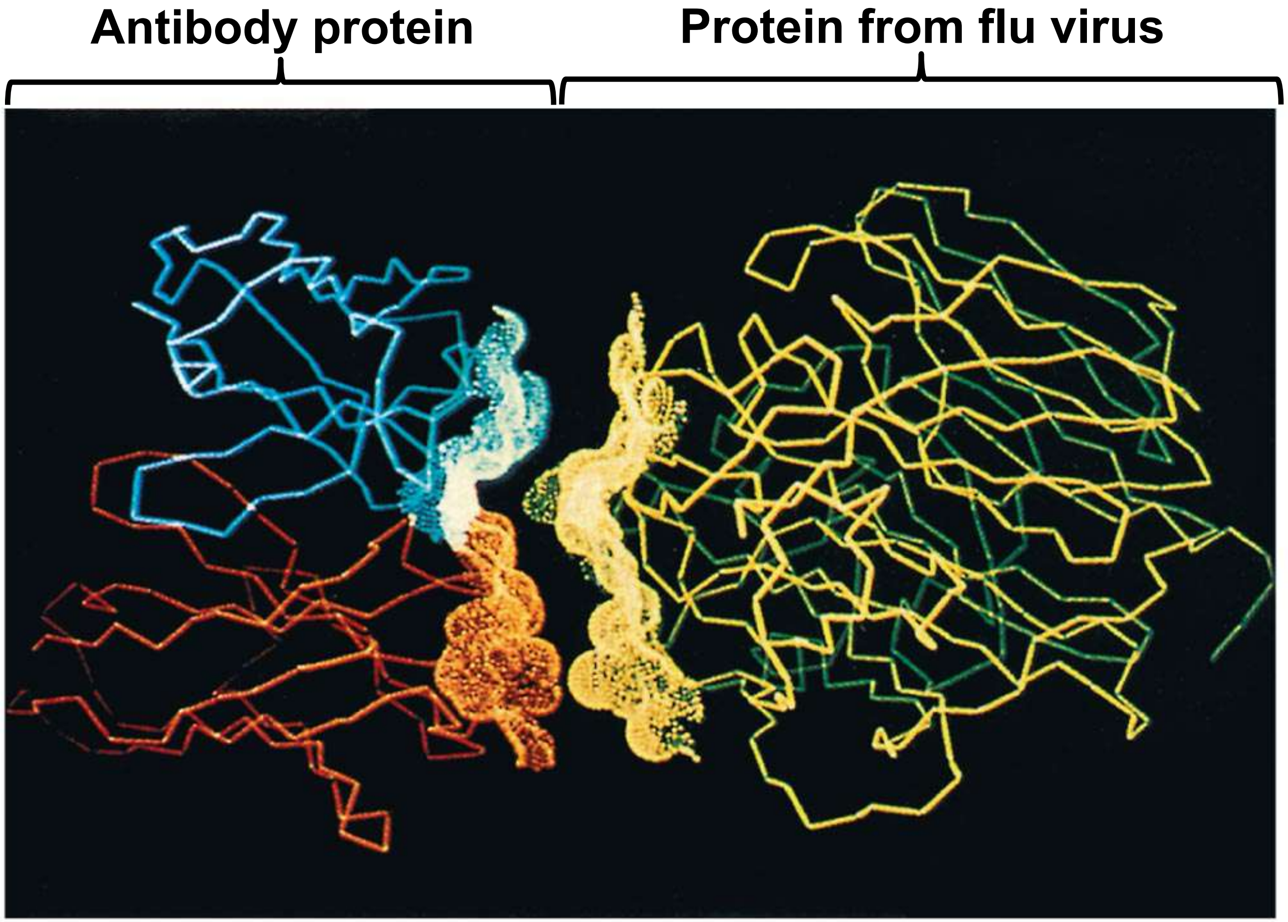


(a) A ribbon model of lysozyme



(b) A space-filling model of lysozyme

An antibody binding to a protein from a flu virus

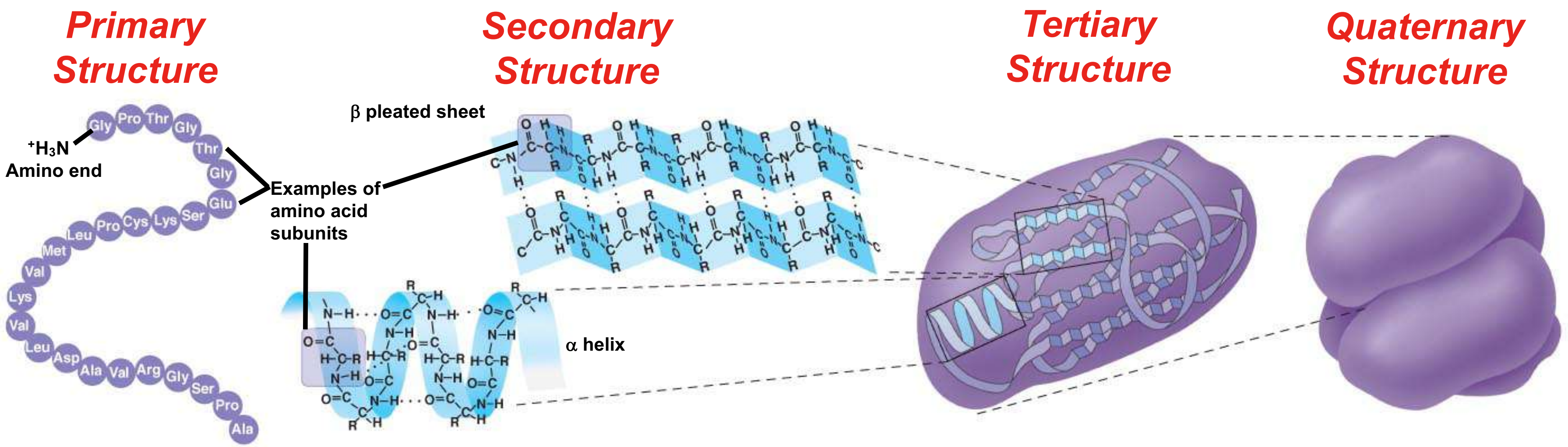


Four Levels of Protein Structure -- becoming Functional Proteins:

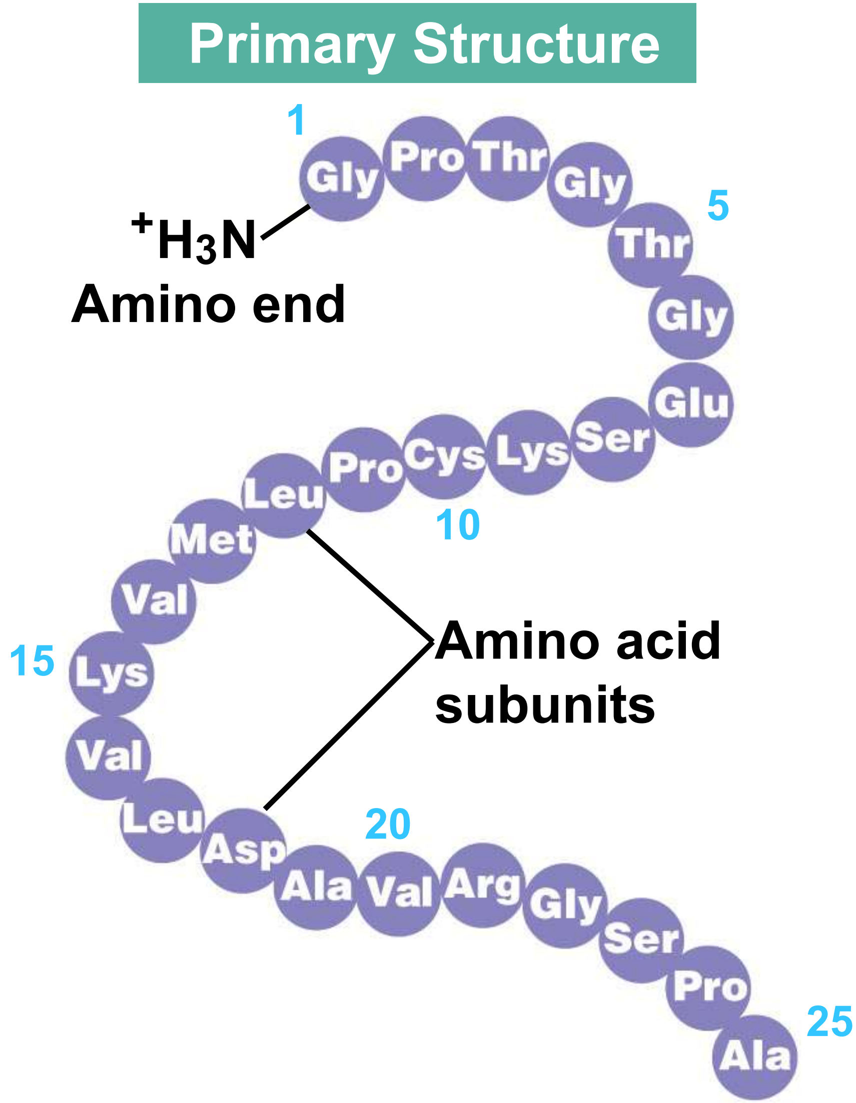
- The ***primary*** structure of a protein is its *unique* sequence of amino acids in a *polypeptide chain.*
- ***Secondary*** structure consists of *regular* coils and folds in the polypeptide backbone made by *hydrogen bonds.*
- ***Tertiary*** structure is determined by interactions among various side chains *R groups.*
- ***Quaternary*** structure results when a protein consists of *multiple* polypeptide *chains.*

- ***Primary structure*** is the sequence of amino acids in a *polypeptide chain* (protein). This is like the order of letters in a long word.
- Primary structure is determined by inherited genetic information (DNA).

4 Levels of protein structure

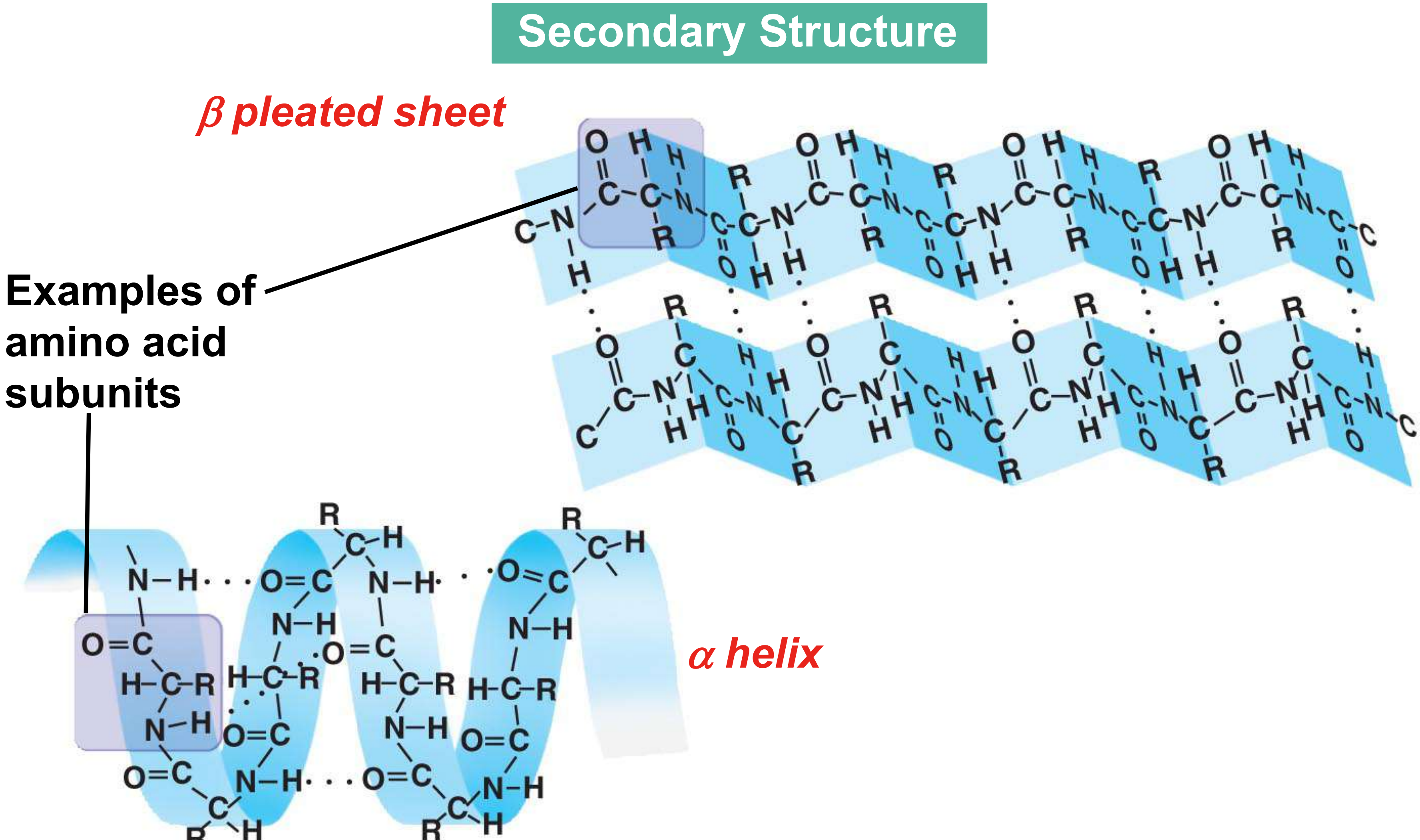


Primary Structure = the Sequence of Amino Acids determined by DNA



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

Levels of protein structure—secondary structure



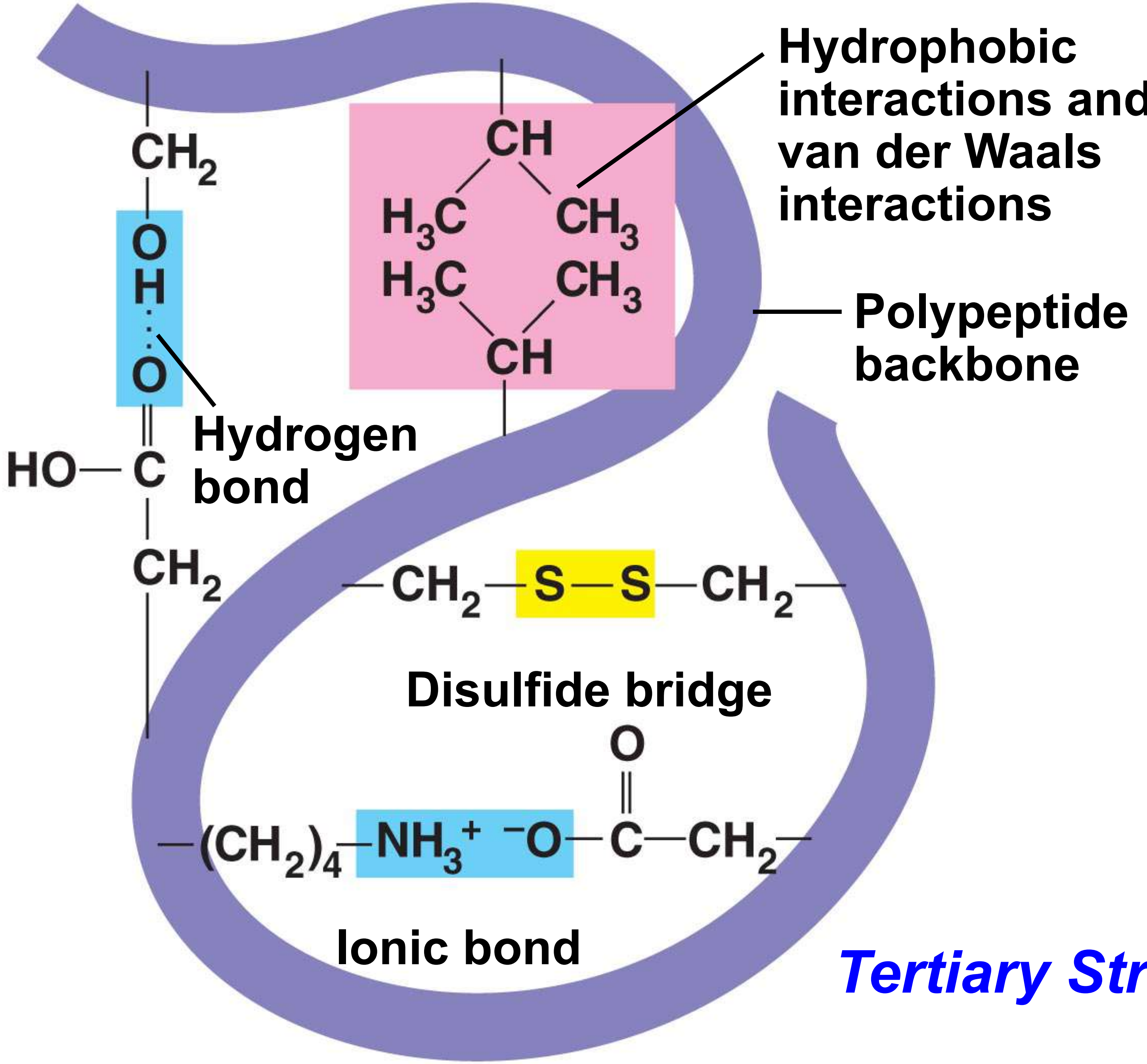
Levels of protein structure—secondary structure

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 *R group interactions* fold the polypeptide into a *globular* shape.
- 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.

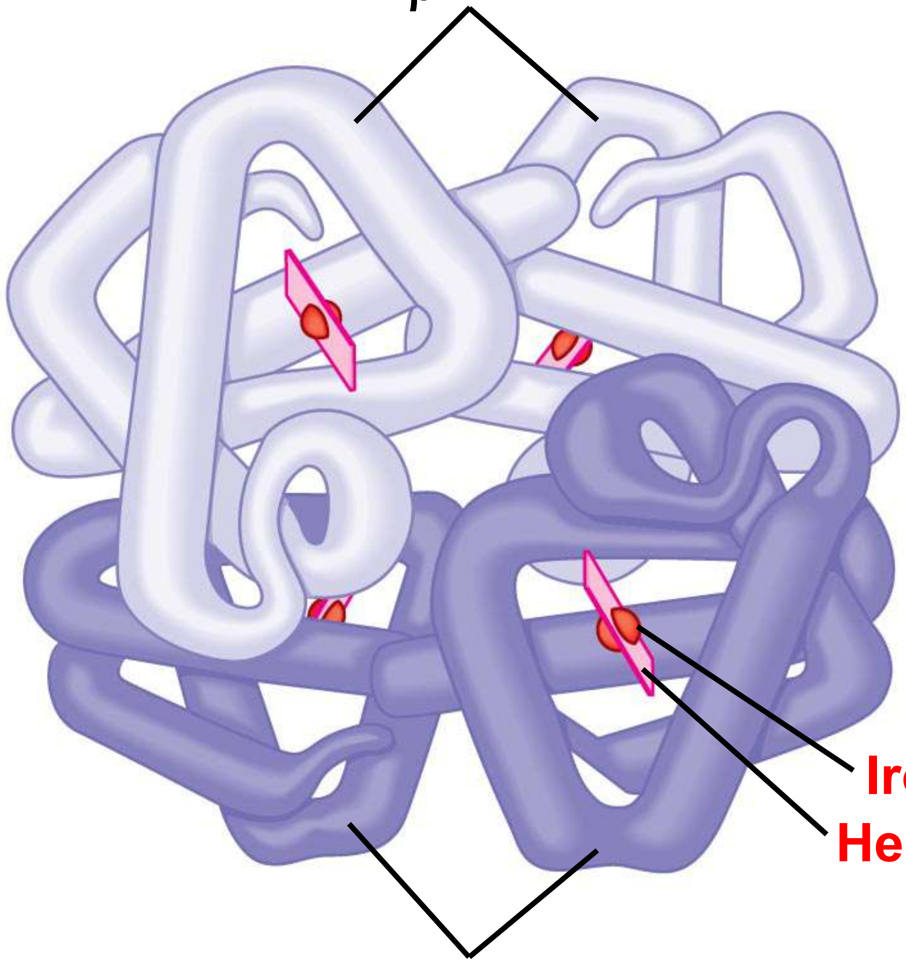


Tertiary Structure

- ***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 each with an iron heme group.

Quaternary structures

Collagen

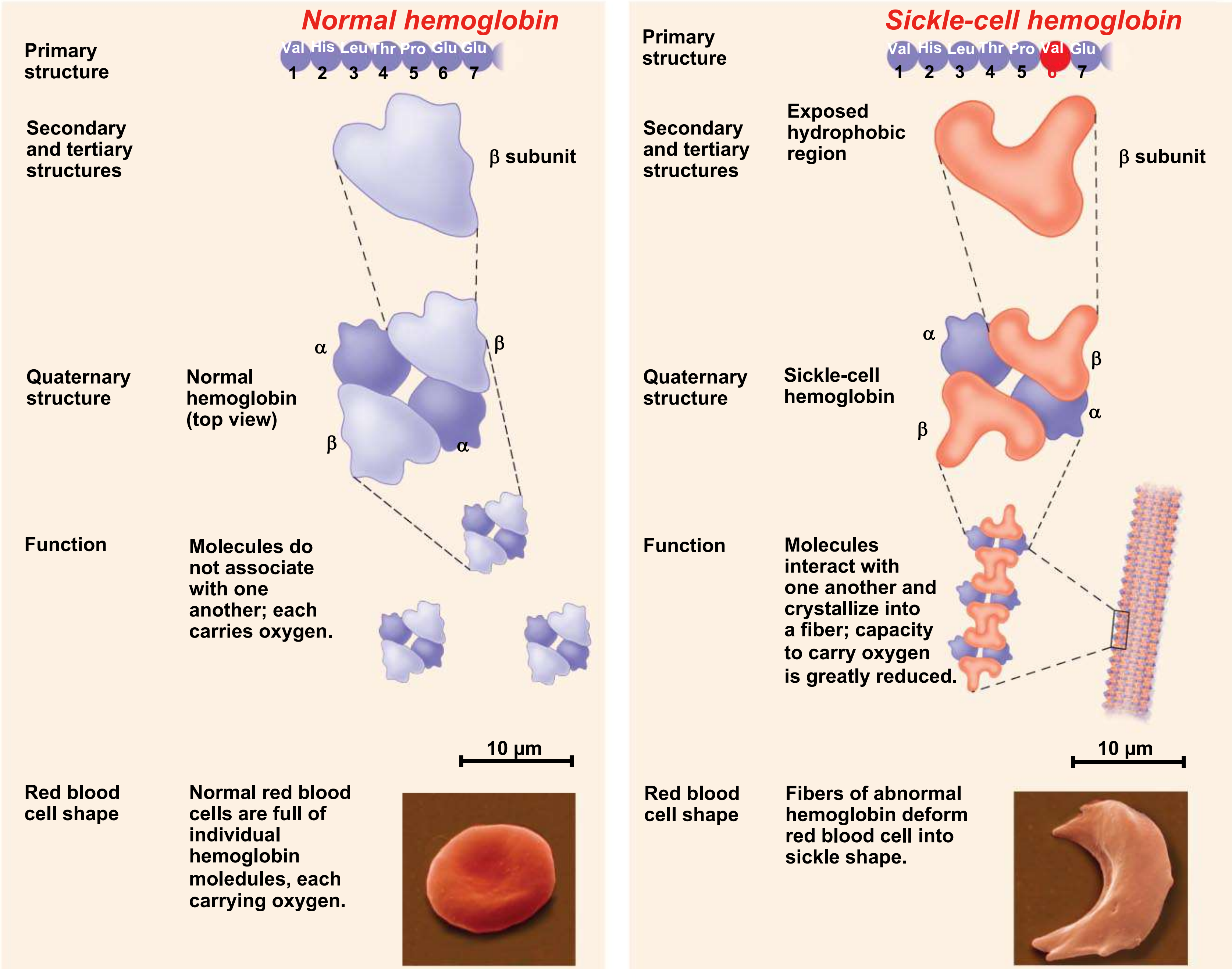


Hemoglobin

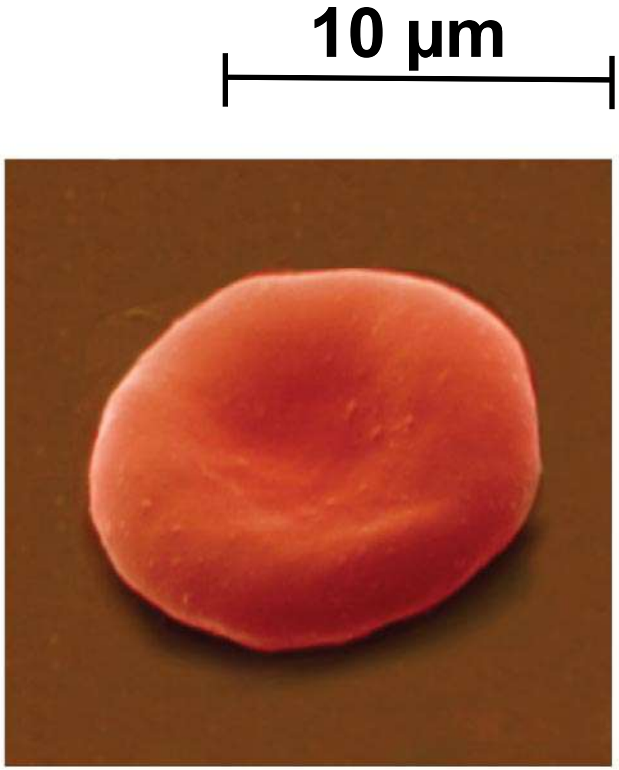
Sickle-Cell Disease: A Change in DNA and Primary Structure

- A slight change in a proteins DNA can change its primary structure (amino acid sequence). This 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.

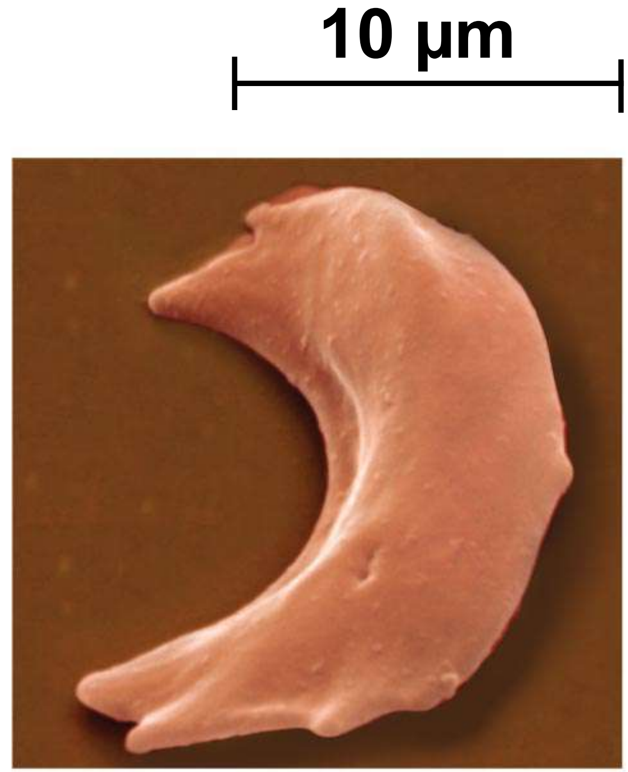
A single amino acid substitution in a protein causes sickle-cell disease



A single amino acid substitution in a protein causes sickle-cell disease



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

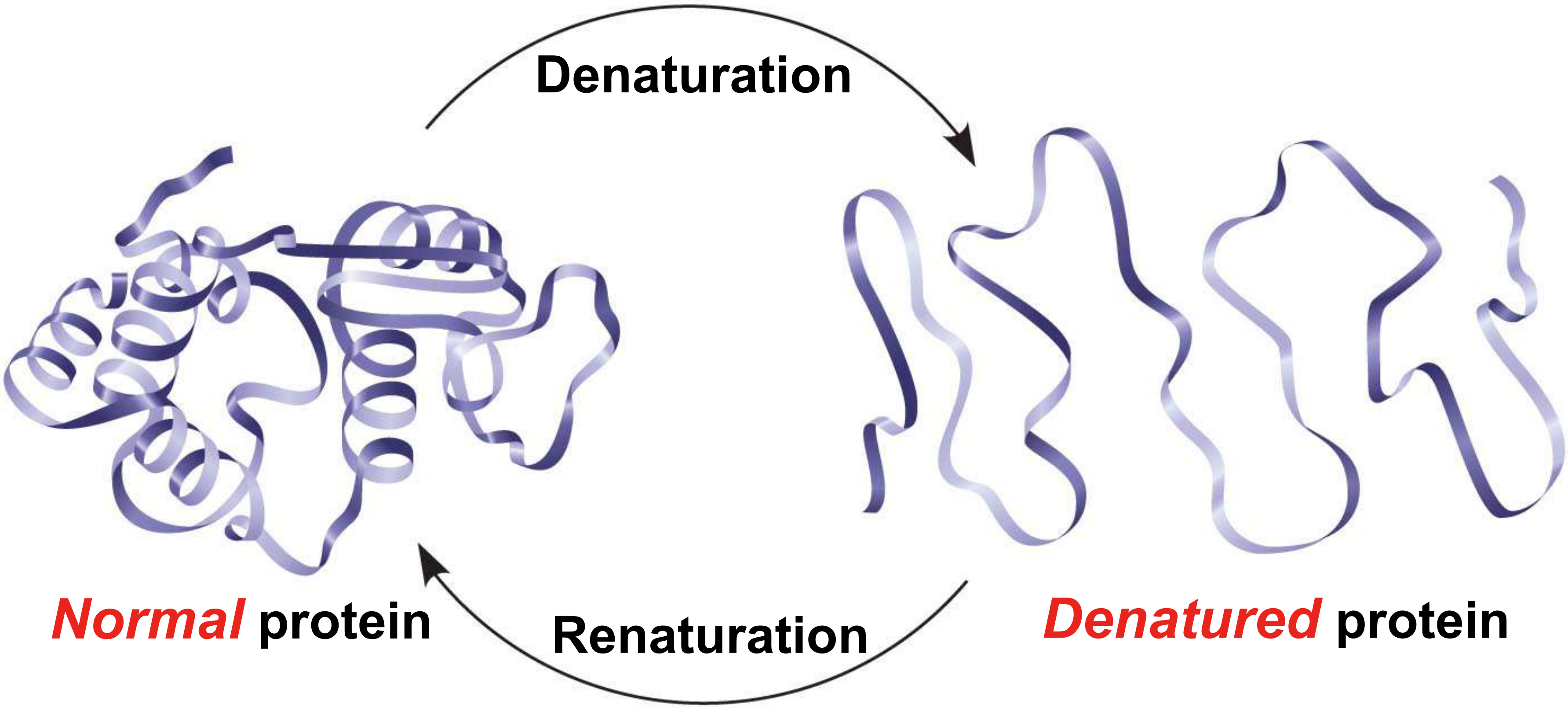


Fibers of abnormal hemoglobin deform red blood cell into sickle shape.

Environmental Factors Affect Protein Structure

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

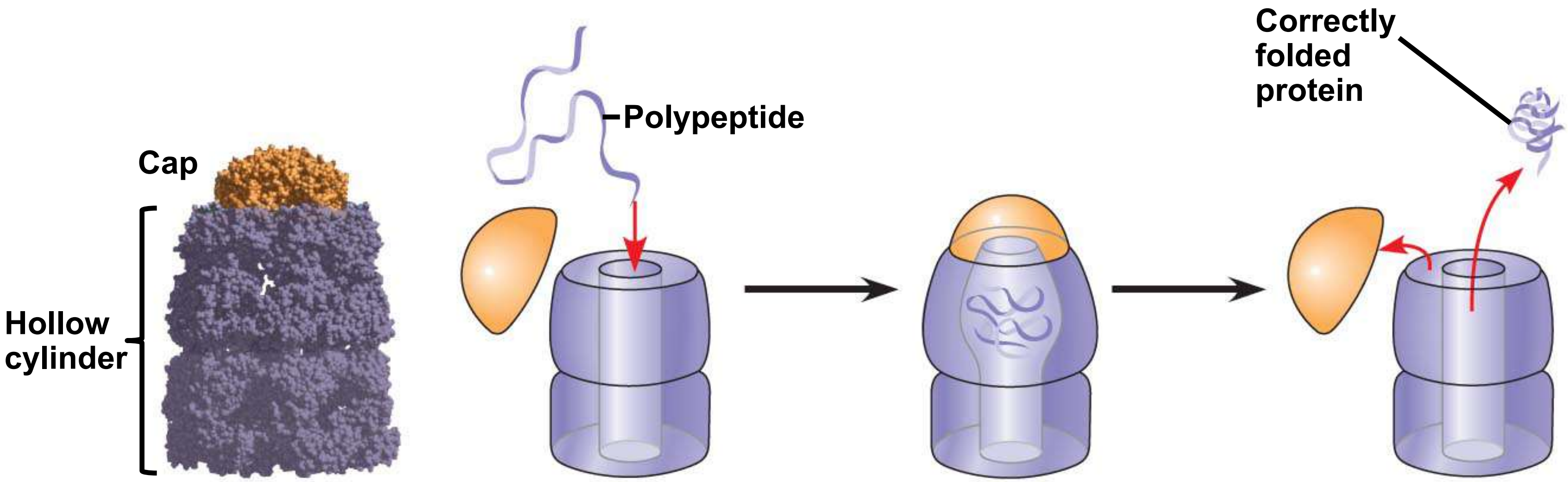
Denaturation and renaturation of a protein



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.

Protein Folding in a cell: a chaperonin in action



Chaperonin (fully assembled)

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.

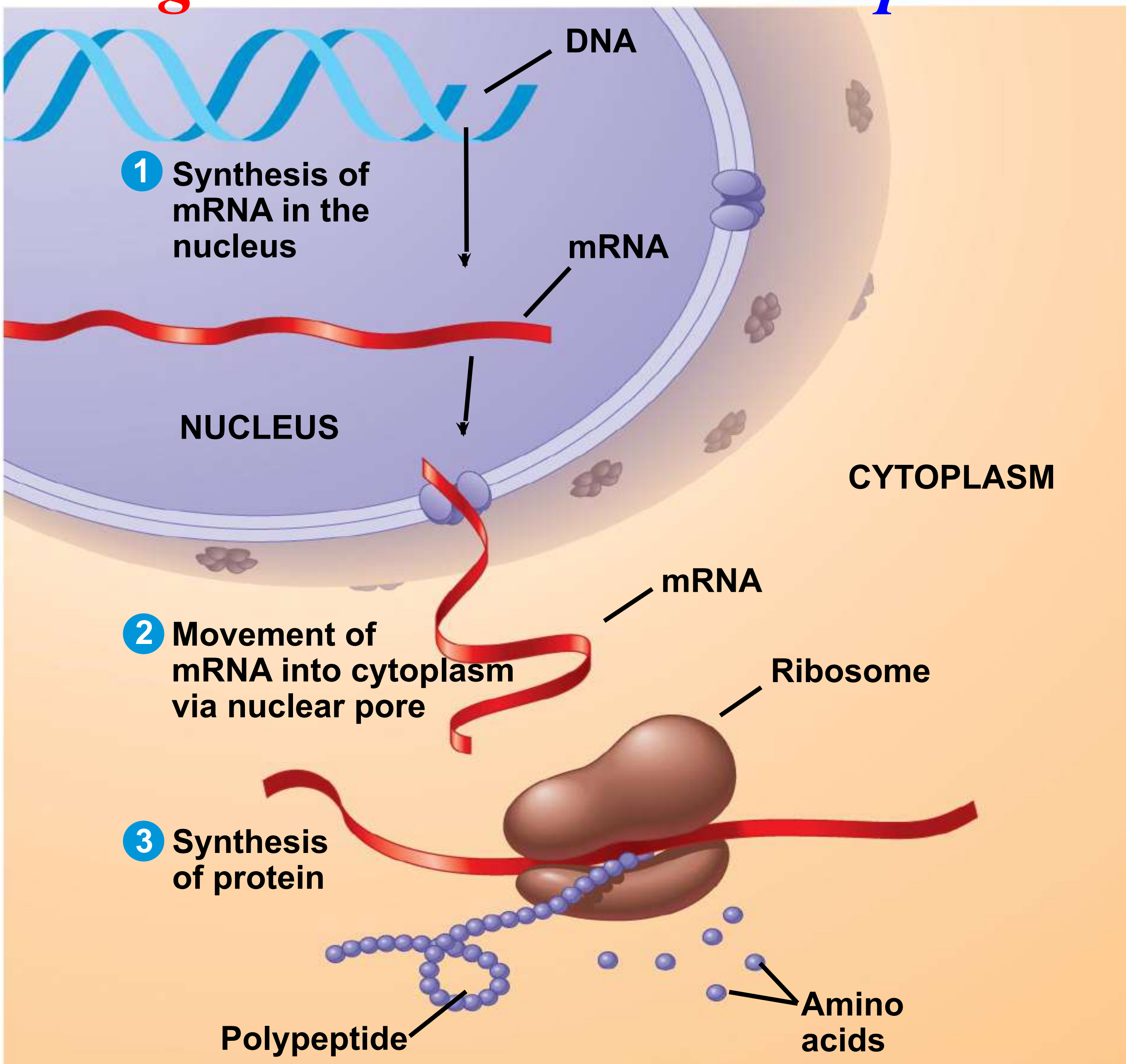
Nucleic acids store and transmit hereditary information

- The amino acid sequence of a polypeptide is programmed by a unit of inheritance called a ***gene.***
- *Genes are unique sequences of DNA nucleotides*.
- ***DNA*** = **deoxyribonucleic acid**

The Roles of Nucleic Acids = Instructions

- There are two types of nucleic acids:
  - ***Deoxyribonucleic acid* (*DNA*)**
  - ***Ribonucleic acid* (*RNA*)**
- DNA provides directions for its own replication and the synthesis of messenger RNA (mRNA)
- Through mRNA, DNA controls protein synthesis.
- Protein synthesis occurs in ribosomes.

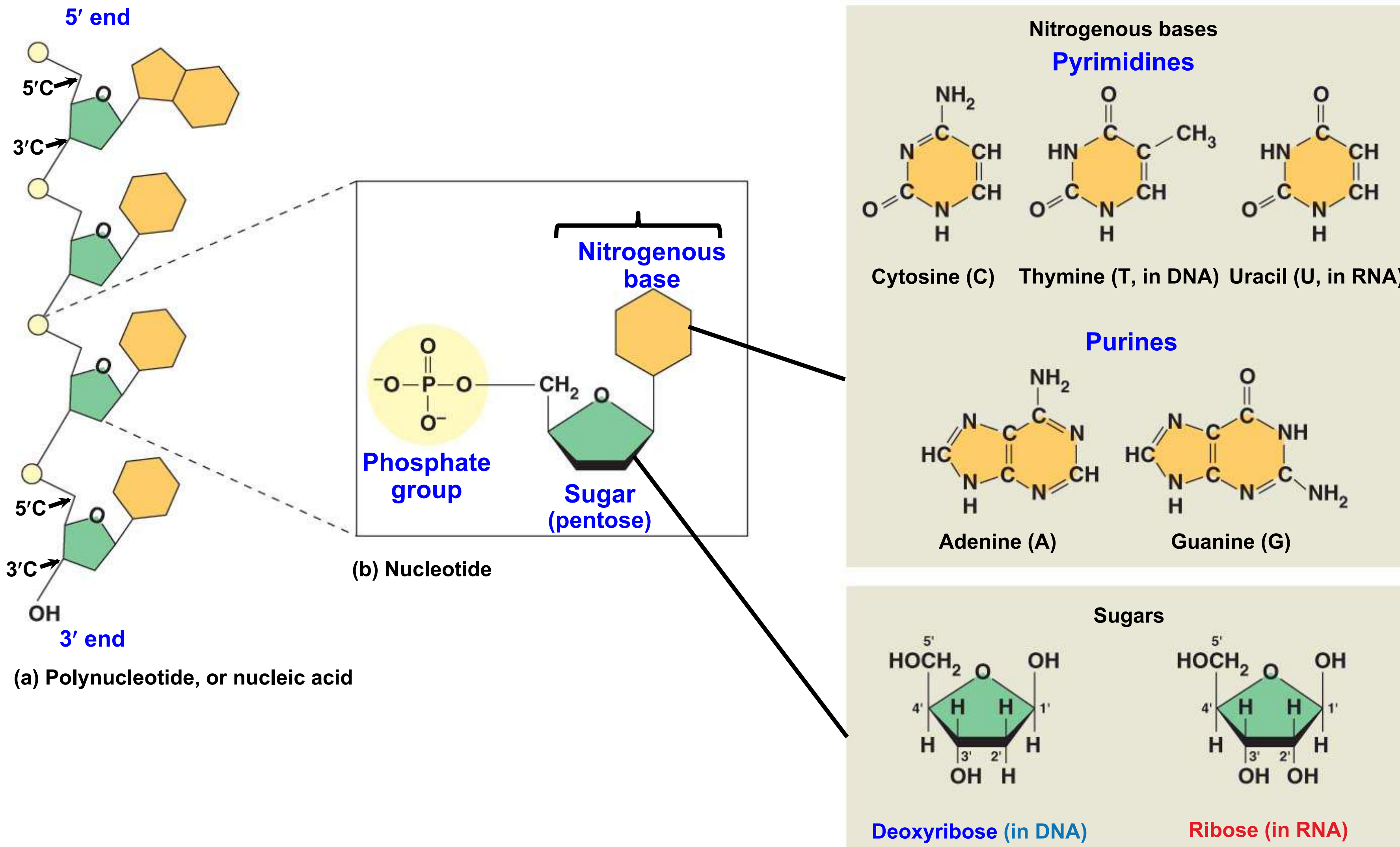
Central Dogma: DNA → RNA → protein



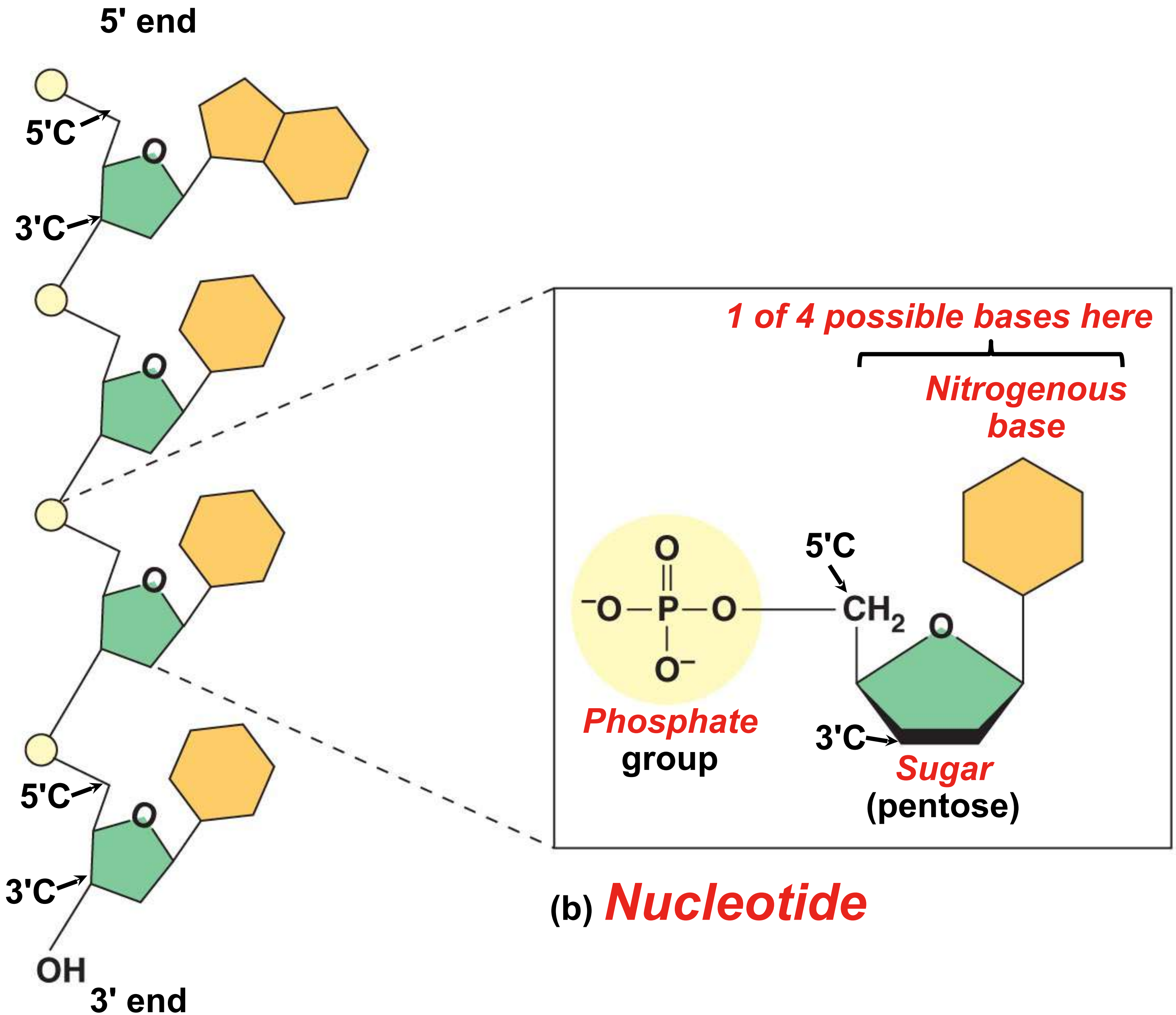
The Structure of Nucleic Acids

- ***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 a phosphate group.*
- The portion of a nucleotide without the phosphate group is called a *nucleoside.*

Components of nucleic acids

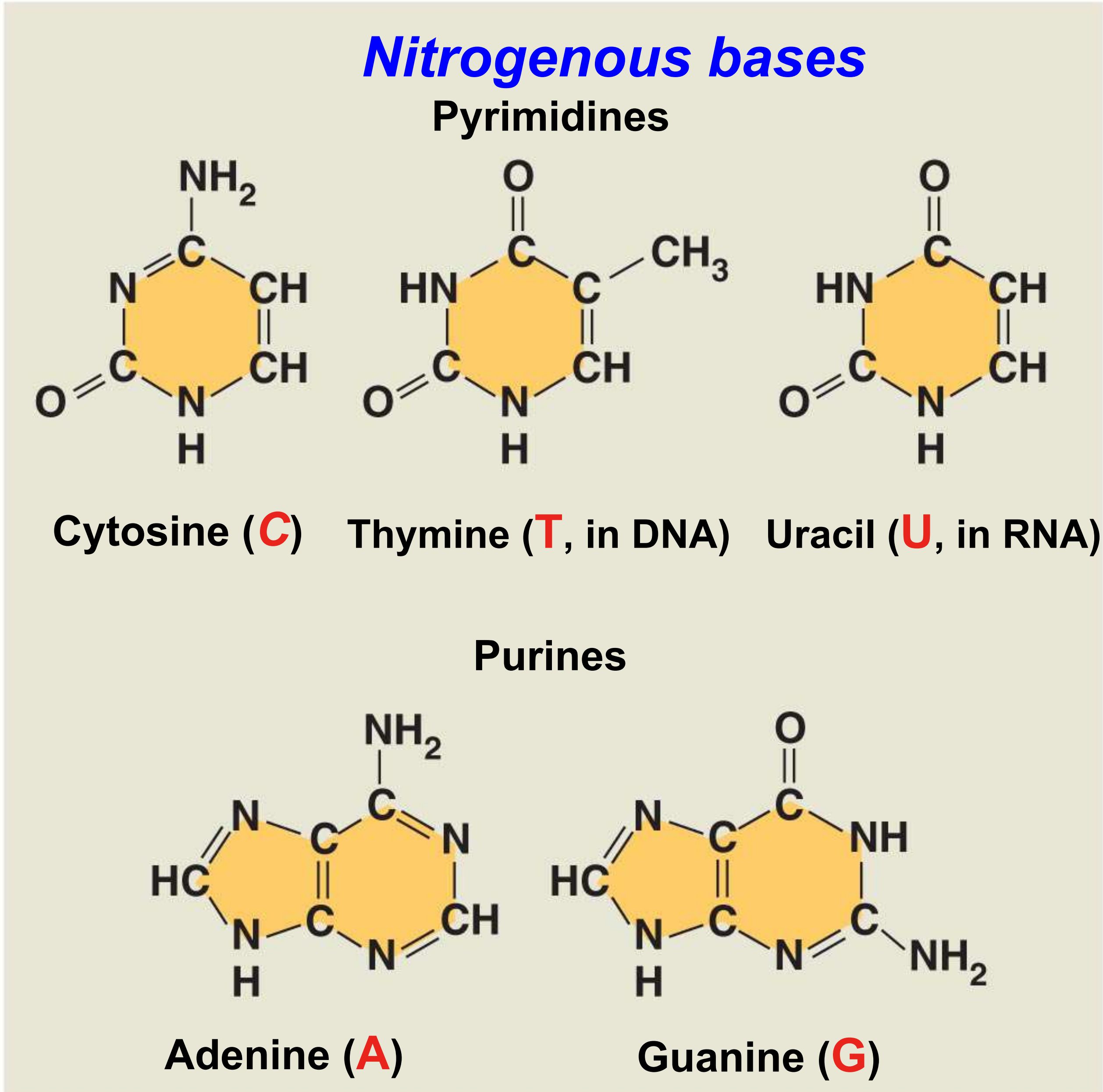


(c) Nucleoside components: sugars

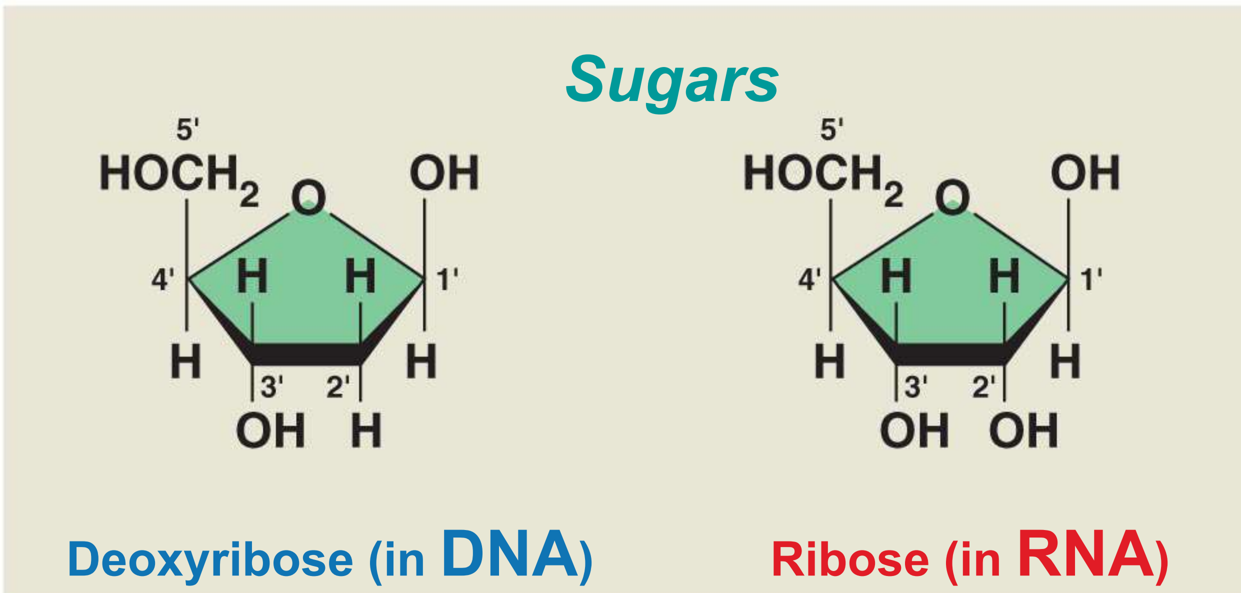


(b) ***Nucleotide***

Polymer chain = nucleic acid



Nucleoside components: nitrogenous bases



Nucleoside components: sugars

Nucleotide Monomers

- There are two families of nitrogenous bases:
  - **Pyrimidines: C T (U)** (cytosine, thymine, and uracil) have a single six-membered ring
  - **Purines**: **A G** (adenine and guanine) have a 6-membered ring fused to a 5-membered ring
- In DNA, the sugar is **deoxyribose**
- In RNA, the sugar is **ribose**.
- Nucleotide = nucleoside + phosphate group. Nucleoside = nitrogenous base + sugar

Nucleotide Polymers

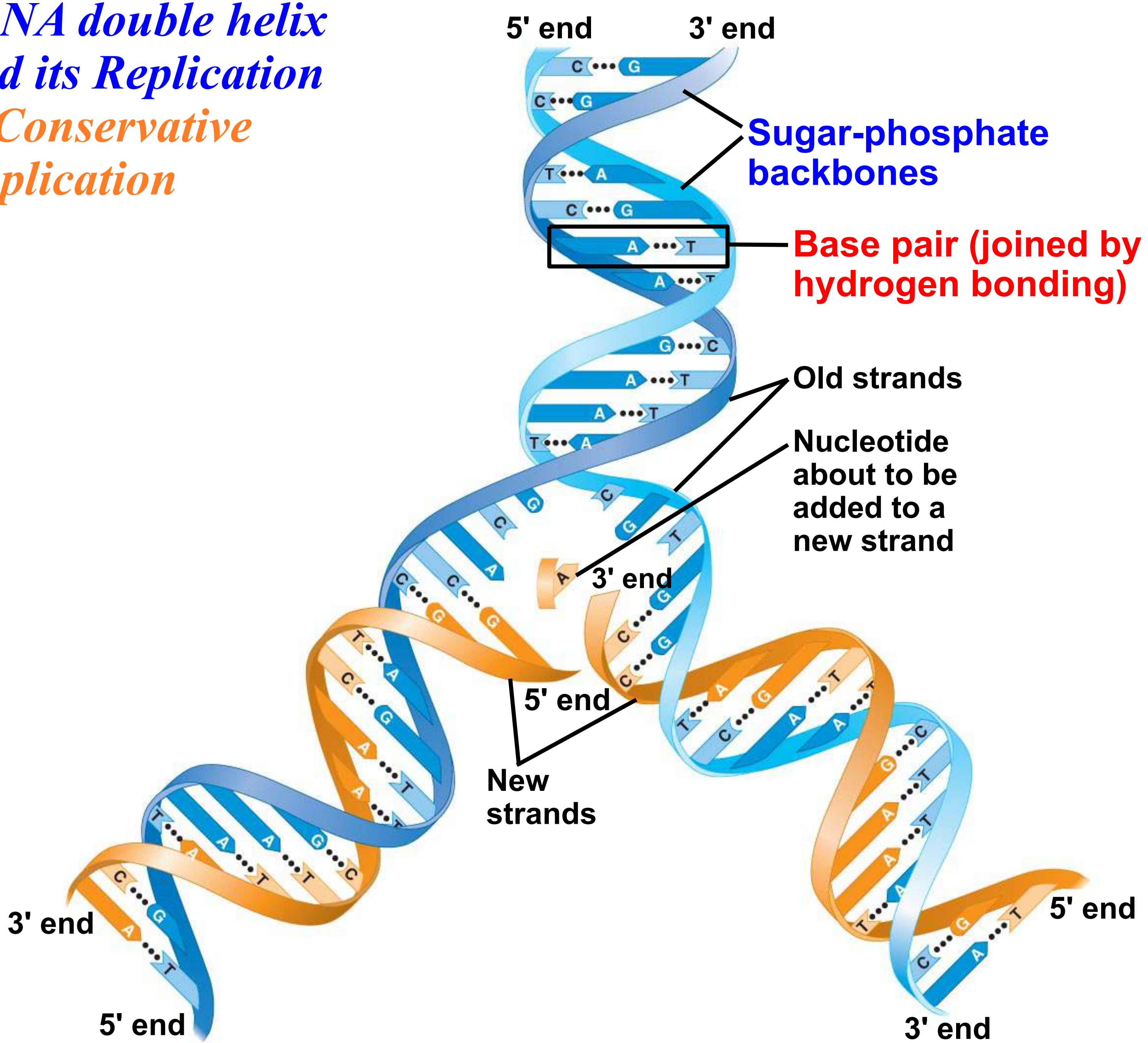
- Nucleotide polymers are linked together by dehydration synthesis to build a polynucleotide.
- Adjacent nucleotides are joined by covalent bonds that form between the –OH group on the 3′ carbon of one nucleotide and the phosphate on the 5′ carbon on the next.
- These links called phosphodiester bonds create a backbone of sugar-phosphate units.
- 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′ → 3′ directions from each other, an arrangement referred to as ***antiparallel.***
- One DNA molecule includes many genes
- The nitrogenous bases in DNA pair-up forming hydrogen bonds: ***A - T*** and ***C - G***

The DNA double helix and its Replication

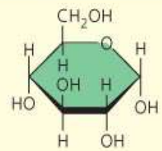
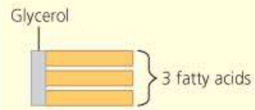
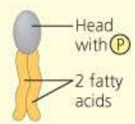
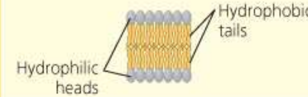
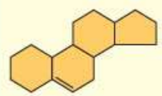
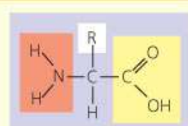
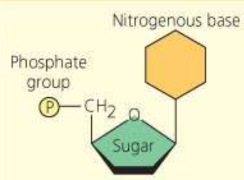
Semi-Conservative Replication



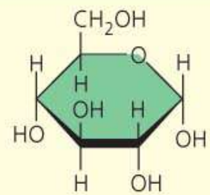
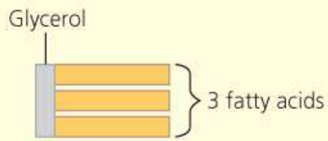
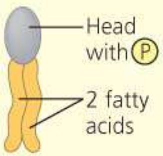
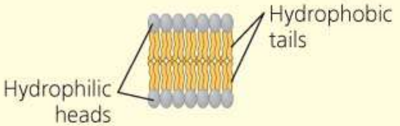
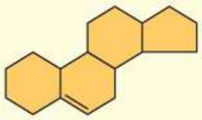
DNA and Proteins as Tape Measures of Evolution

- The unique linear sequences of nucleotides in DNA molecules are inherited, passed from parents to offspring.
- Two closely related species are more similar in their DNA sequences (genes) and proteins than are more distantly related species.
- Molecular biology compares DNA sequences and can be used to assess evolutionary kinship.

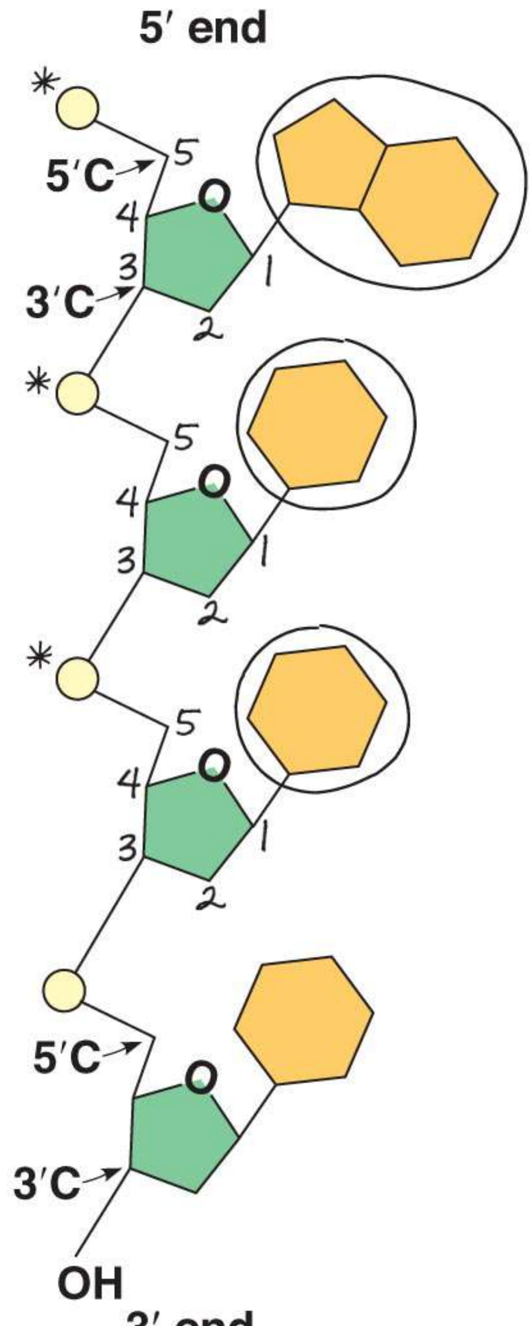
Review:

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)
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

Review :

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)

Nucleic Acid :
Chain of Nucleotides



You should be able to draw and explain a review chart of organic molecules:

	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

You should now be able to:

1. List and describe the four major classes of organic molecules.
2. Explain: monomers, polymers, dehydration synthesis with the type of covalent bond for each.
3. Distinguish between monosaccharides, disaccharides, and polysaccharides. Give examples of each.
4. Explain lipids in general. Distinguish between saturated and unsaturated fats. Describe phospholipids, amphipathic molecules.
5. Describe steroids

You should now be able to:

6. Explain proteins, amino acids.
7. Explain the four levels of protein structure.
8. Explain DNA and RNA.
9. Distinguish between the following: pyrimidine and purine / nucleotide and nucleoside / ribose and deoxyribose / the 5′ end and 3′ end of a nucleotide
10. Apply the Base-Pair Rule: A-T(U) C-G
11. Explain: anti-parallel, double helix.