CAMPBELL BIOLOGY IN FOCUS

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3 Carbon and the Molecular Diversity of Life

Lecture Presentations by
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Simon Fraser University

SECOND EDITION

Overview: Carbon Compounds and Life

- Aside from water, living organisms consist mostly of carbon-based compounds C H O N
- Carbon is unparalleled in its ability to form large, complex, and diverse molecules – 4 valence e-
- A compound containing carbon is said to be an **organic compound**

$C_6H_{12}O_6$ – Have covalent Bonds

– Large

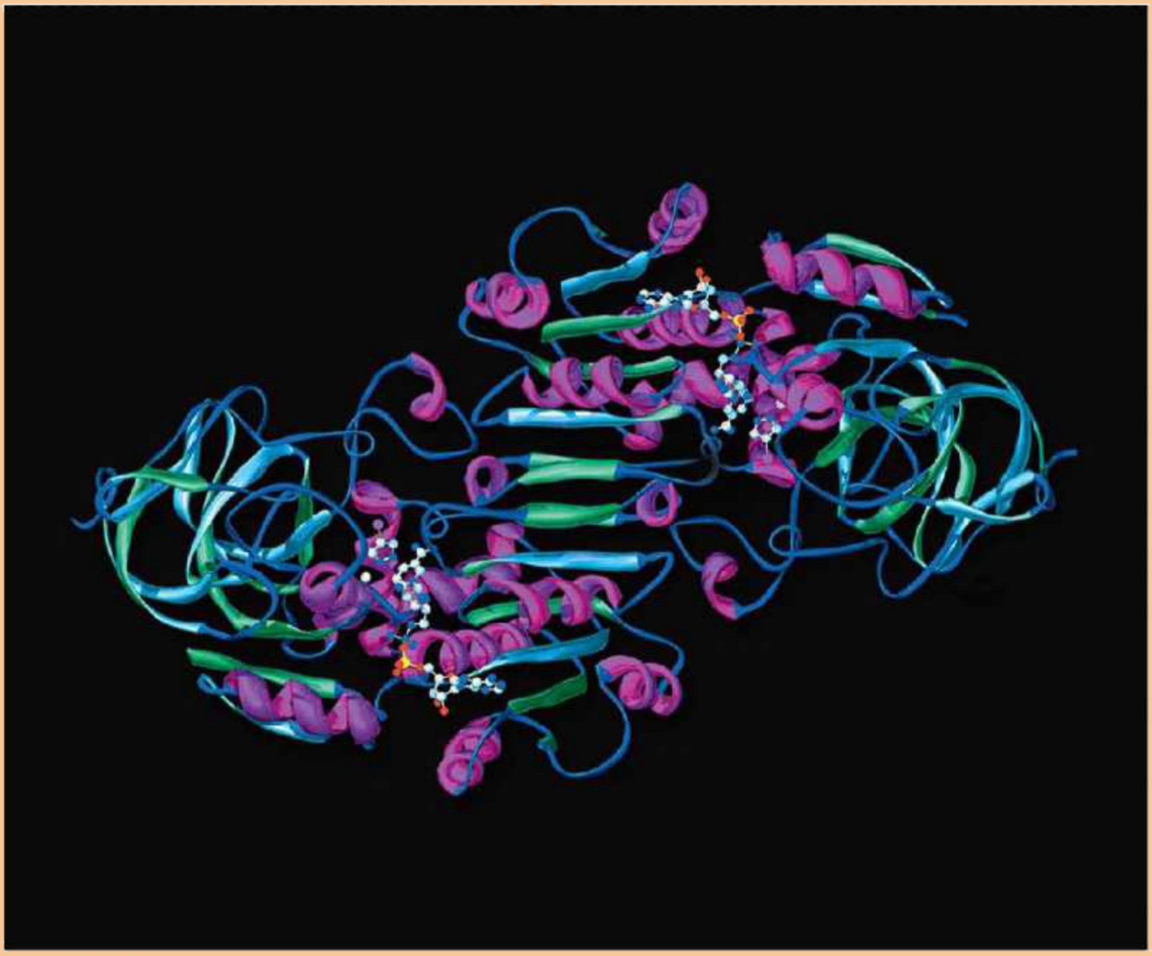
CO_2 – lots of H's

DNA → RNA → Protein → Traits

communication molecules

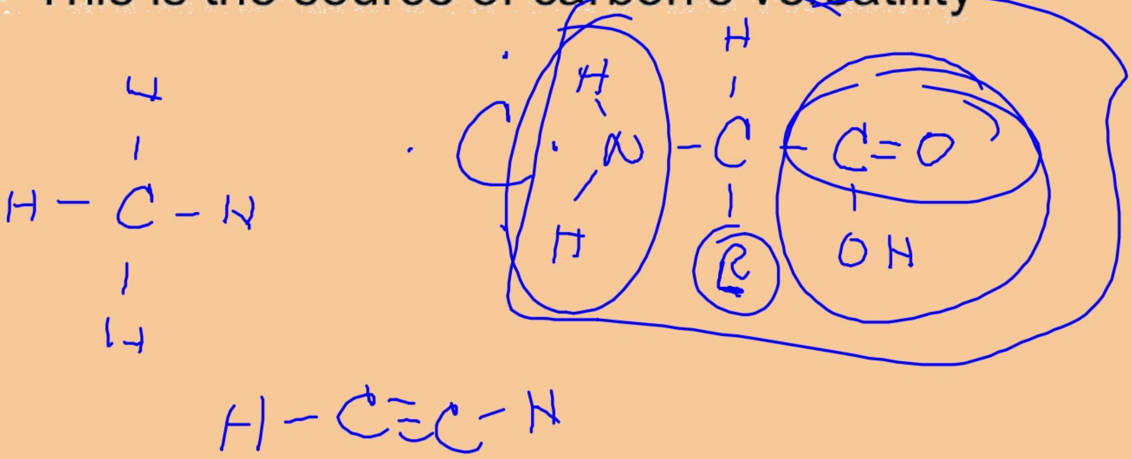
- Critically important molecules of all living things fall into four main classes
  - Carbohydrates – sugar – starch, dietary fiber (energy)
  - Lipids – Fats/oils (triglycerides) phospholipids – cell membrane
  - Proteins - structure – collagen + provides function (enzymes)
  - Nucleic acids – DNA + RNA
- The first three of these can form huge molecules called **macromolecules**

Figure 3.1



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

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

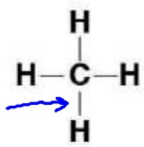
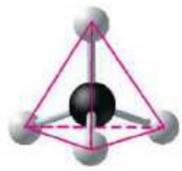
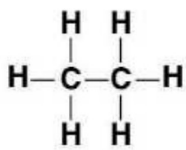
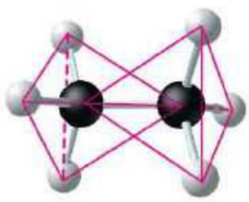
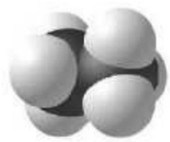
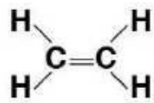
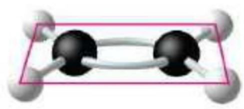


The Formation of Bonds with Carbon

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

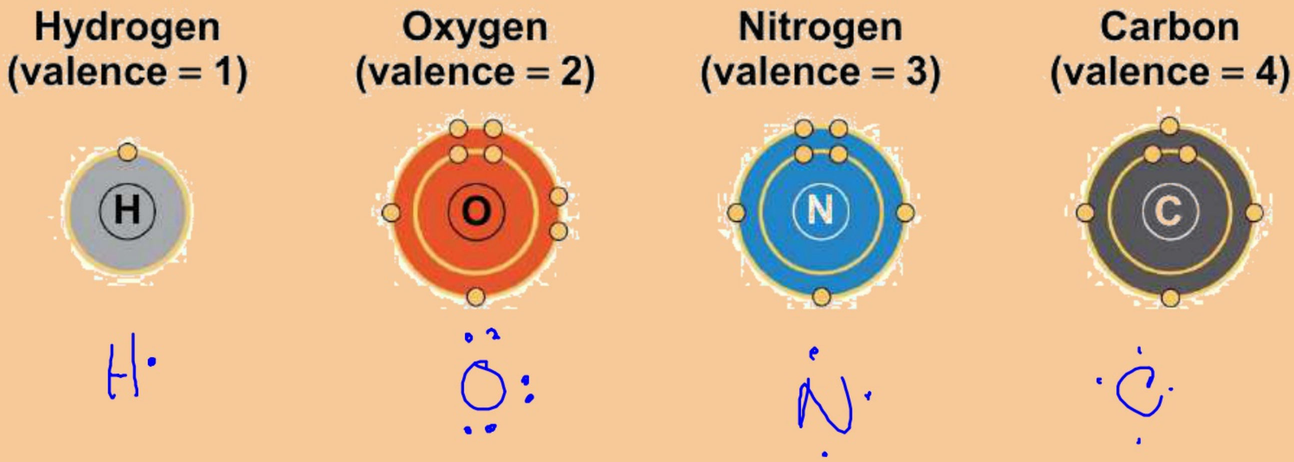
C = C

Figure 3.2

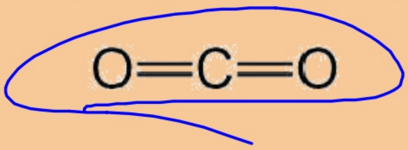
Molecular Shape	Molecular Formula	Structural Formula	Ball-and-Stick Model	Space-Filling Model
(a) Tetrahedral: methane	CH_4			
(b) More than one tetrahedral group: ethane	C_2H_6			
(c) Flat: ethene (ethylene)	C_2H_4			

- The electron configuration of carbon gives it covalent compatibility with many different elements
- The valences of carbon and its most frequent partners (hydrogen, oxygen, and nitrogen) are the "building code" that governs the architecture of living molecules

Figure 3.3


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

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



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

Figure 3.UN01

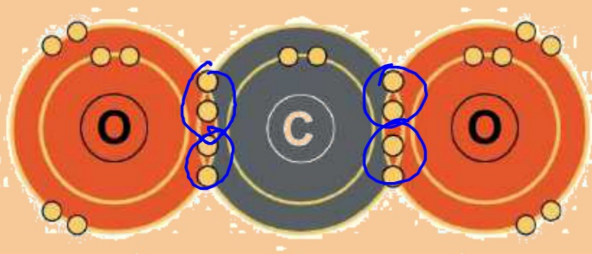
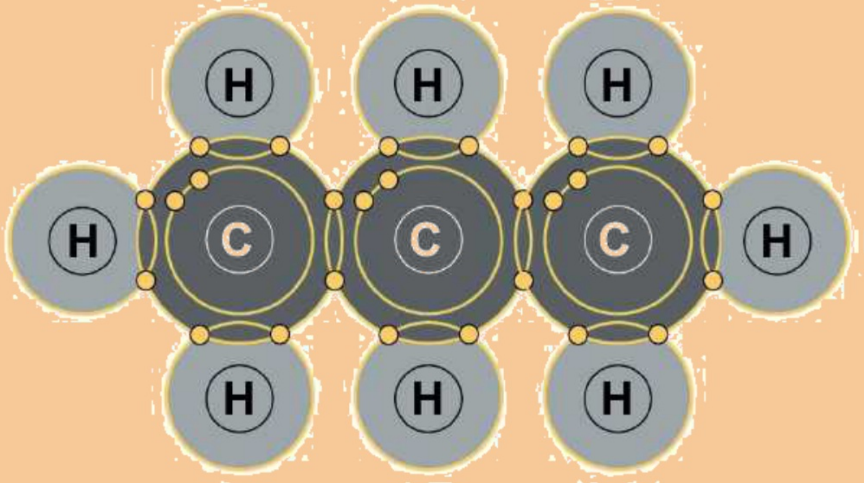


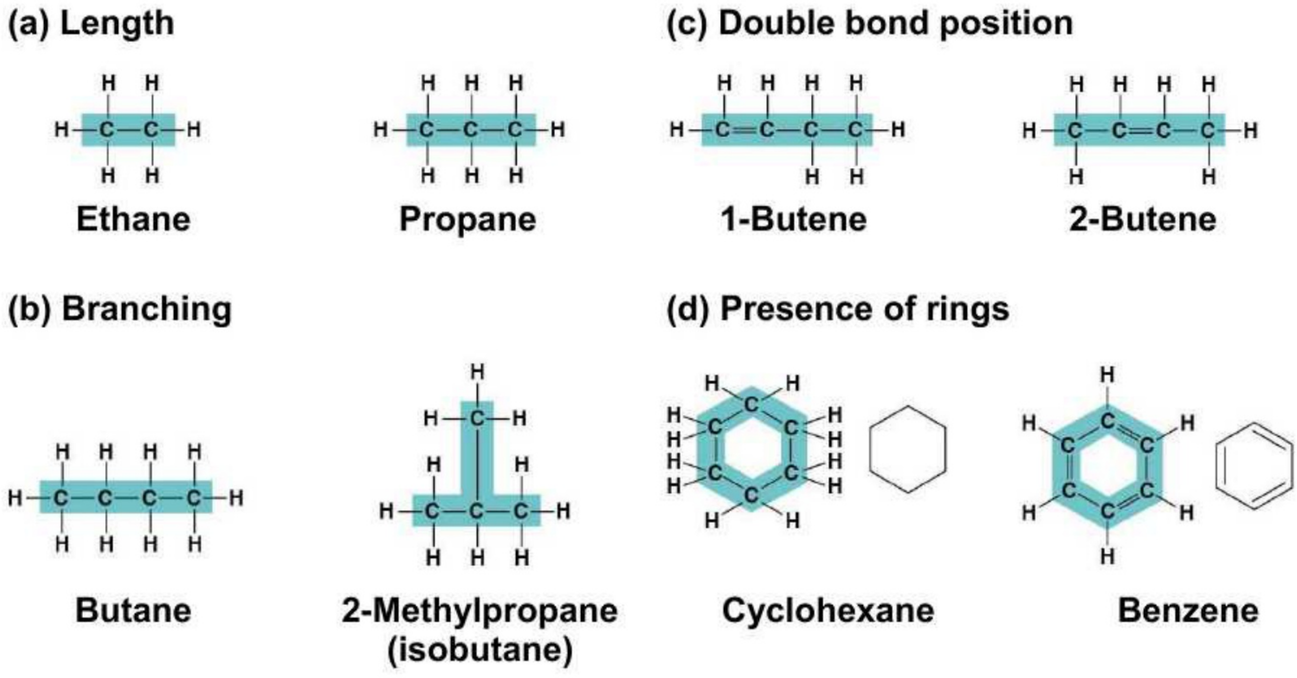
Figure 3.UN02



Molecular Diversity Arising from Variation in Carbon Skeletons

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

Figure 3.4



(a) Length
Ethane
Propane
(c) Double bond position
1-Butene
2-Butene
(b) Branching
Butane
2-Methylpropane
(isobutane)
(d) Presence of rings
Cyclohexane
Benzene

Hydrocarbons

- **Hydrocarbons** are organic molecules consisting of only carbon and hydrogen
- Many organic molecules, such as fats, have hydrocarbon components
- Hydrocarbons can undergo reactions that release a large amount of energy

Fossil Fuels

Isomers

equal parts

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

$C_6H_{12}O_6$ = Different structures

Glucose
Fructose
galactose

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

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

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

Figure 3.5-1

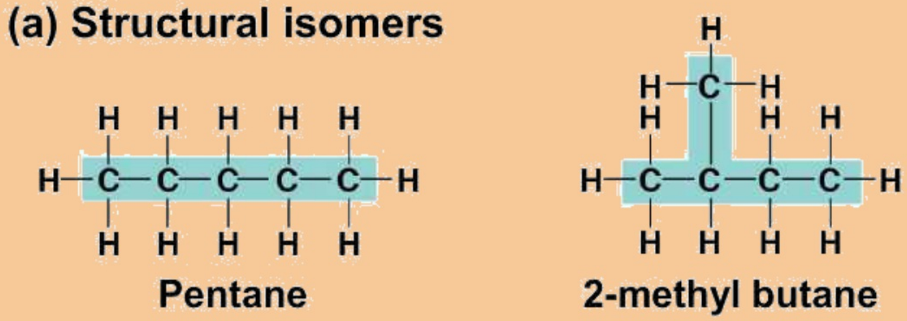

(a) Structural isomers
H
H C H
H H H H H H H H H
H C C C C C H H C C C C H
H H H H H H H H H
Pentane
2-methyl butane

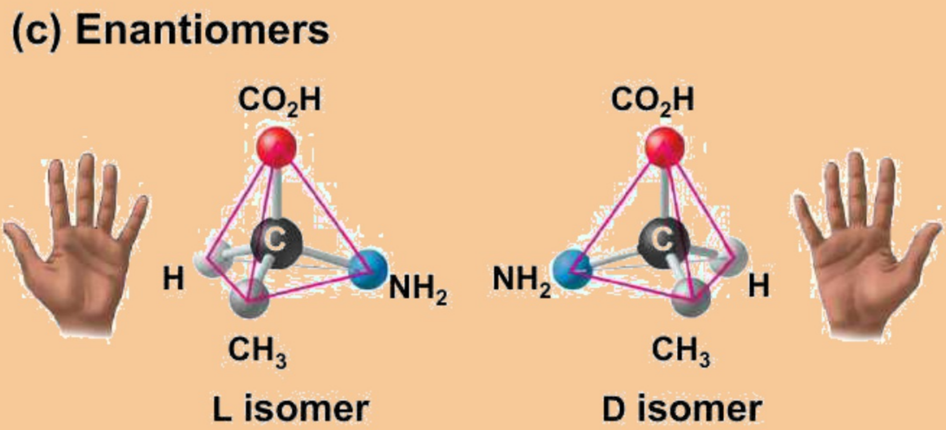
Figure 3.5-2

(b) *Cis-trans* isomers

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

trans isomer: The two Xs are on opposite sides.

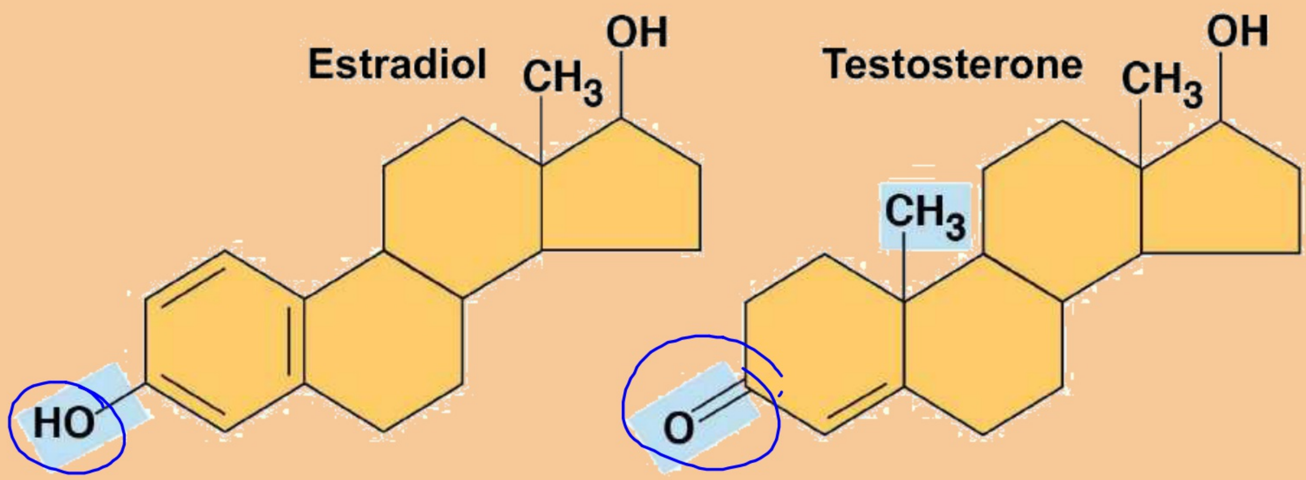
Figure 3.5-3


(c) Enantiomers
CO2H
H
C
NH2
CH3
L isomer
CO2H
NH2
C
H
CH3
D isomer

The Chemical Groups Most Important to Life

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

Figure 3.UN03



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

Figure 3.6-1

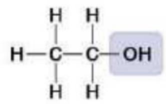
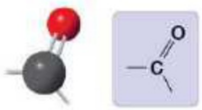
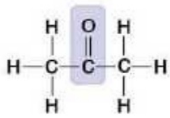
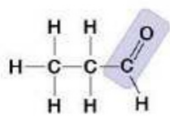
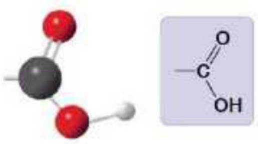
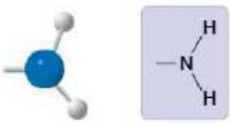
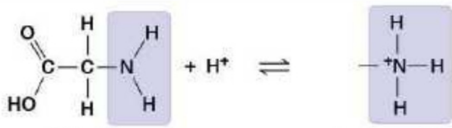
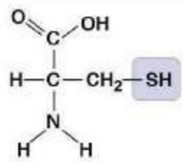
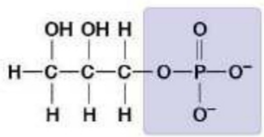
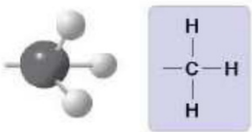
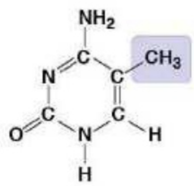
Chemical Group	Compound Name	Examples
Hydroxyl group (—OH)  (may be written HO—)	Alcohol	 Ethanol
Carbonyl group (>C═O) 	Ketone Aldehyde	 Acetone  Propanal
Carboxyl group (—COOH) 	Carboxylic acid, or organic acid	 Acetic acid; Ionized form of —COOH
Amino group (—NH_2) 	Amine	 Glycine; Ionized form of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

Figure 3.6-2

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

ATP: An Important Source of Energy for Cellular Processes

- An organic phosphate molecule, **adenosine triphosphate** (**ATP**), has an important function in the cell
  Ribose Adenine 3 P
- ATP consists of an organic molecule called adenosine attached to a string of three phosphate groups
- ATP stores the potential to react with water, releasing energy that can be used by the cell

Concept 3.2: Macromolecules are polymers, built from monomers

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

The Synthesis and Breakdown of Polymers

- Cells make and break down polymers by the same mechanisms (dehydrutn synthesis)
- A **dehydration reaction** occurs when two monomers bond together through the loss of a water molecule $C_6H_{12}O_6 + C_6H_{12}O_6 \longrightarrow C_{12}H_{22}O_{11} + H_2O$ (sucrose) OH^- H^+
- Polymers are disassembled to monomers by **hydrolysis**, a reaction that is essentially the reverse of the dehydration reaction (Breaking)
- These processes are facilitated by **enzymes**, which speed up chemical reactions

Figure 3.7

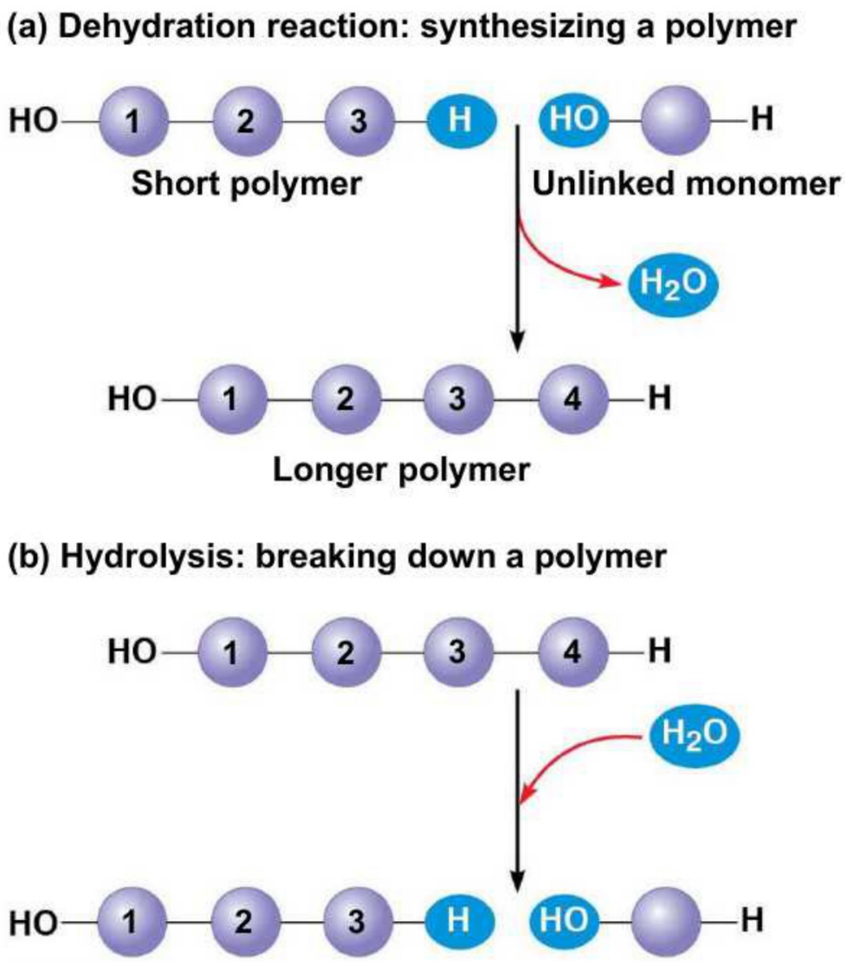

(a) Dehydration reaction: synthesizing a polymer
HO
1
2
3
H
HO
H
Short polymer
Unlinked monomer
H_2O
HO
1
2
3
4
H
Longer polymer
(b) Hydrolysis: breaking down a polymer
HO
1
2
3
4
H
H_2O
HO
1
2
3
H
HO
H

Figure 3.7-1

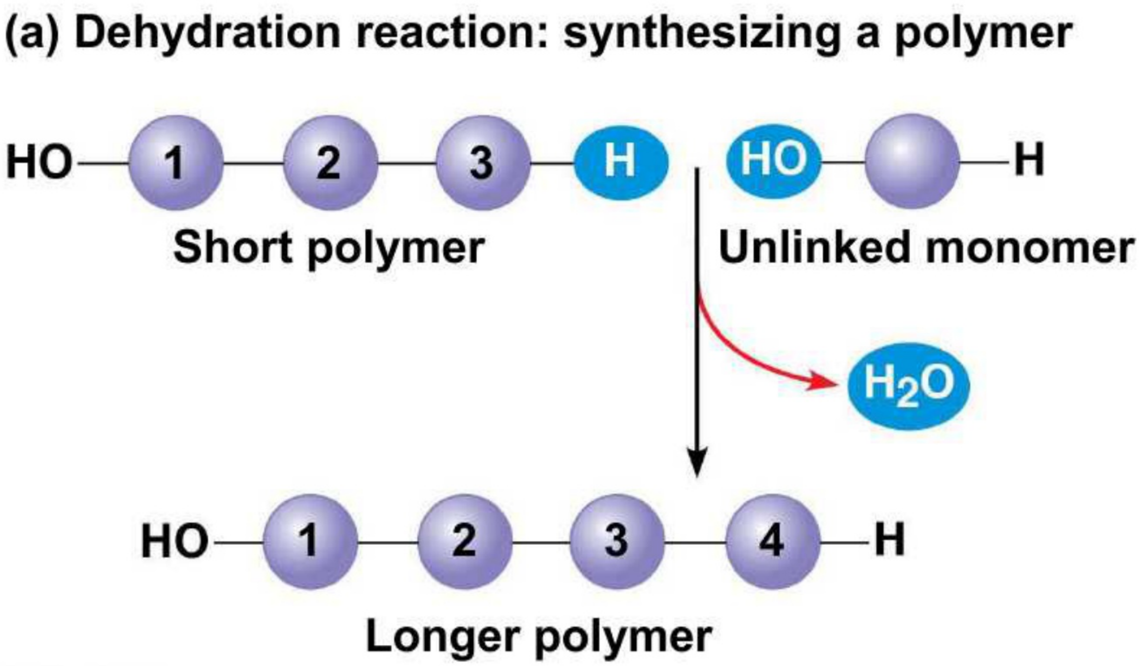
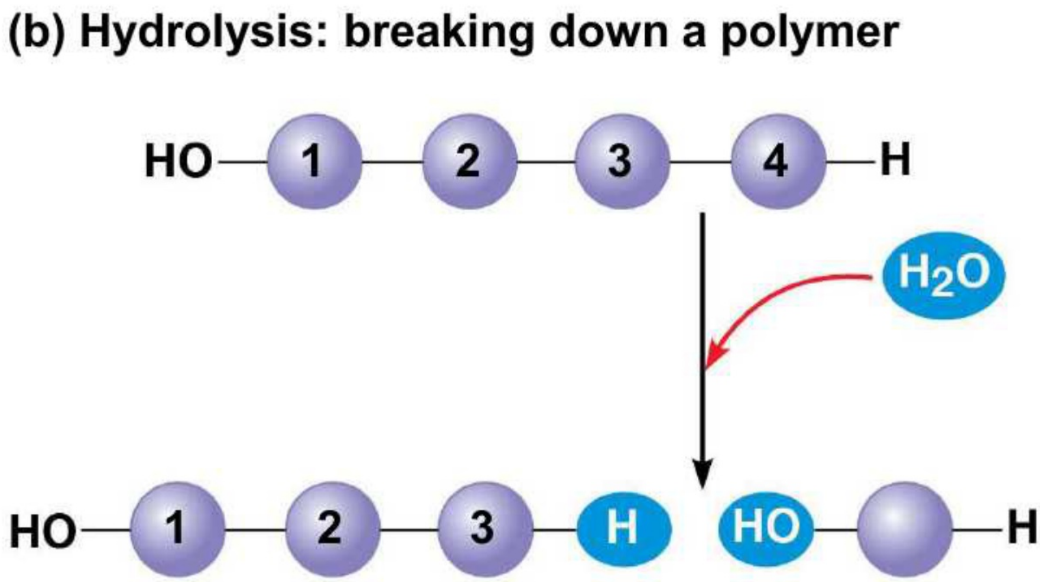

(a) Dehydration reaction: synthesizing a polymer
HO
1
2
3
H
HO
H
Short polymer
Unlinked monomer
H_2O
HO
1
2
3
4
H
Longer polymer

Figure 3.7-2



(b) Hydrolysis: breaking down a polymer
HO
1
2
3
4
H
H2O
HO
1
2
3
H
HO
H

The Diversity of Polymers

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

Concept 3.3: Carbohydrates serve as fuel and building material

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

one sugar

glucose fructose 3-7 C atoms

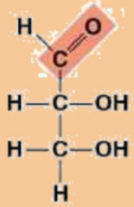
Starch

Sugars

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

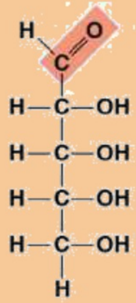
Figure 3.8

Triose: three-carbon sugar ($C_3H_6O_3$)



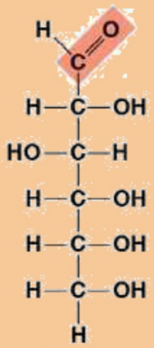
Glyceraldehyde
An initial breakdown product of glucose in cells

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

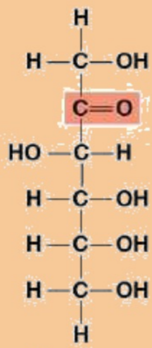


Ribose
A component of RNA

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



Glucose

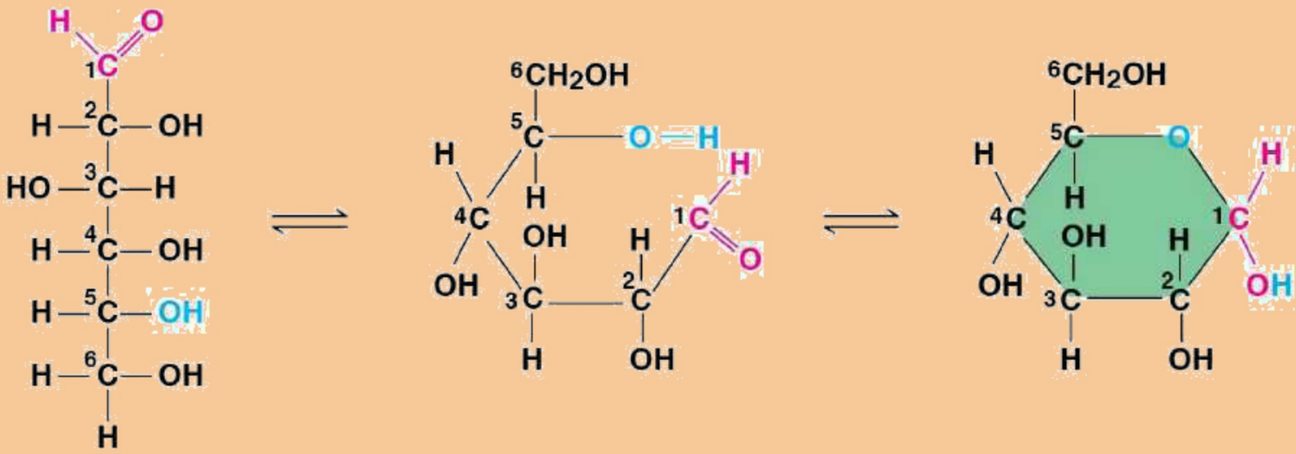


Fructose

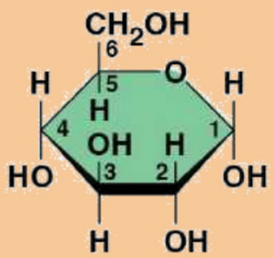
Energy sources for organisms

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

Figure 3.9



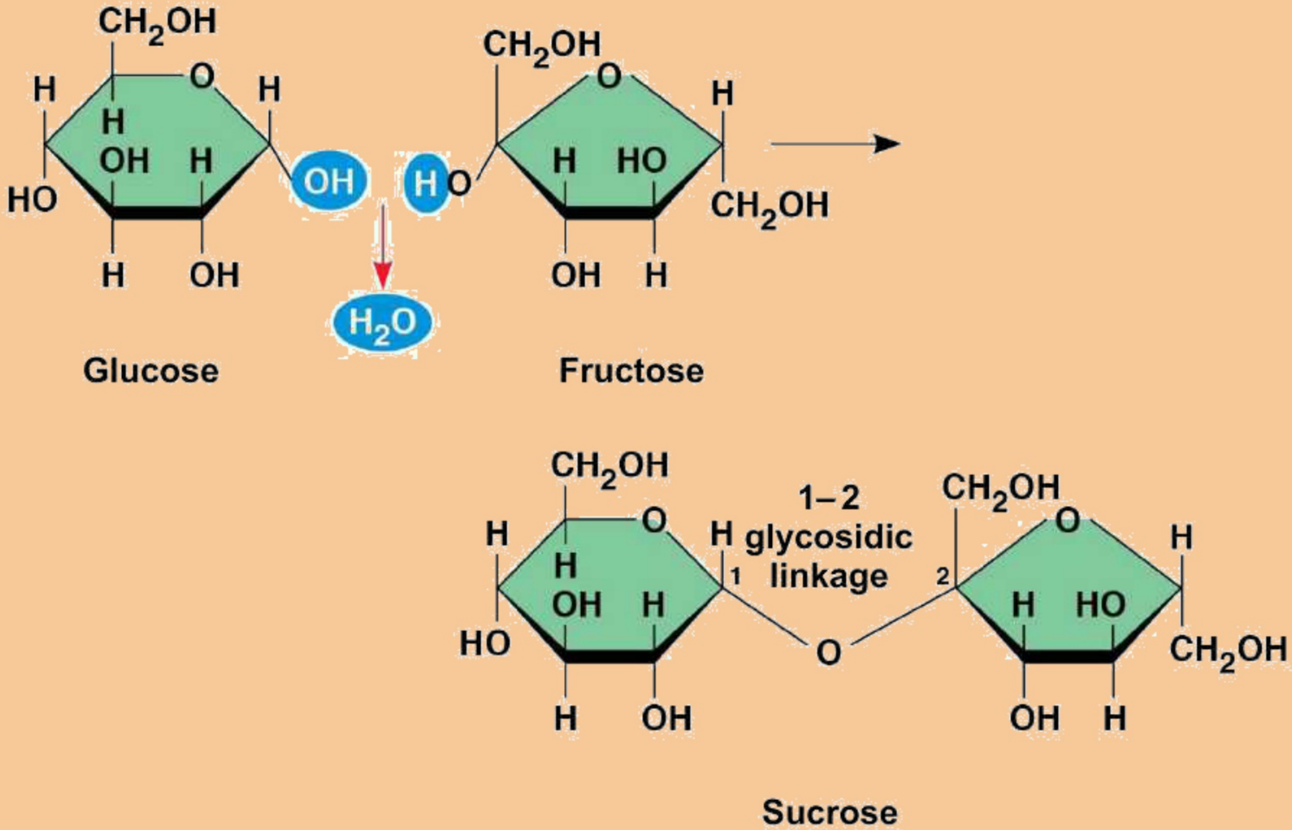
(a) Linear and ring forms



(b) Abbreviated ring structure

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

Figure 3.10-s2



Polysaccharides

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

Storage Polysaccharides

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

Amylase

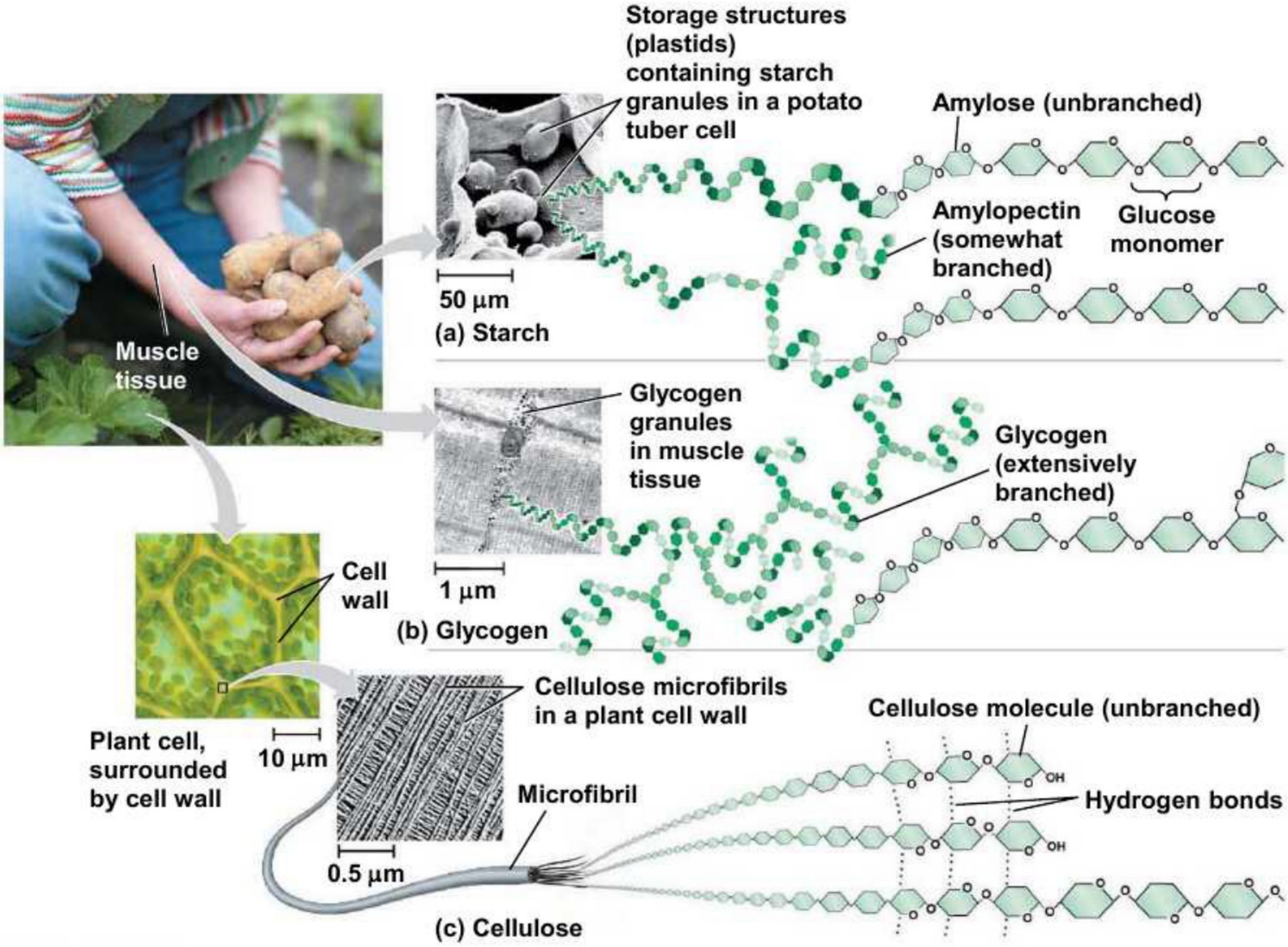
Amylose (starch)

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

Blood sugar

provides instant energy

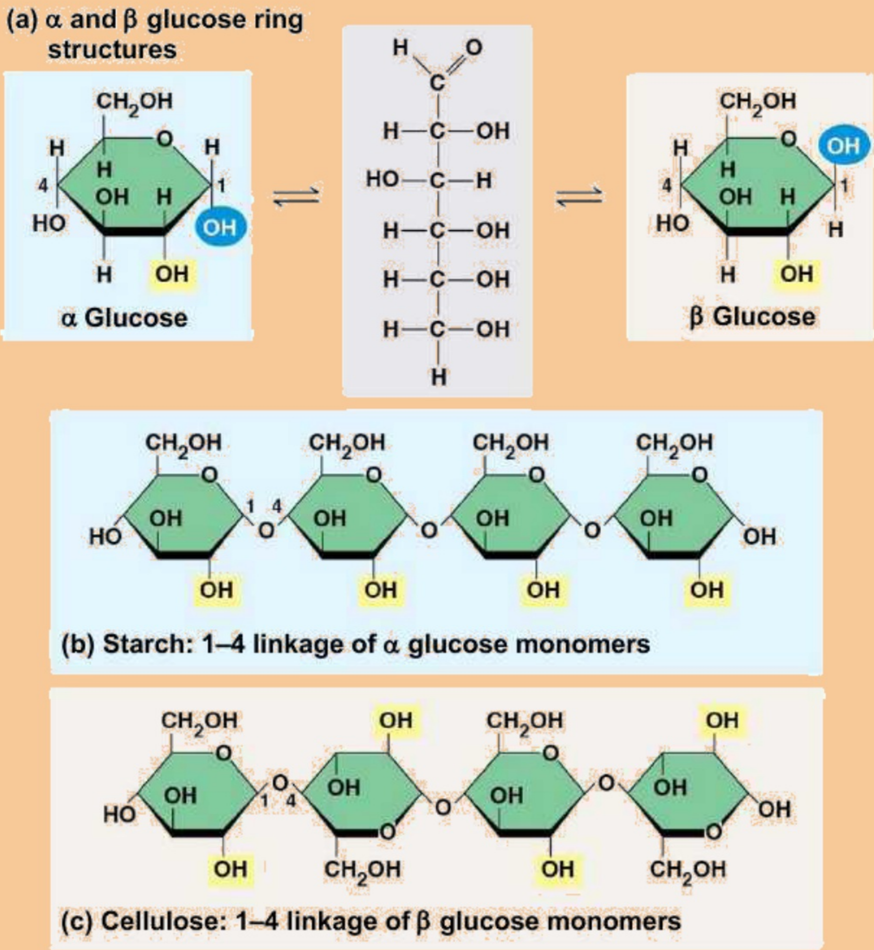
Figure 3.11


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

Structural Polysaccharides

- The polysaccharide **cellulose** is a major component of the tough wall of plant cells
- Like starch and glycogen, cellulose is a polymer of glucose, but the glycosidic linkages in cellulose differ - we don't digest
- The difference is based on two ring forms for glucose

Figure 3.12


(a) α and β glucose ring structures
CH2OH
H
O
H
4
H
OH
H
1
HO
OH
H
OH
α Glucose
H
O
C
H—C—OH
HO—C—H
H—C—OH
H—C—OH
H—C—OH
H
β Glucose
(b) Starch: 1–4 linkage of α glucose monomers
(c) Cellulose: 1–4 linkage of β glucose monomers

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

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

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

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

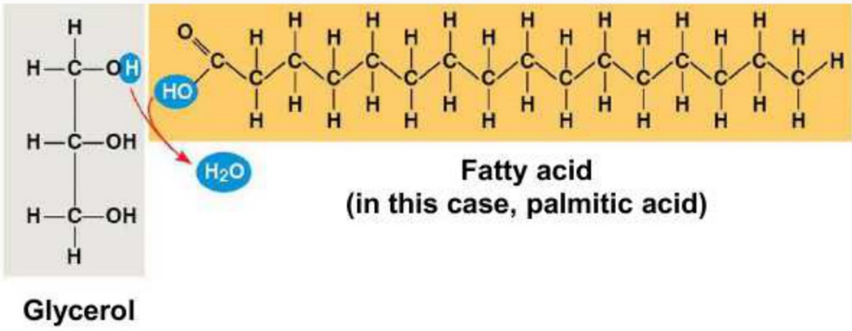
Concept 3.4: Lipids are a diverse group of hydrophobic molecules

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

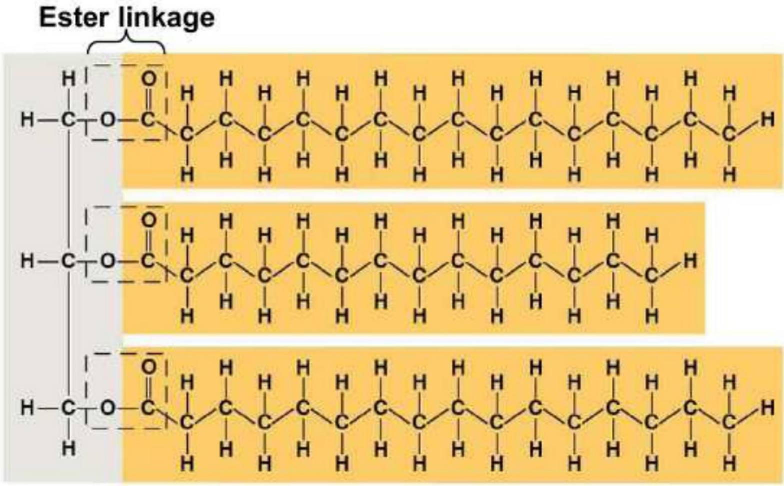
Fats

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

Figure 3.13

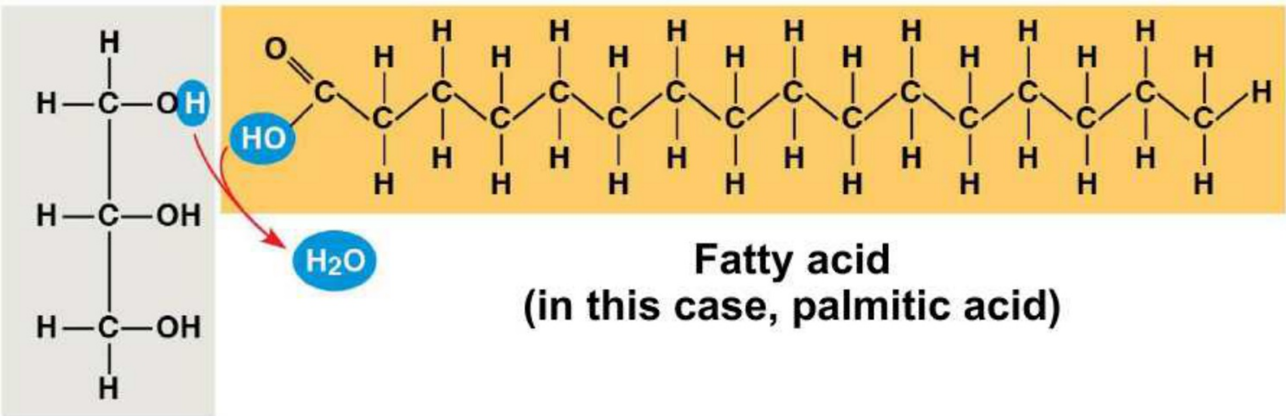


(a) One of three dehydration reactions in the synthesis of a fat



(b) Fat molecule (triacylglycerol)

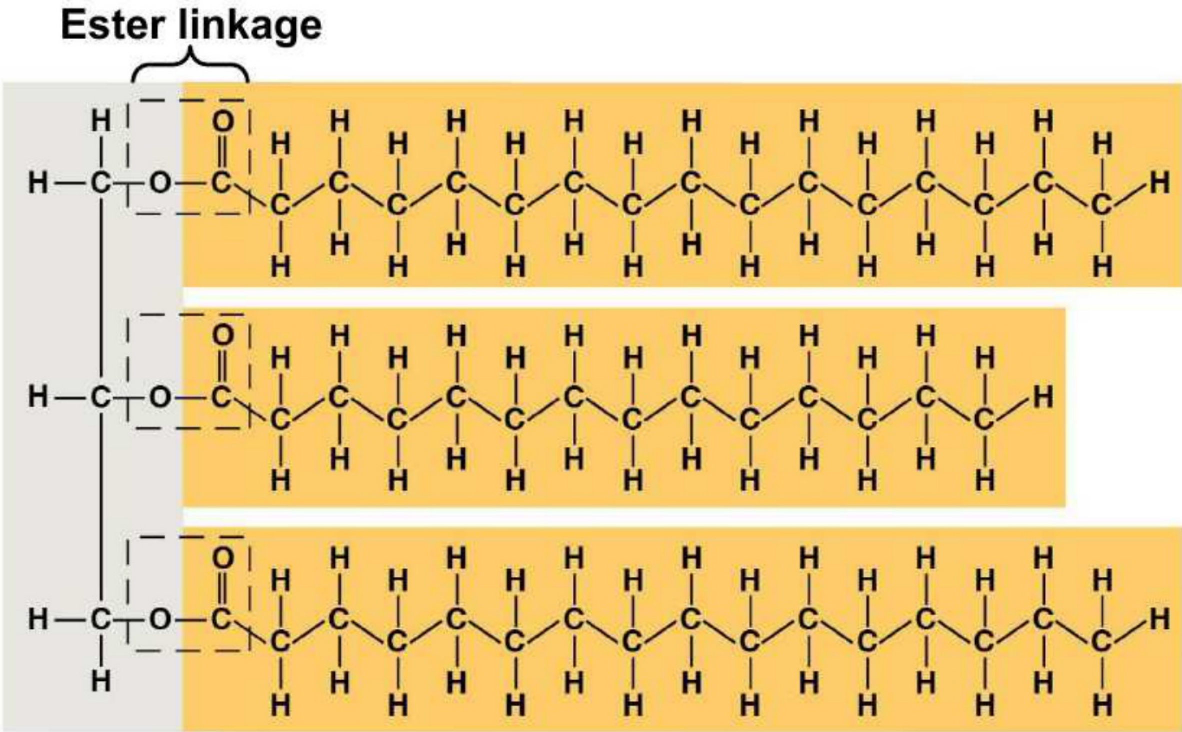
Figure 3.13-1



Glycerol

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

Figure 3.13-2



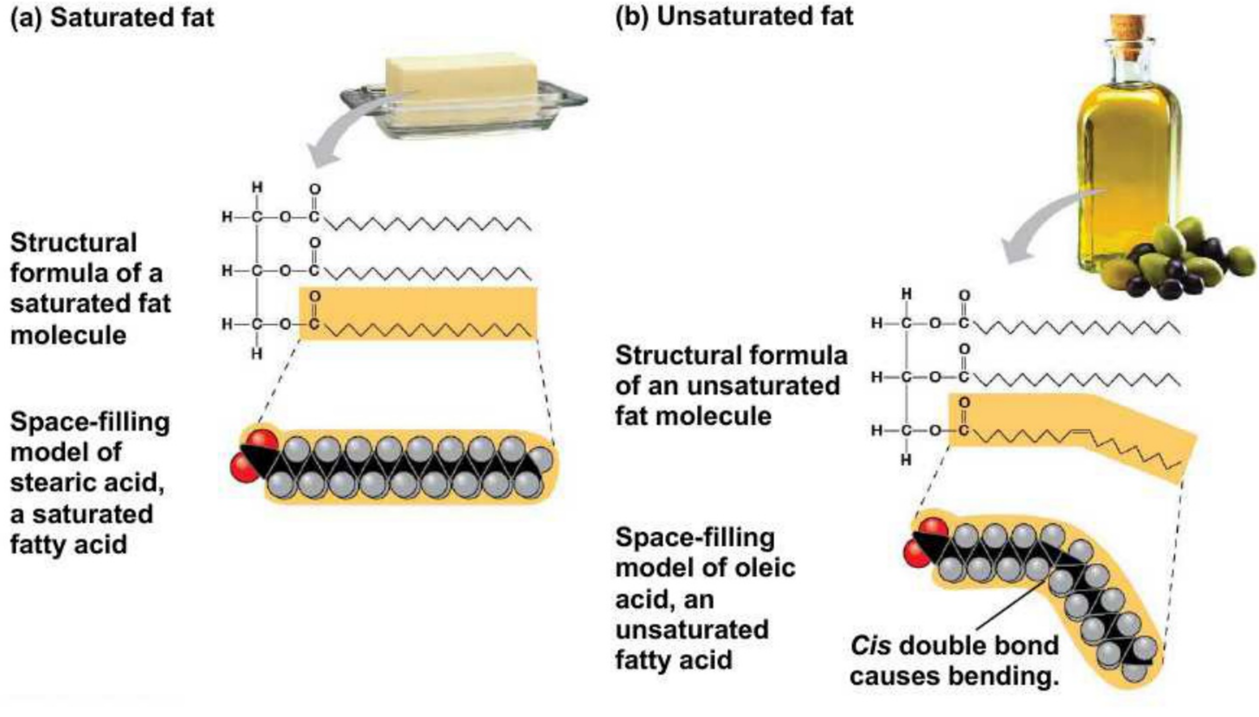
(b) Fat molecule (triacylglycerol)

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

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

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

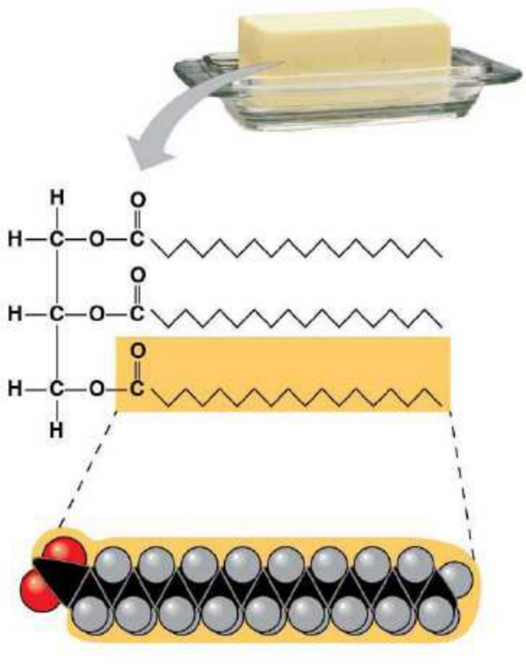
Figure 3.14



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

Figure 3.14-1

(a) Saturated fat



Structural formula of a saturated fat molecule

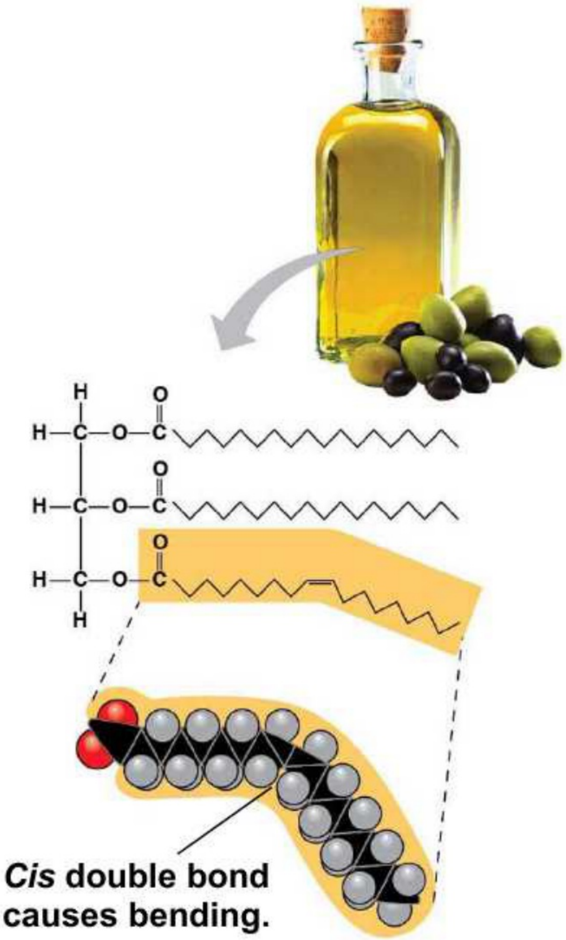
Space-filling model of stearic acid, a saturated fatty acid

Figure 3.14-2

(b) Unsaturated fat

Structural formula of an unsaturated fat molecule

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



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

Phospholipids

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

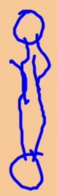
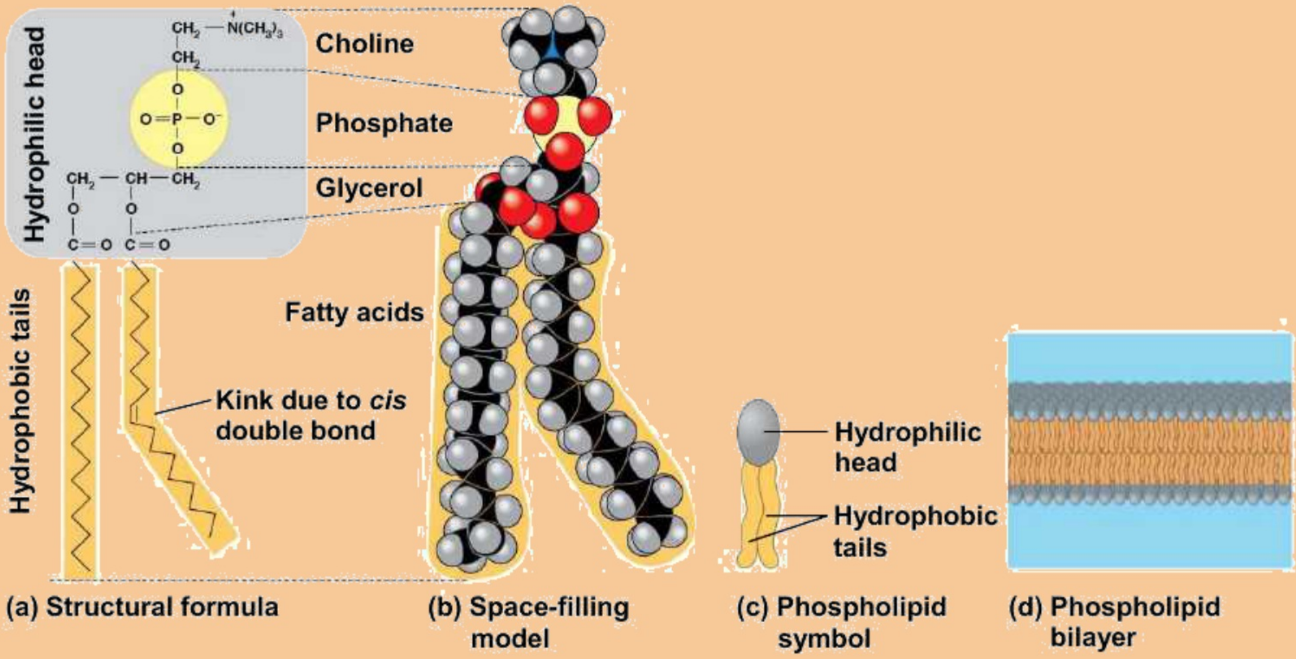
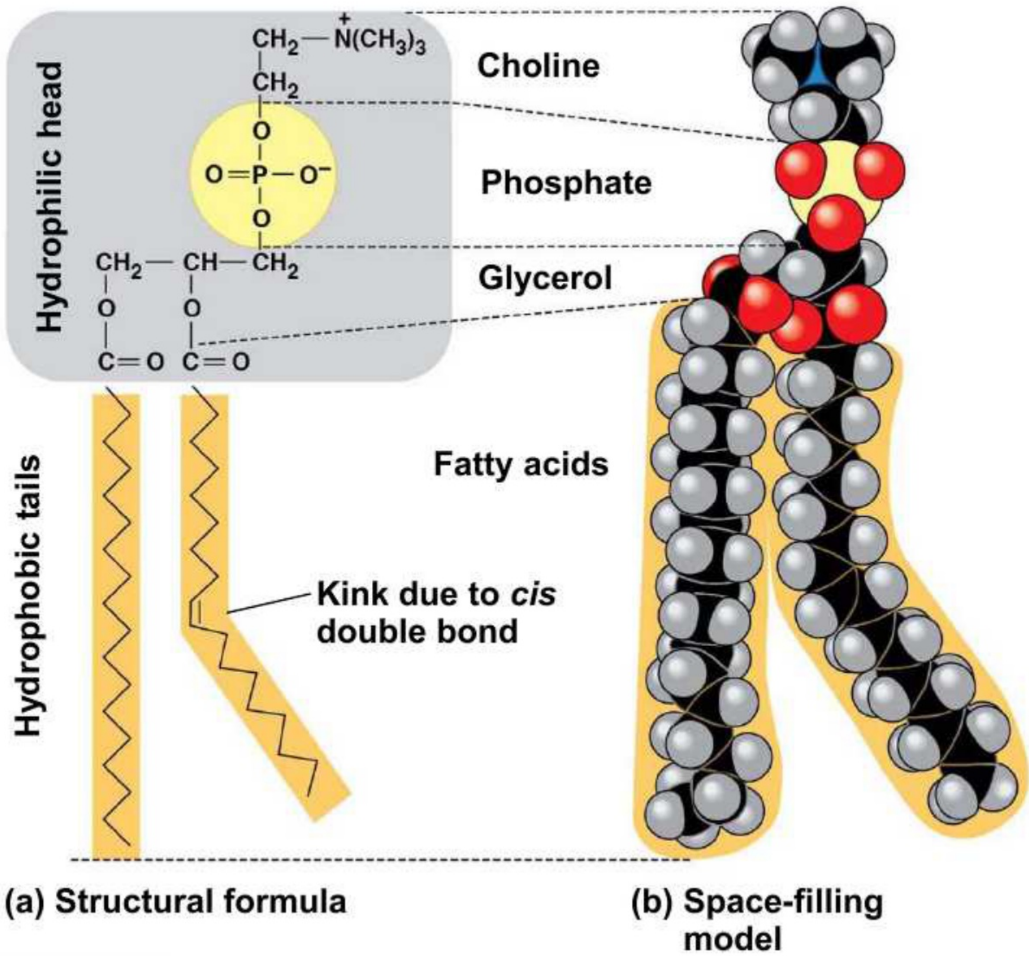


Figure 3.15



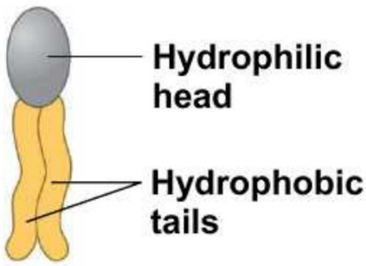
Hydrophilic head
CH_2 — $\overset{+}{N}(CH_3)_3$
CH_2
O
O=P—O⁻
O
CH_2 — CH — CH_2
O
C=O
Choline
Phosphate
Glycerol
Fatty acids
Hydrophobic tails
Kink due to *cis* double bond
Hydrophilic head
Hydrophobic tails
(a) Structural formula
(b) Space-filling model
(c) Phospholipid symbol
(d) Phospholipid bilayer

Figure 3.15-1

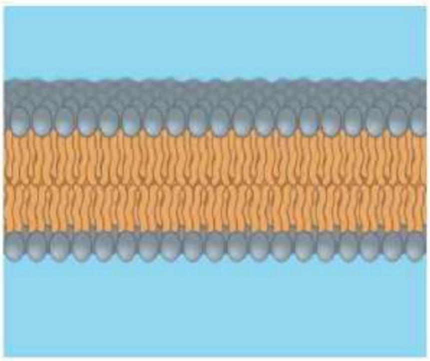


Hydrophilic head
CH_2 — $\overset{+}{N}(CH_3)_3$
CH_2
O
O=P—O⁻
O
CH_2 — CH — CH_2
O
O
C=O C=O
Choline
Phosphate
Glycerol
Fatty acids
Hydrophobic tails
Kink due to *cis* double bond
(a) Structural formula
(b) Space-filling model

Figure 3.15-2



(c) Phospholipid symbol

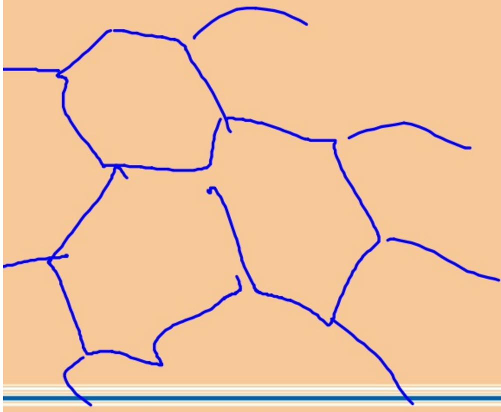


(d) Phospholipid bilayer

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

Steroids

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



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

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

Figure 3.17

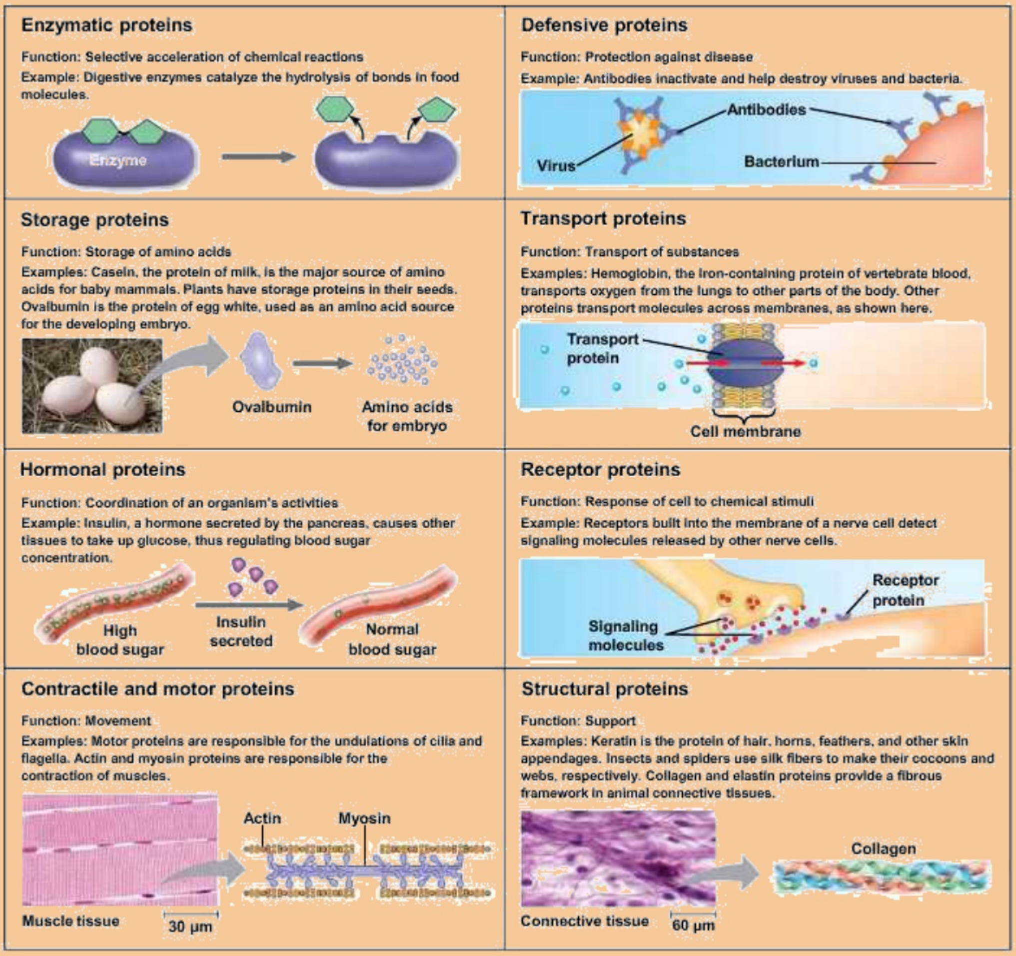

Enzymatic proteins
Function: Selective acceleration of chemical reactions
Example: Digestive enzymes catalyze the hydrolysis of bonds in food molecules.
Enzyme
Defensive proteins
Function: Protection against disease
Example: Antibodies inactivate and help destroy viruses and bacteria.
Antibodies
Virus
Bacterium
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.
Ovalbumin
Amino acids for 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.
Transport protein
Cell membrane
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 3.17-1

Enzymatic proteins

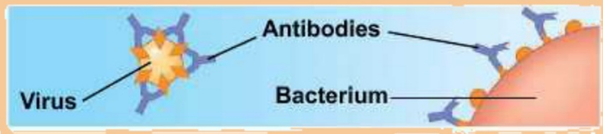
Function: Selective acceleration of chemical reactions

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.

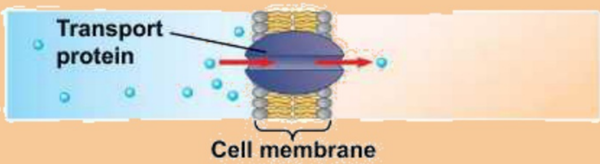


Figure 3.17-2

Hormonal proteins

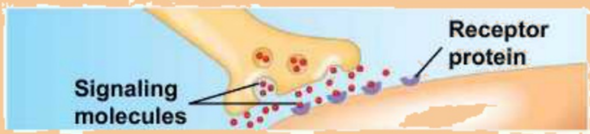
Function: Coordination of an organism's activities

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

Receptor proteins

Function: Response of cell to chemical stimuli

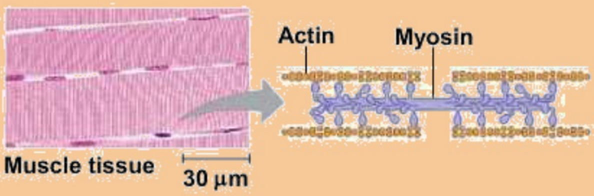
Example: Receptors built into the membrane of a nerve cell detect signaling molecules released by other nerve cells.



Contractile and motor proteins

Function: Movement

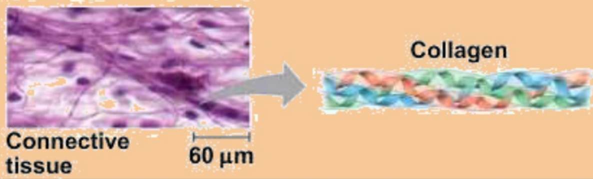
Examples: Motor proteins are responsible for the undulations of cilia and flagella. Actin and myosin proteins are responsible for the contraction of muscles.



Structural proteins

Function: Support

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



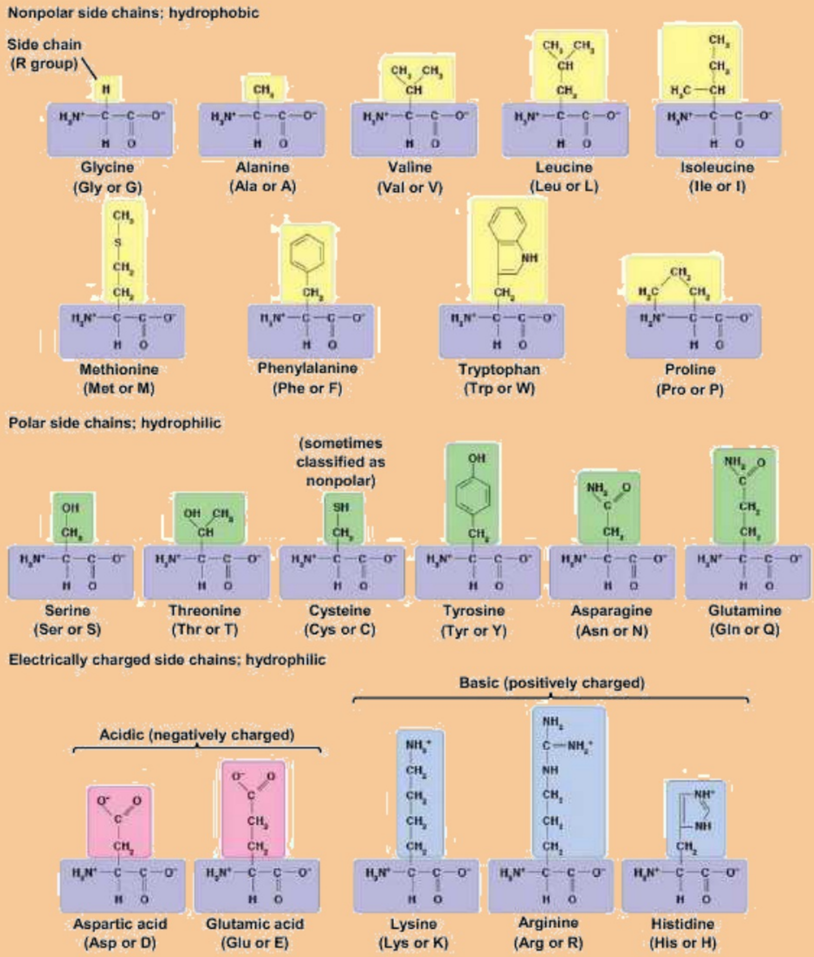
- Life would not be possible without enzymes
- Enzymatic proteins act as **catalysts**, to speed up chemical reactions without being consumed in the reaction

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

Amino Acid Monomers

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

Figure 3.18



Nonpolar side chains; hydrophobic
Side chain (R group)
Glycine (Gly or G)
Alanine (Ala or A)
Valine (Val or V)
Leucine (Leu or L)
Isoleucine (Ile or I)
Methionine (Met or M)
Phenylalanine (Phe or F)
Tryptophan (Trp or W)
Proline (Pro or P)
Polar side chains; hydrophilic
(sometimes classified as nonpolar)
Serine (Ser or S)
Threonine (Thr or T)
Cysteine (Cys or C)
Tyrosine (Tyr or Y)
Asparagine (Asn or N)
Glutamine (Gln or Q)
Electrically charged side chains; hydrophilic
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 3.18-1

Nonpolar side chains; hydrophobic

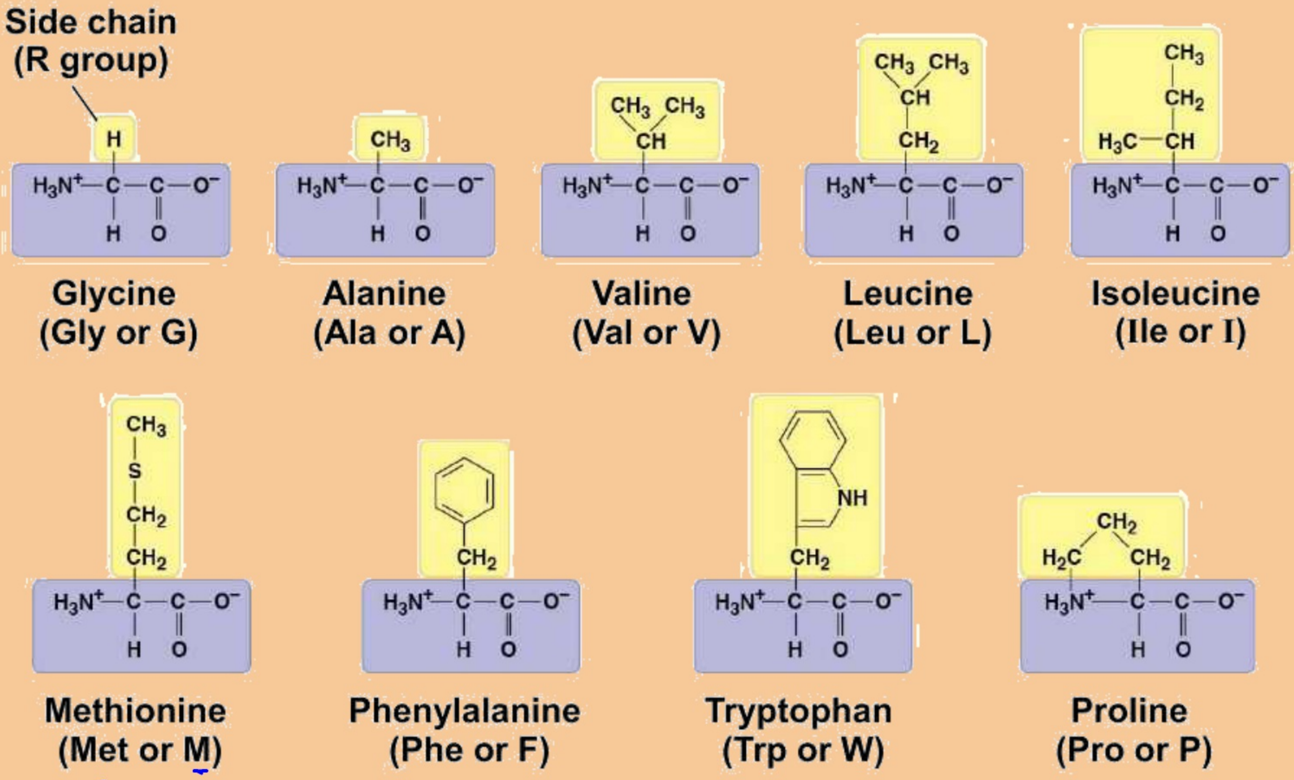


Figure 3.18-2

Polar side chains; hydrophilic

(sometimes classified as nonpolar)

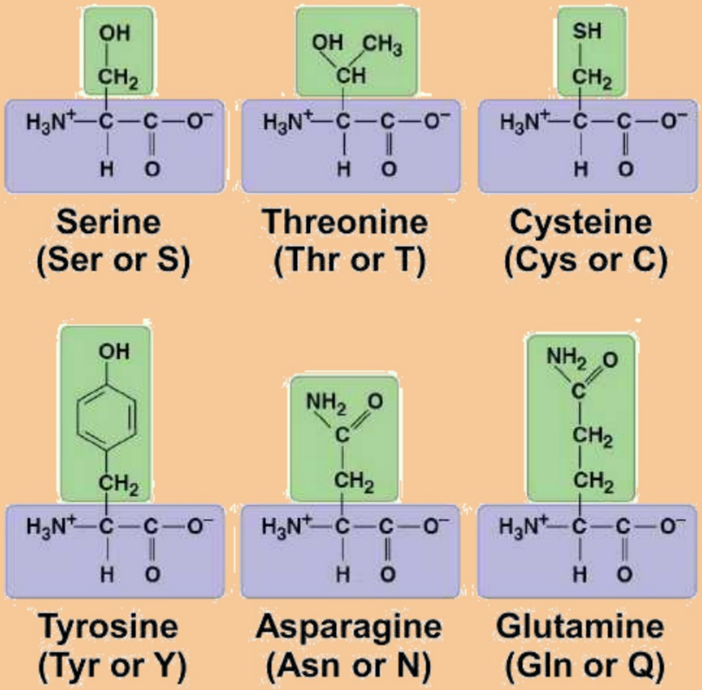
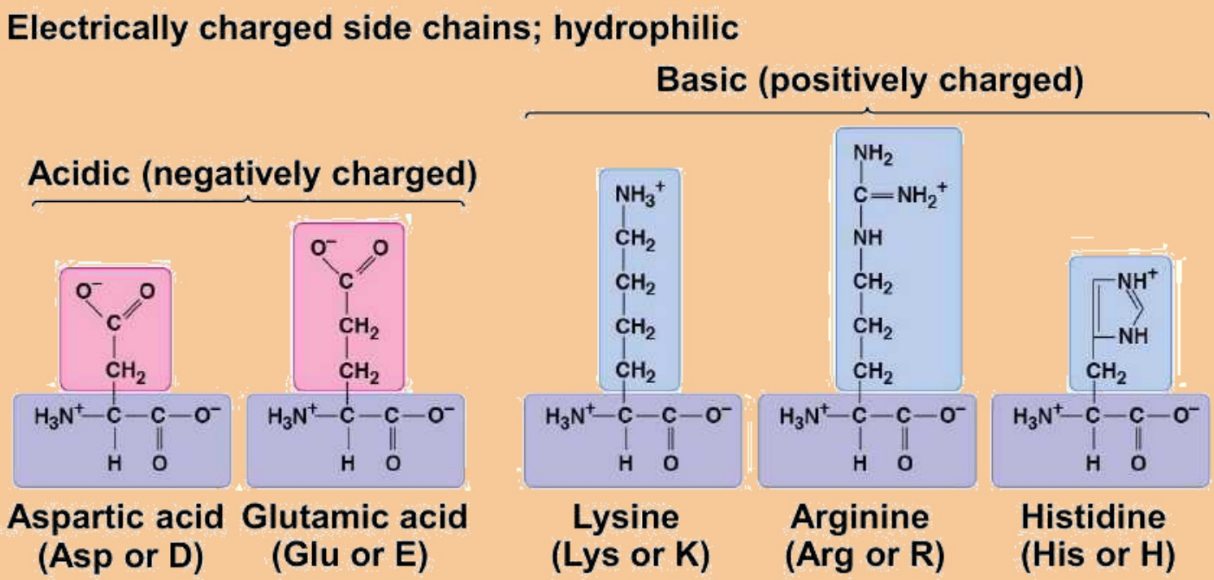


Figure 3.18-3



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

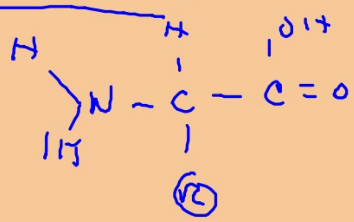
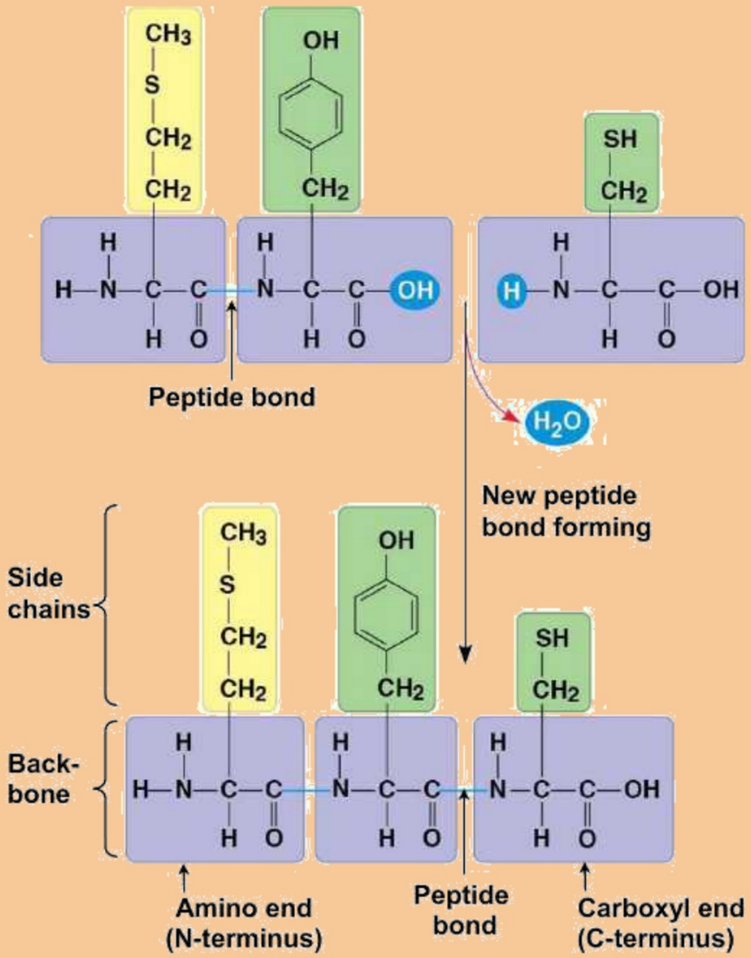


Figure 3.19



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

Figure 3.19-1

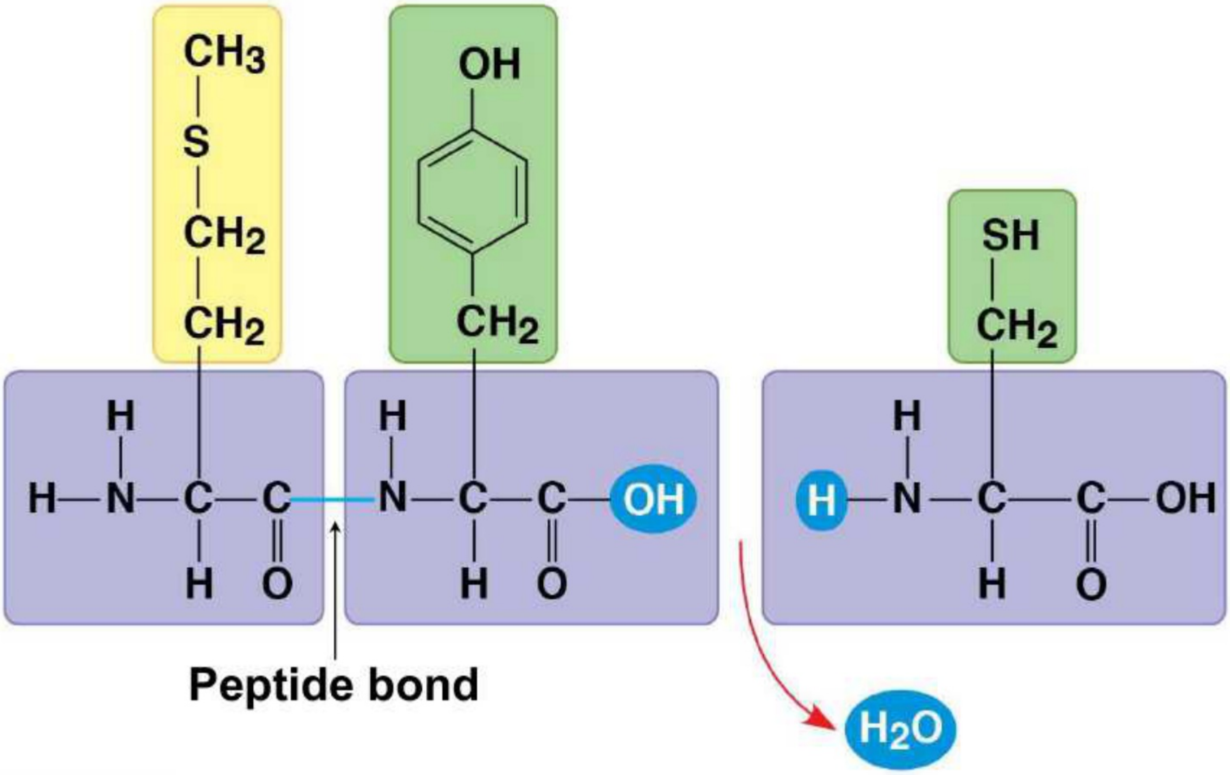
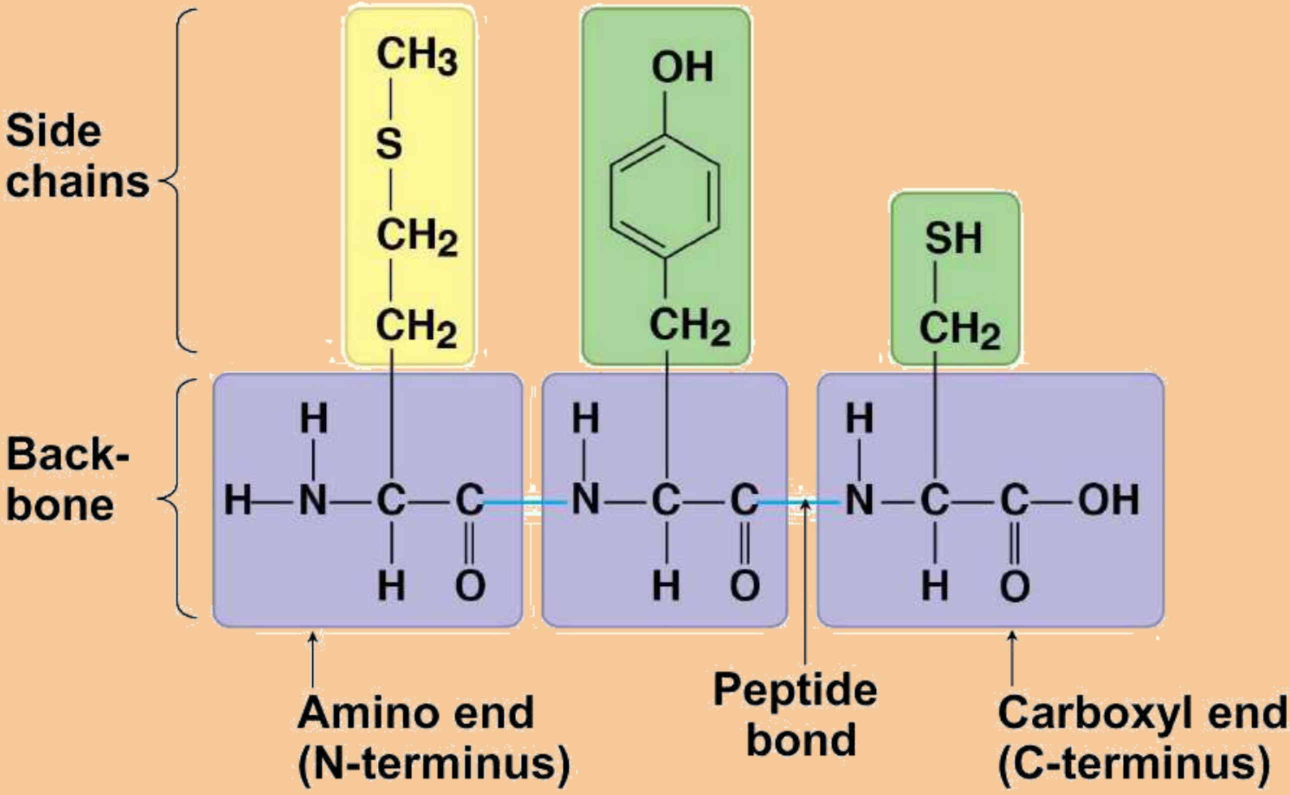

CH3
S
CH2
CH2
OH
SH
CH2
CH2
H
H—N—C—C
O
H
N—C—C—OH
H
O
H
H—N—C—C—OH
H
O
Peptide bond
H2O

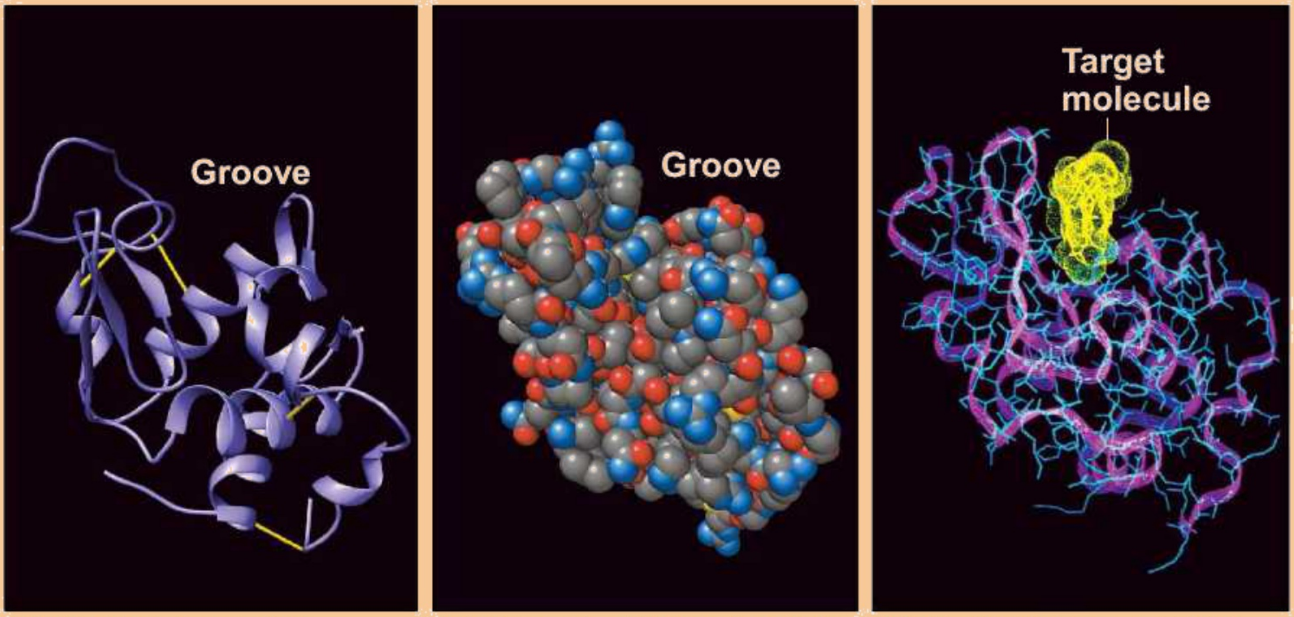
Figure 3.19-2


Side chains
Backbone
CH_3
S
CH_2
CH_2
OH
CH_2
SH
CH_2
H
H—N—C—C
H O
H
N—C—C
H O
H
N—C—C—OH
H O
Amino end (N-terminus)
Peptide bond
Carboxyl end (C-terminus)

Protein Structure and Function

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

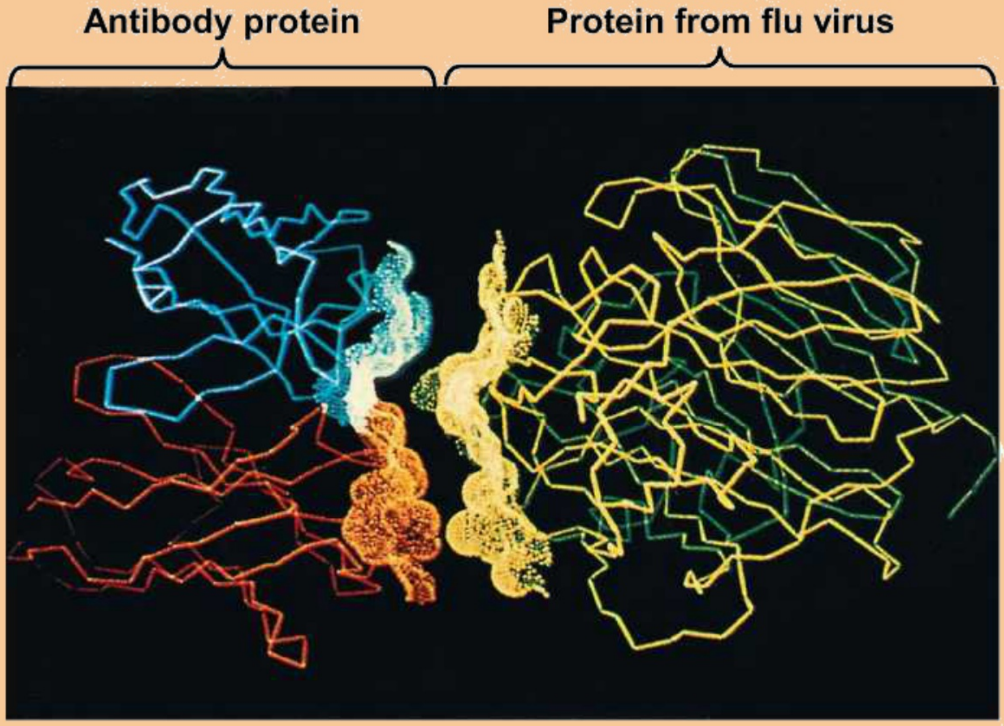
Figure 3.20



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

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

Figure 3.21

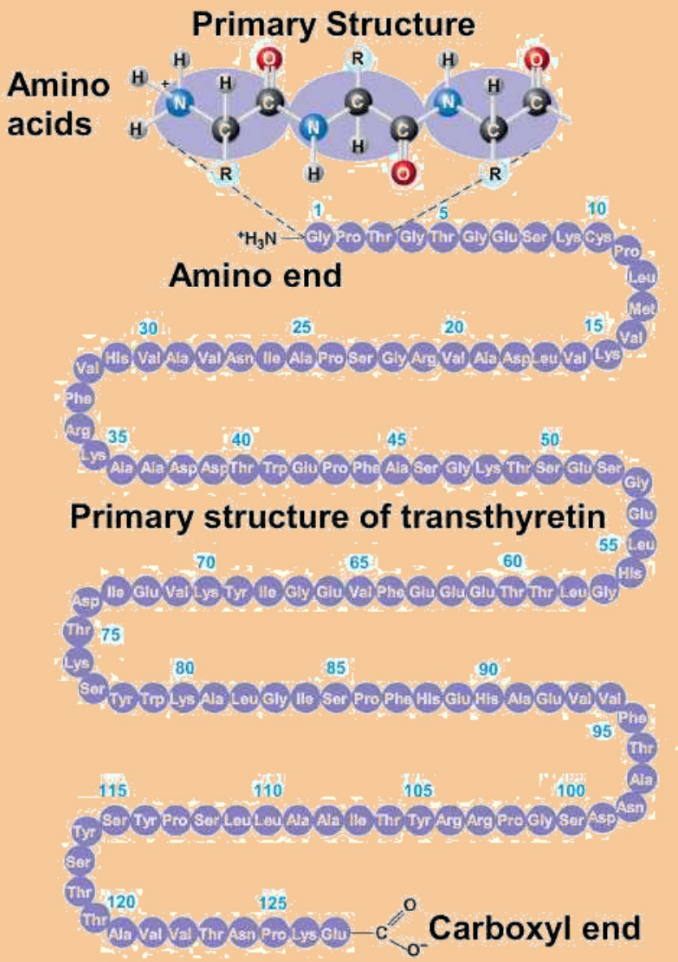


Four Levels of Protein Structure

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

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

Figure 3.22-1



Primary Structure
Amino acids
Amino end
Primary structure of transthyretin
Carboxyl end

Figure 3.22-1a

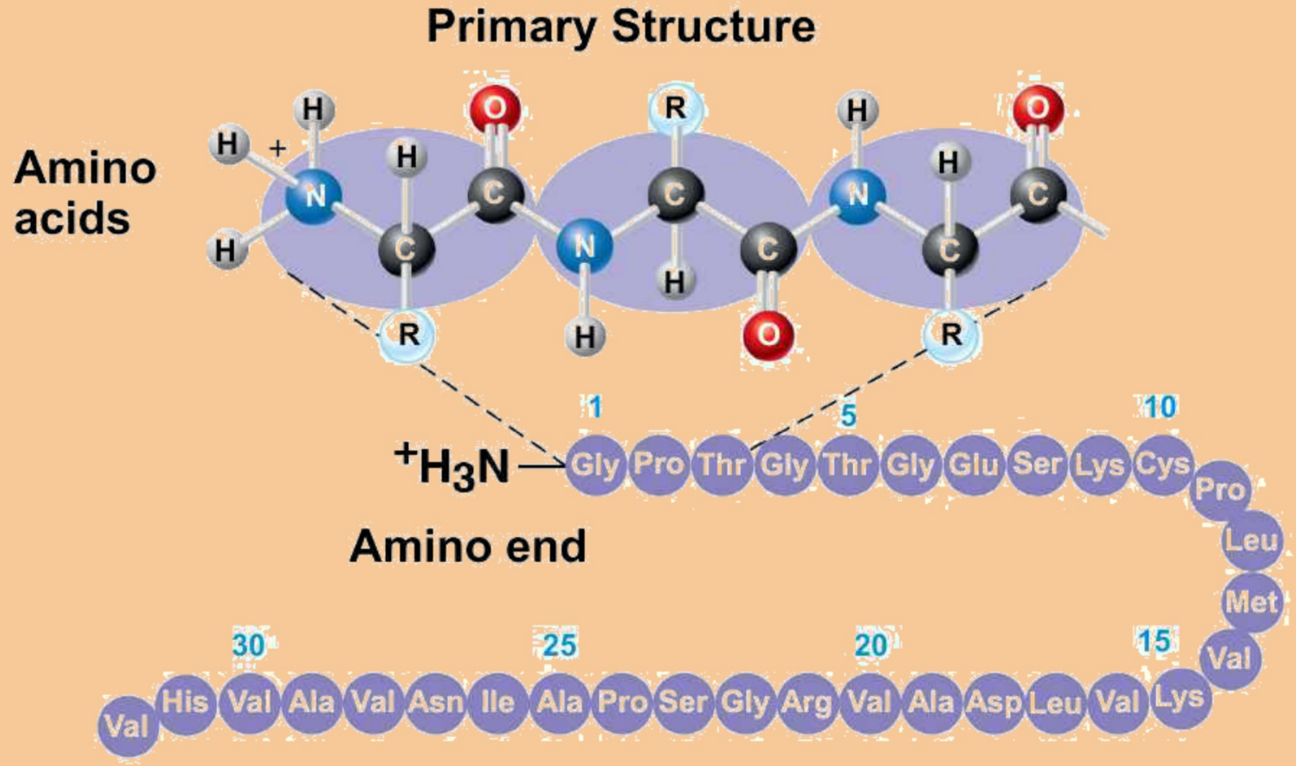


Figure 3.22-2

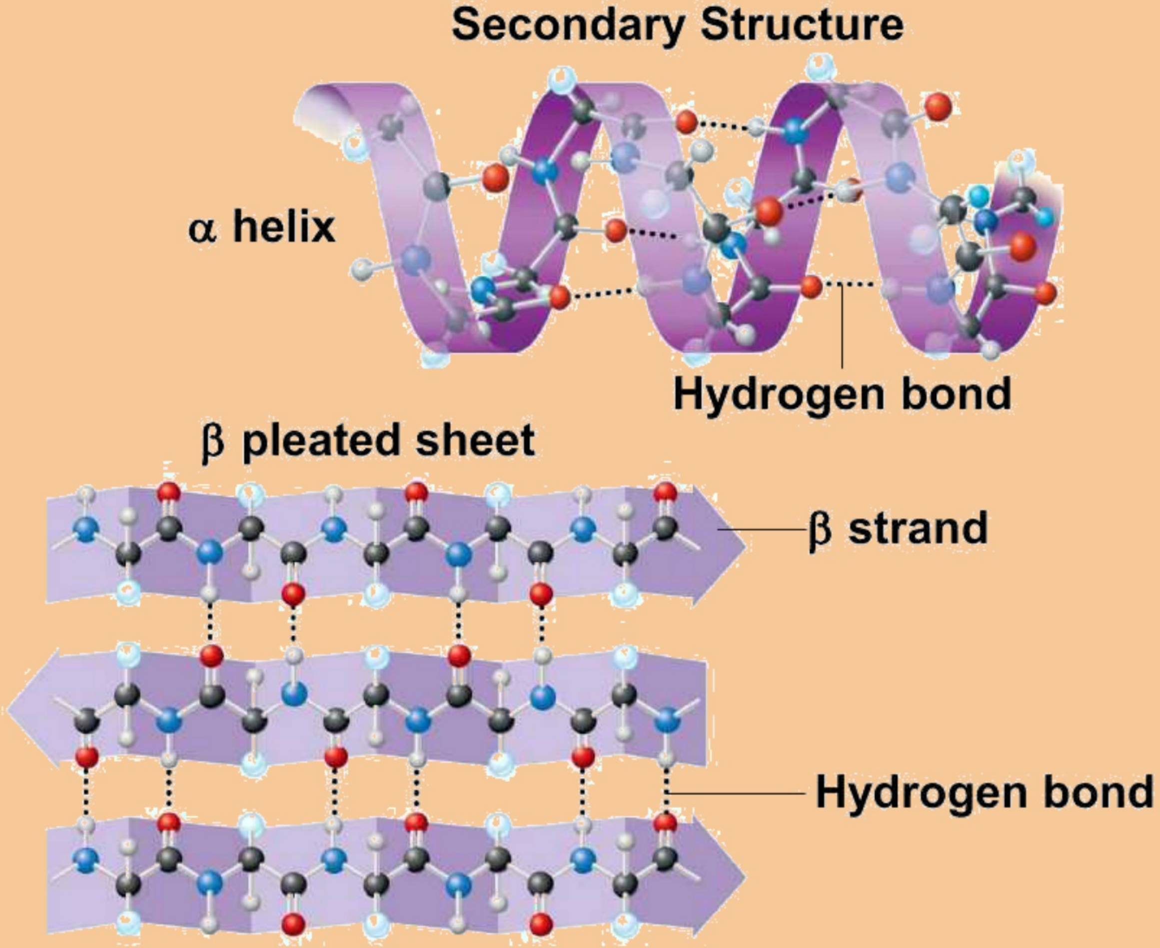

Secondary Structure
α helix
Hydrogen bond
β pleated sheet
β strand
Hydrogen bond

Figure 3.22-3

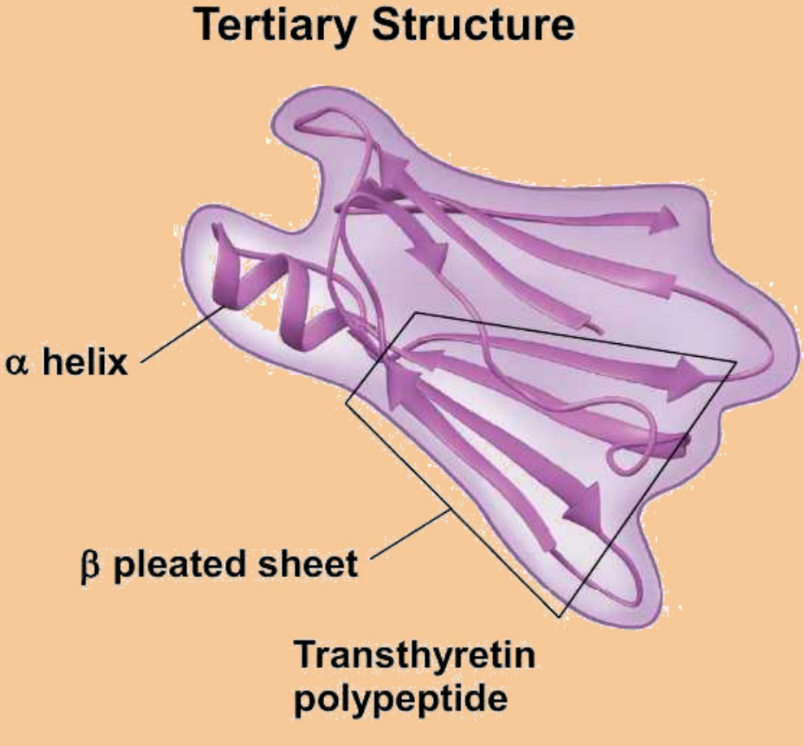

Tertiary Structure
α helix
β pleated sheet
Transthyretin
polypeptide

Figure 3.22-3a

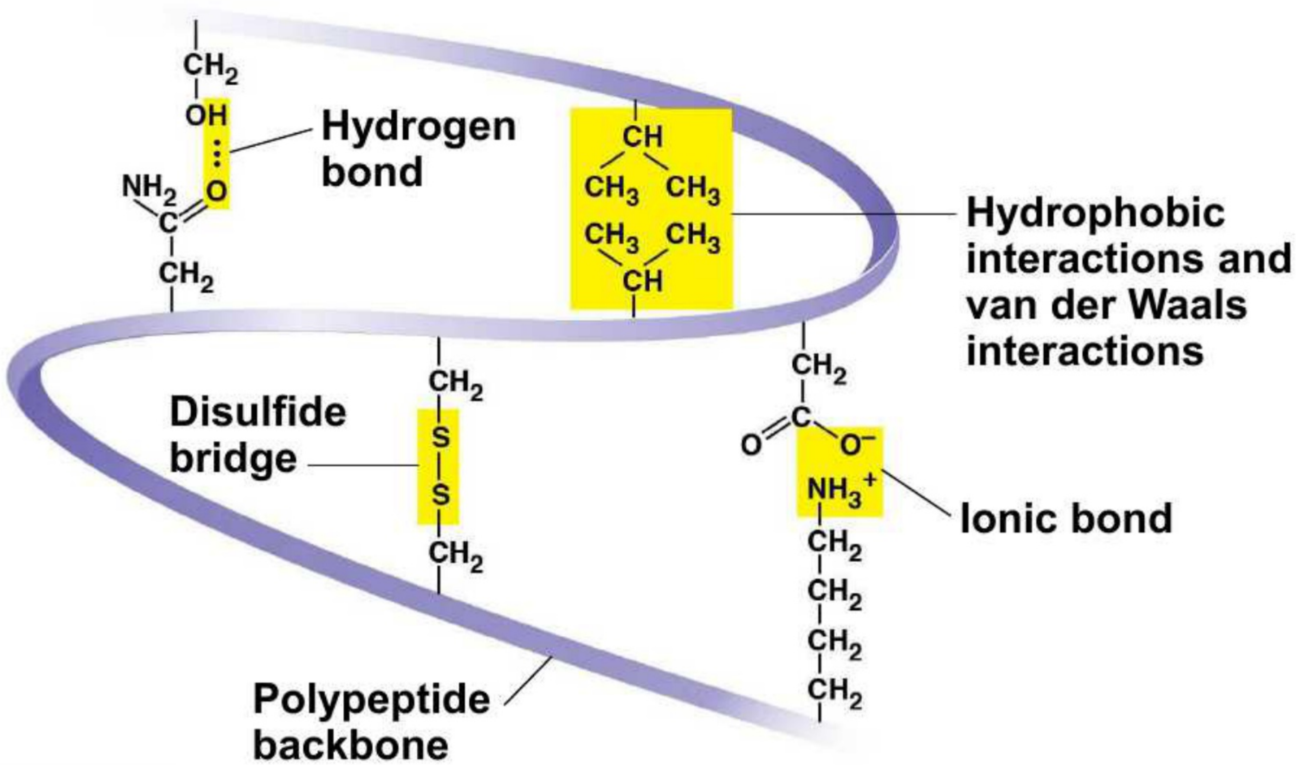


Figure 3.22-4

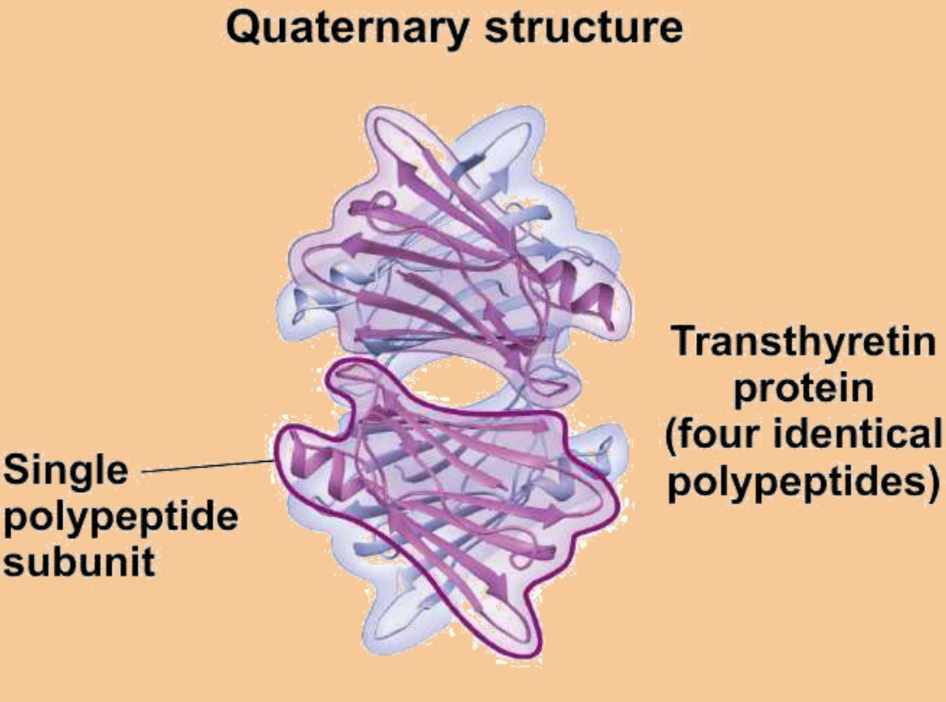
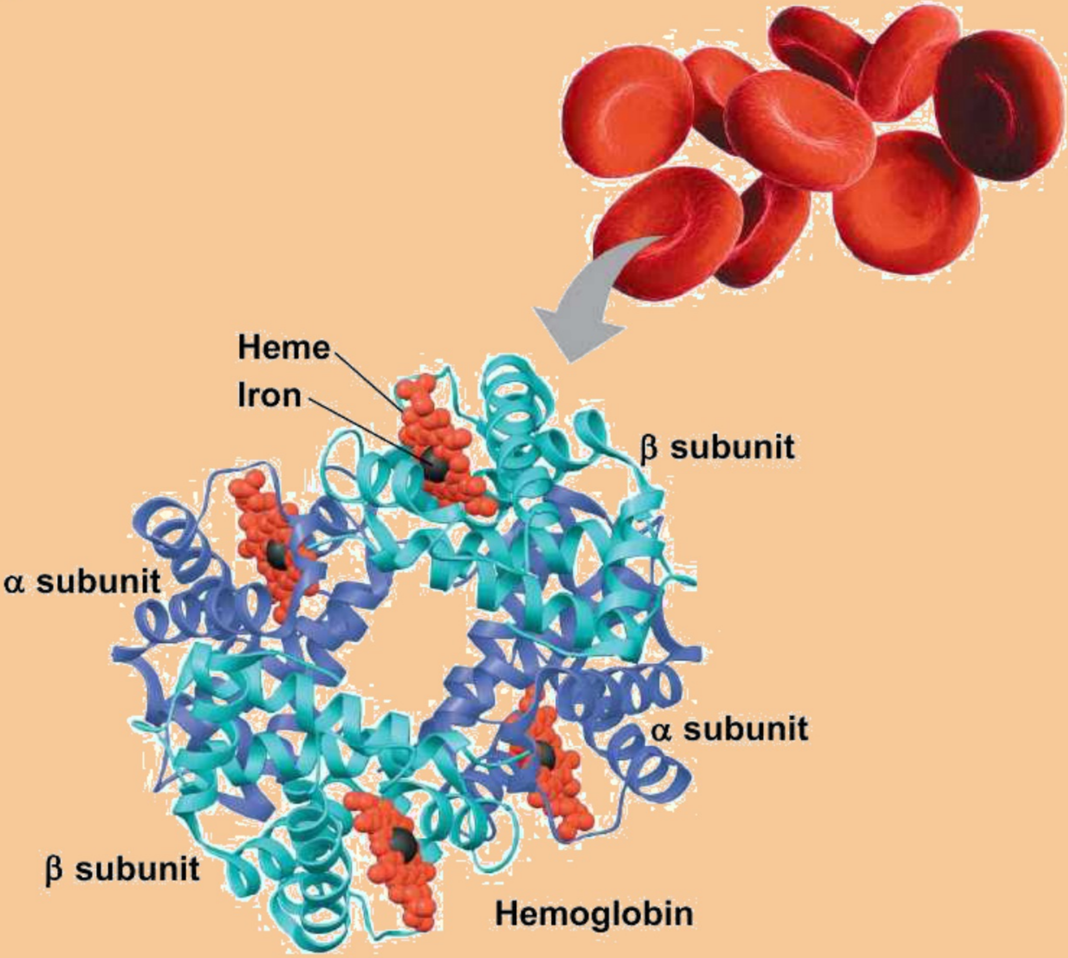

Quaternary structure
Transthyretin protein (four identical polypeptides)
Single polypeptide subunit

Figure 3.22-4a

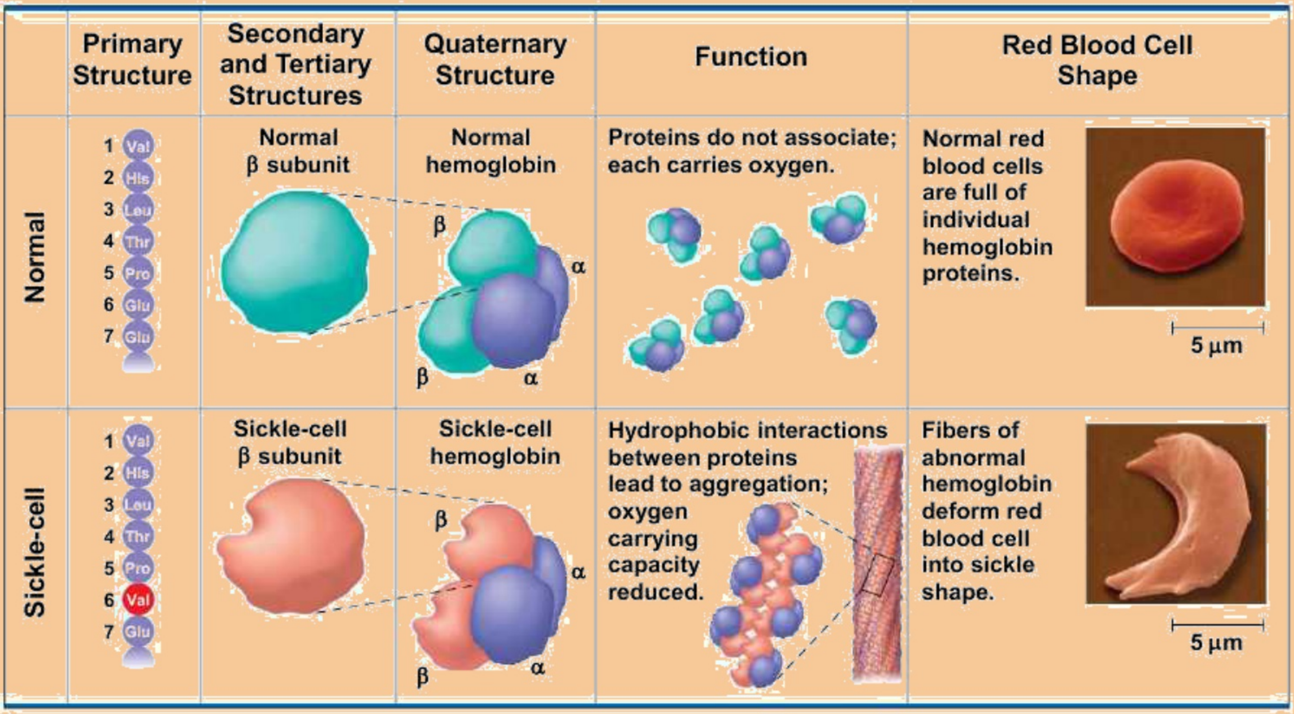
Figure 3.22-4b



Sickle-Cell Disease: A Change in Primary Structure

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

Figure 3.23


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

What Determines Protein Structure?

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

Figure 3.24-s2

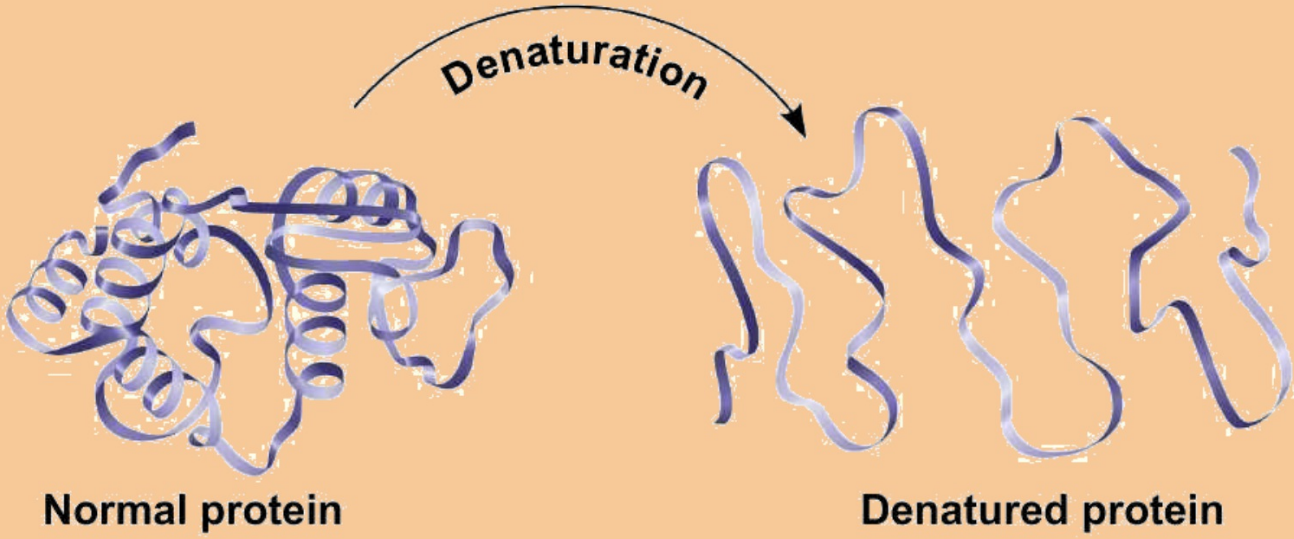
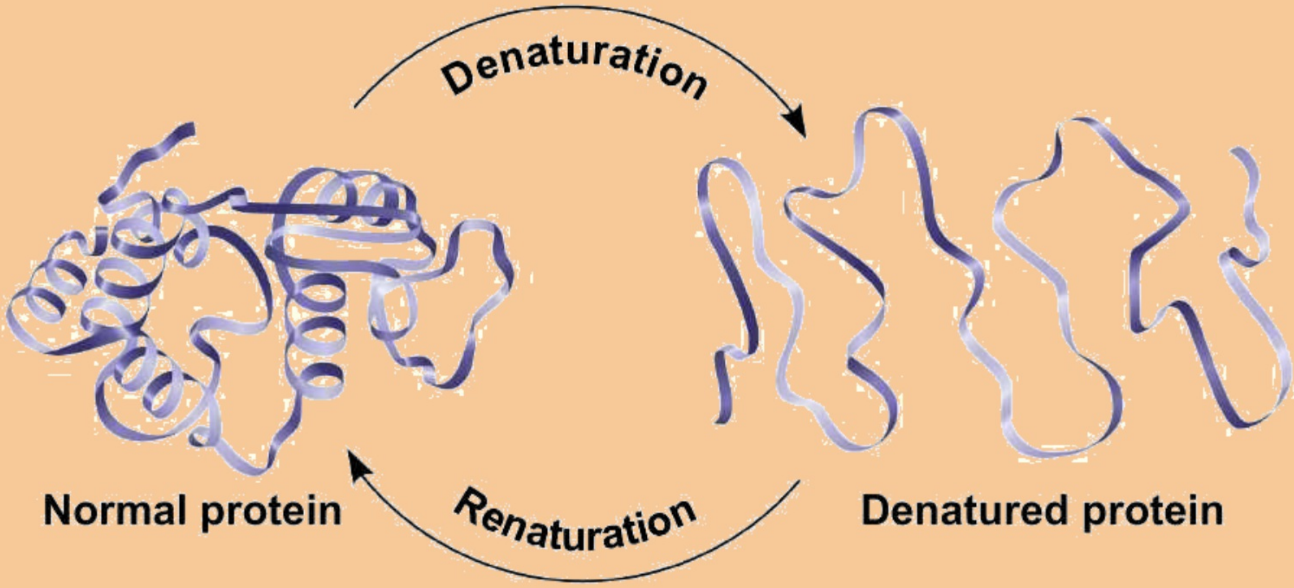


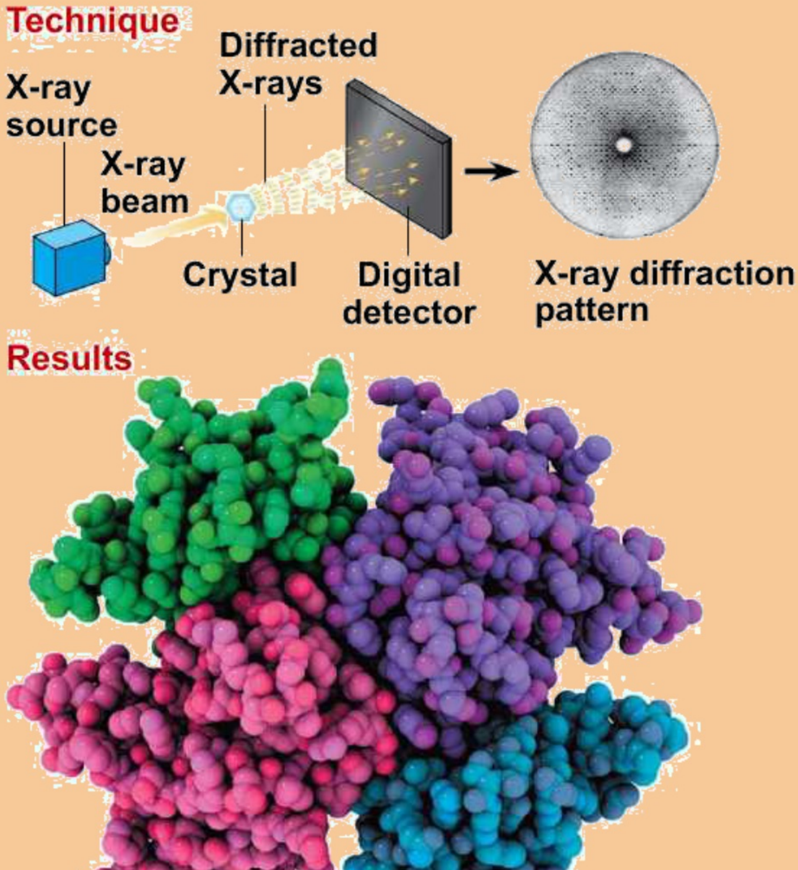
Figure 3.24-s3



Protein Folding in the Cell

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

Figure 3.25


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

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

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

The Roles of Nucleic Acids

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

Figure 3.26-s1

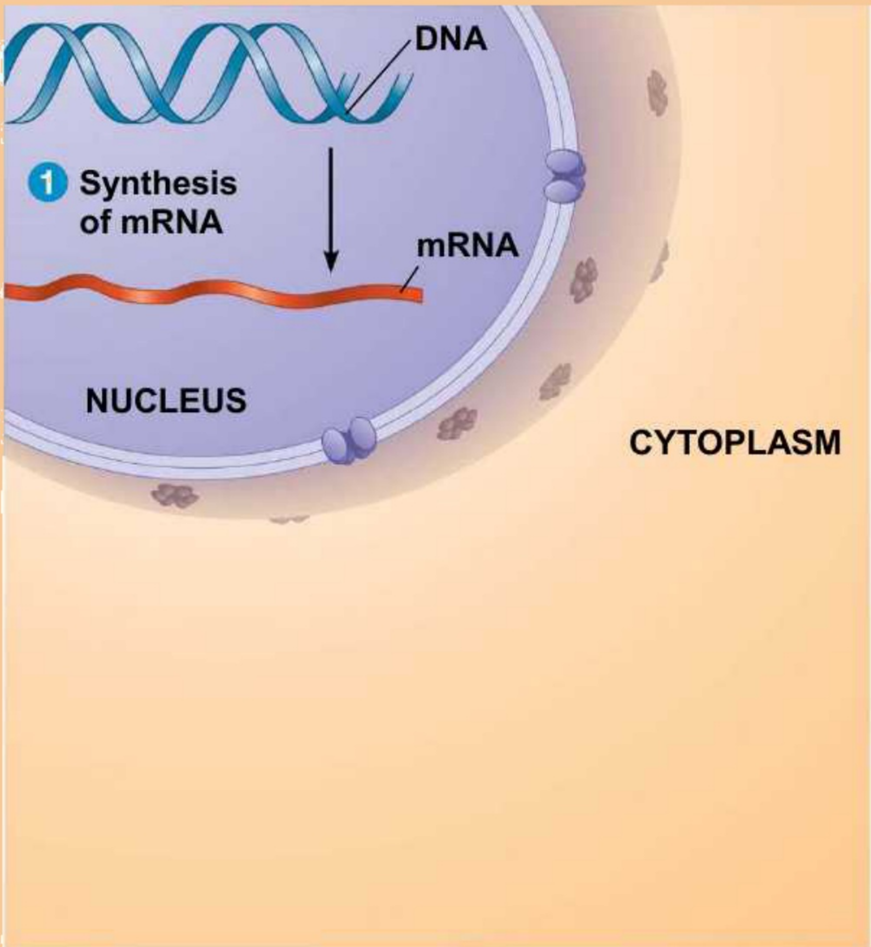


Figure 3.26-s2

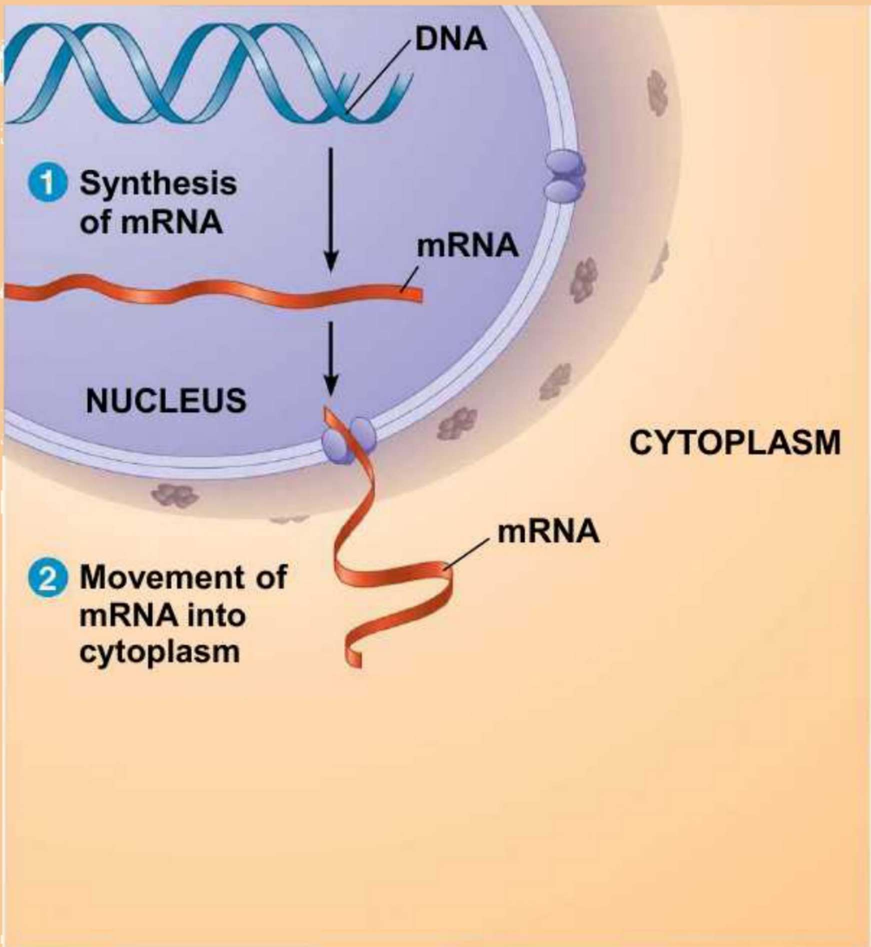
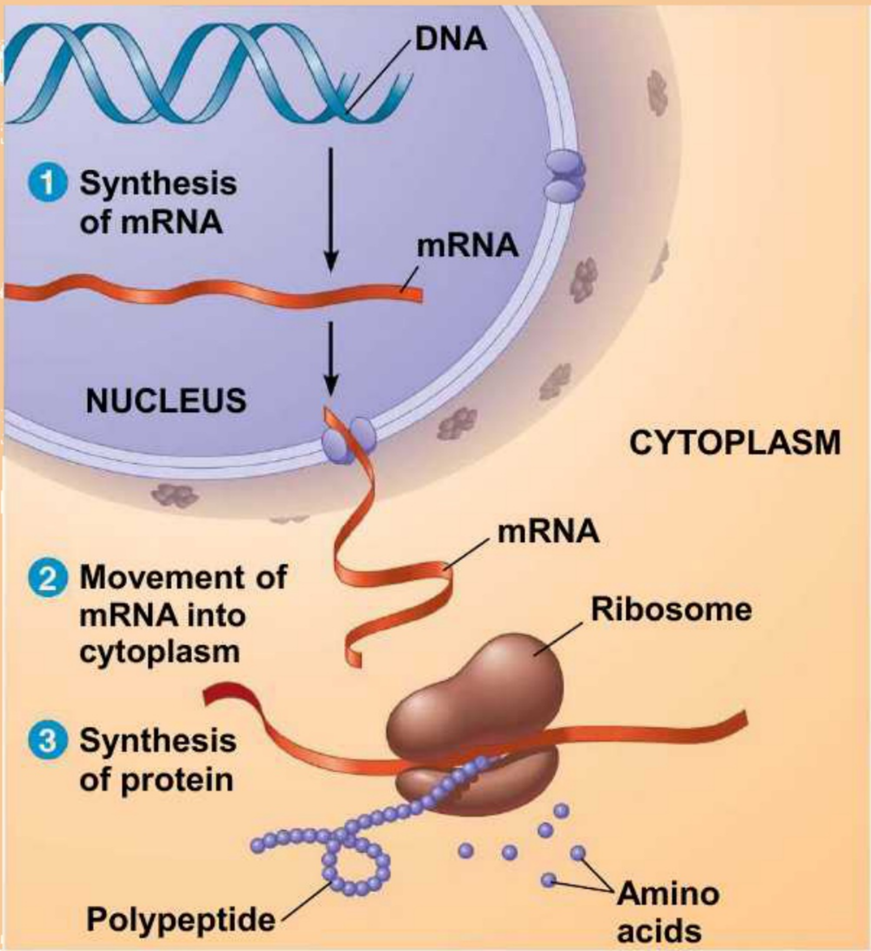


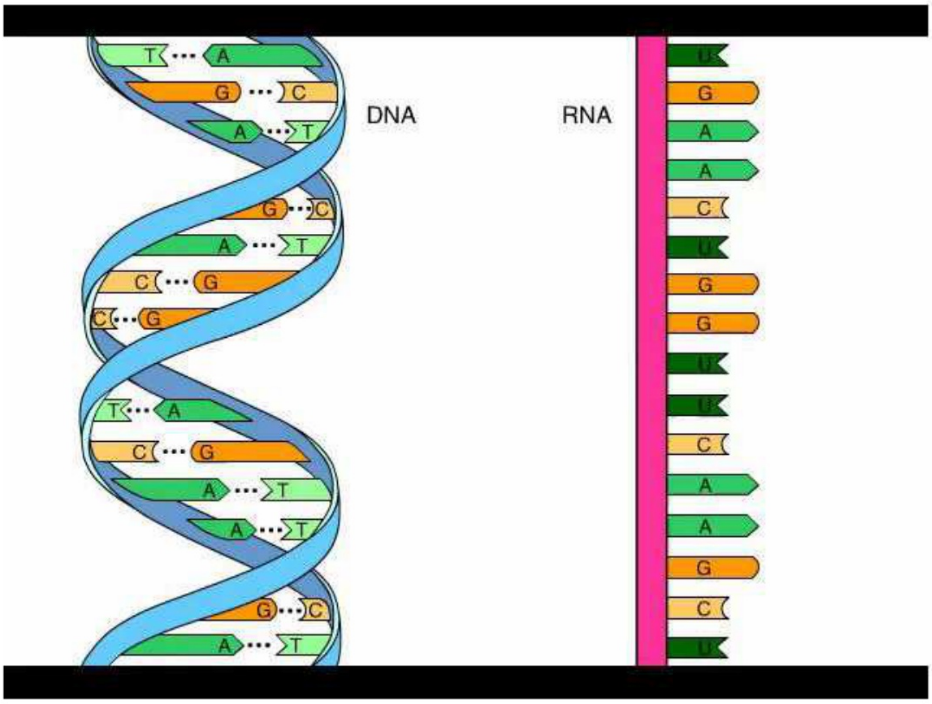
Figure 3.26-s3



The Components of Nucleic Acids

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

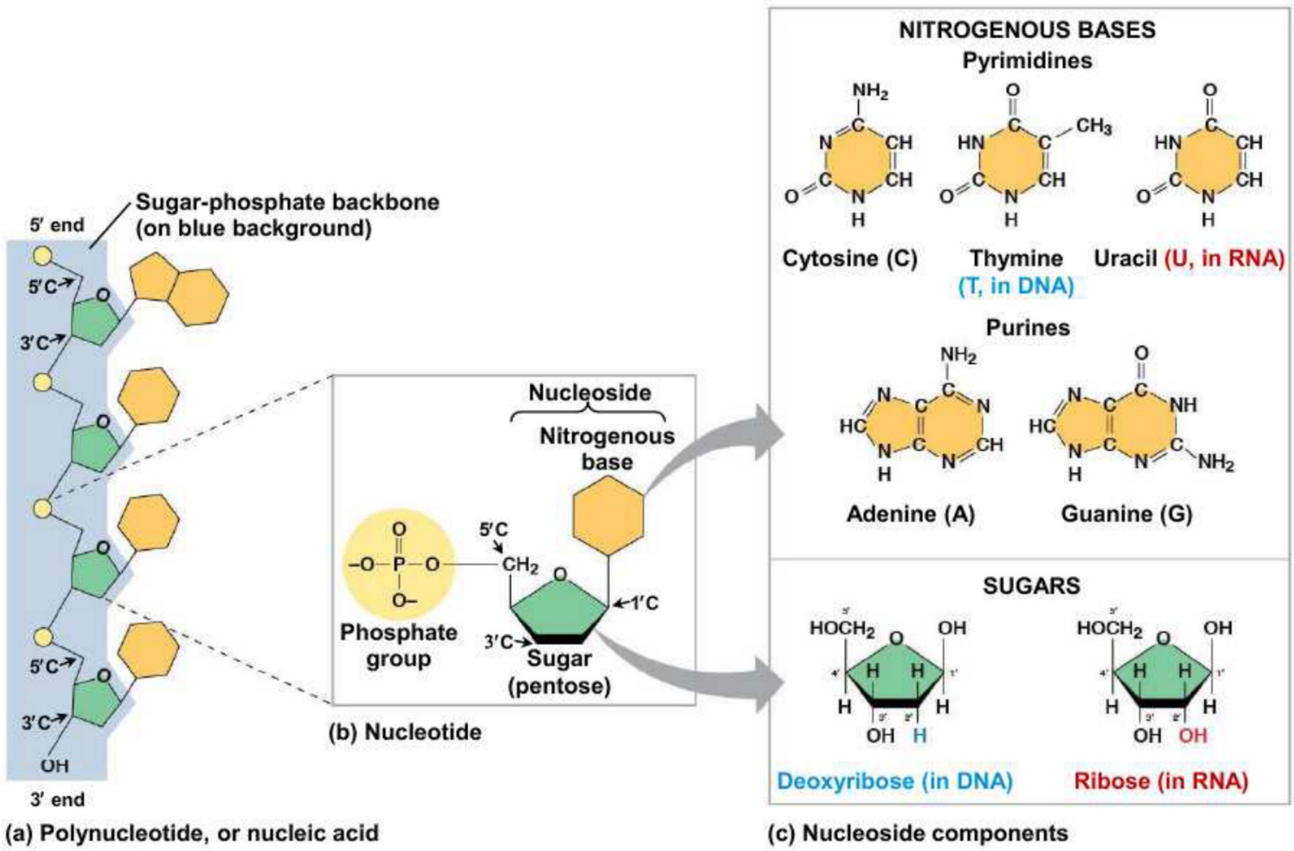
Animation: DNA and RNA Structure



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

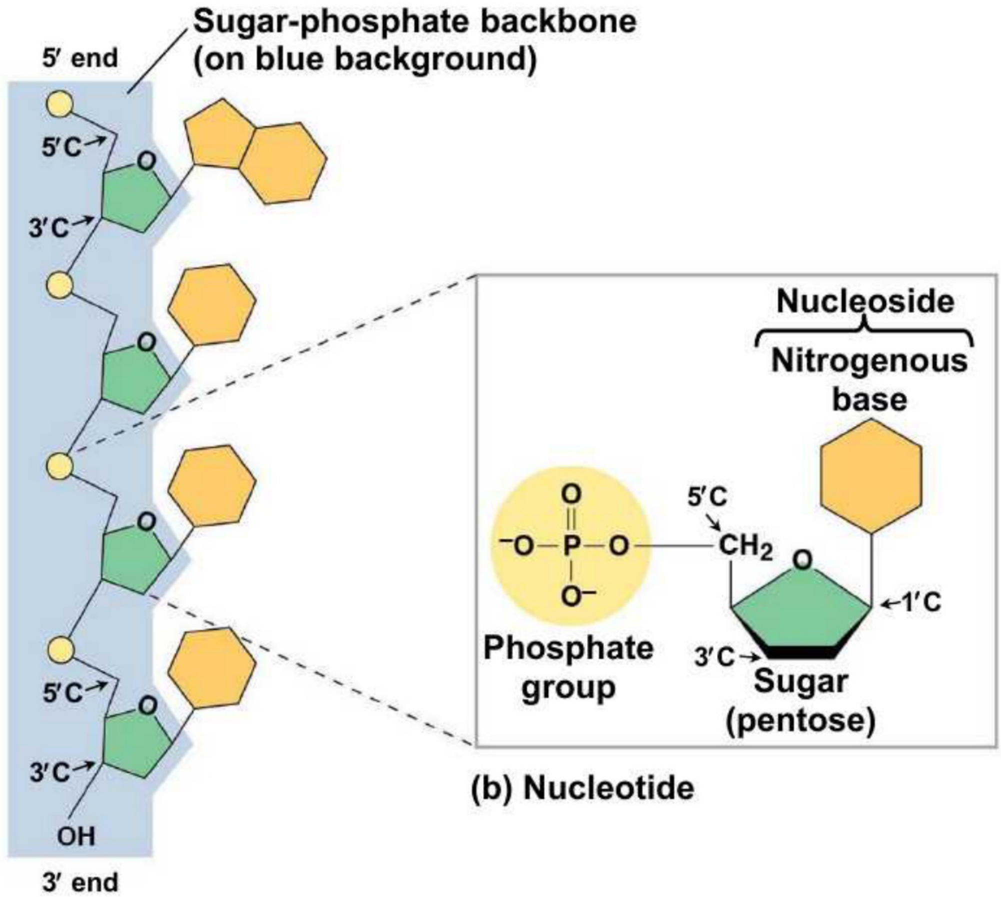
- The sugar in DNA is **deoxyribose**; in RNA it is **ribose**
- A prime (′) is used to identify the carbon atoms in the ribose, such as the 2′ carbon or 5′ carbon
- A nucleoside with at least one phosphate attached is a nucleotide

Figure 3.27



Sugar-phosphate backbone (on blue background)
5′ end
5′C
3′C
OH
3′ end
(a) Polynucleotide, or nucleic acid
Nucleoside
Nitrogenous base
5′C
CH_2
O
1′C
3′C
Phosphate group
Sugar (pentose)
(b) Nucleotide
NITROGENOUS BASES
Pyrimidines
Cytosine (C)
Thymine (T, in DNA)
Uracil (U, in RNA)
Purines
Adenine (A)
Guanine (G)
SUGARS
Deoxyribose (in DNA)
Ribose (in RNA)
(c) Nucleoside components

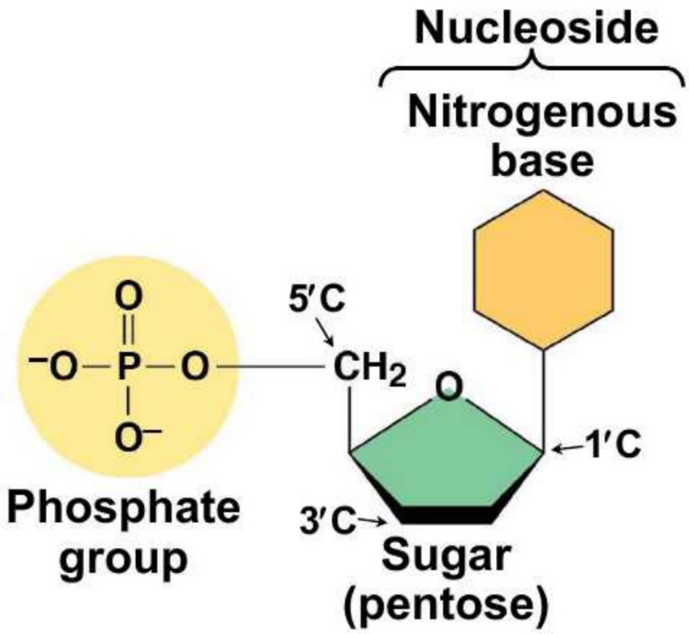
Figure 3.27-1



(b) Nucleotide

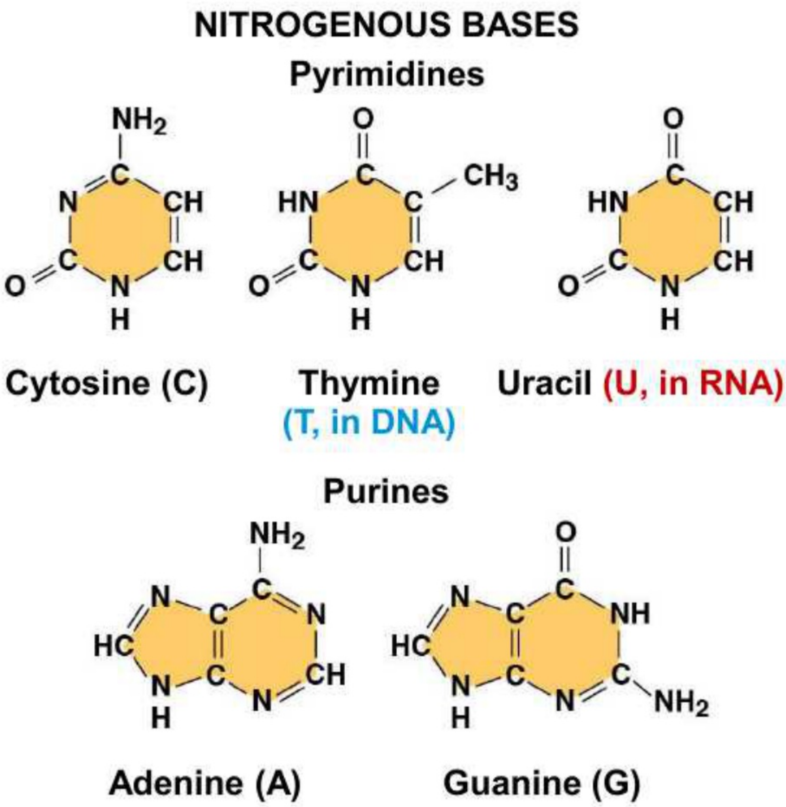
(a) Polynucleotide, or nucleic acid

Figure 3.27-2



(b) Nucleotide

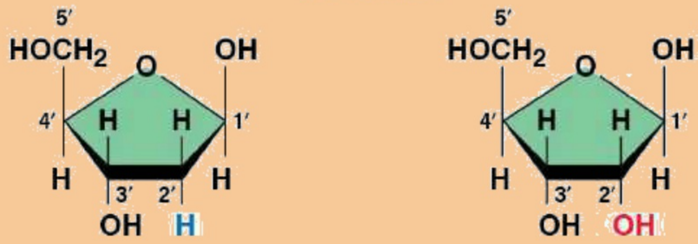
Figure 3.27-3



(c) Nucleoside components

Figure 3.27-4

SUGARS



Deoxyribose (in DNA)

Ribose (in RNA)

(c) Nucleoside components

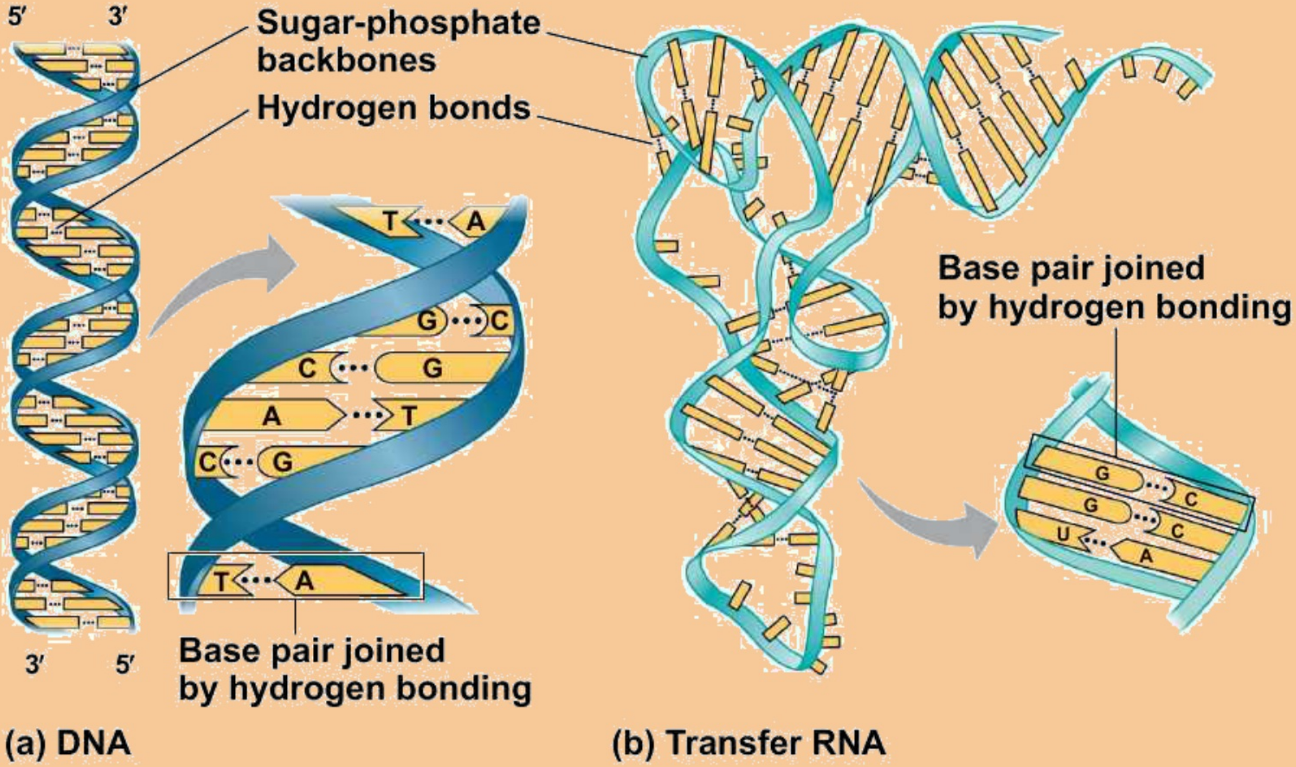
Nucleotide Polymers

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

The Structures of DNA and RNA Molecules

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

Figure 3.28



(a) DNA

(b) Transfer RNA

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

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

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

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

Figure 3.30

MAKE CONNECTIONS: Contributions of Genomics and Proteomics to Biology