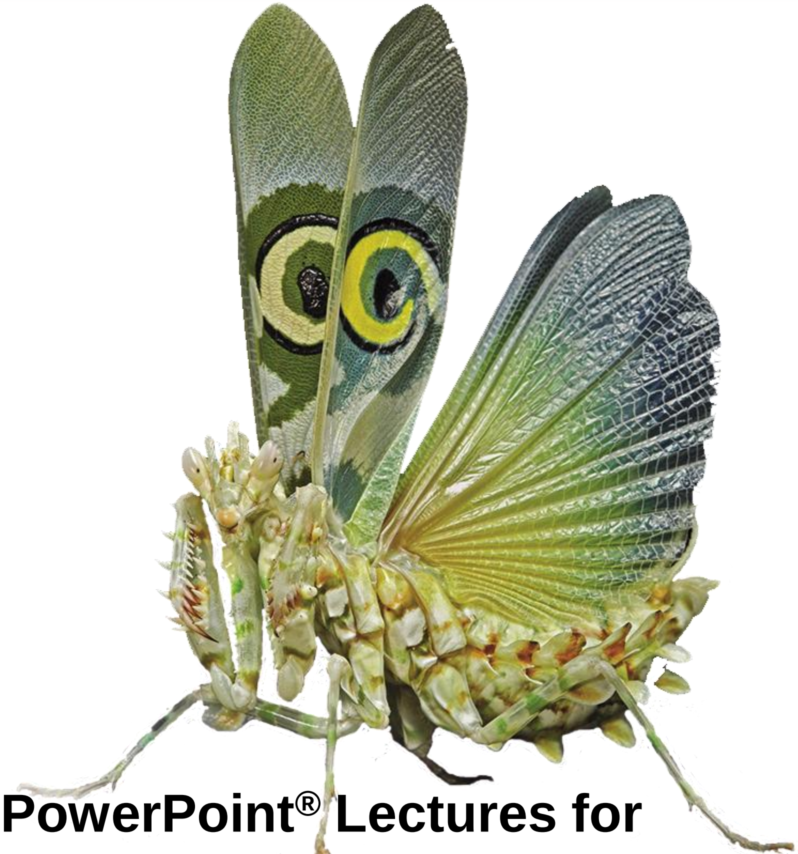
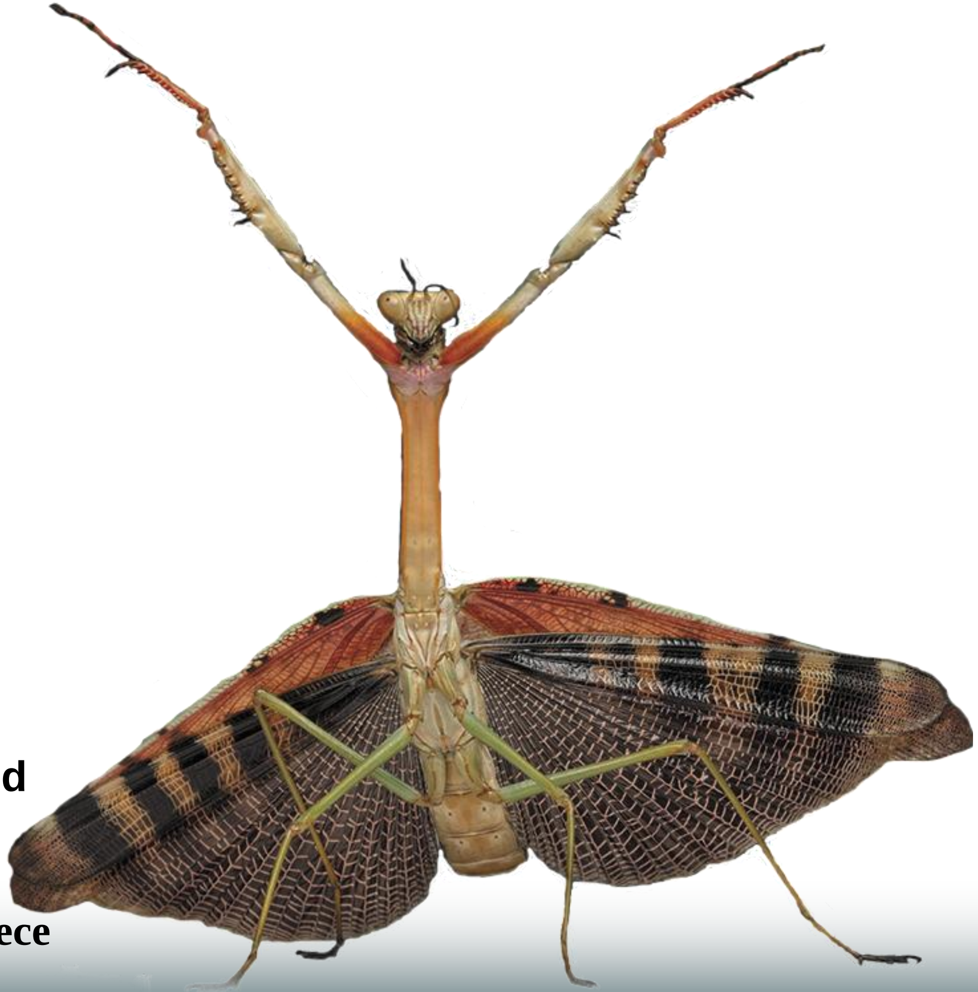
Chapter 3

The Molecules of Life





PowerPoint® Lectures for
***Campbell Essential Biology,* Fifth Edition, and**
Campbell Essential Biology with Physiology,
Fourth Edition

– Eric J. Simon, Jean L. Dickey, and Jane B. Reece

Lectures by Edward J. Zalisko

Biology and Society: Got Lactose?

- Lactose is the main sugar found in milk.
- Lactose intolerance is the inability to properly digest lactose.
  - Instead of lactose being broken down and absorbed in the small intestine,
  - lactose is broken down by bacteria in the large intestine, producing gas and discomfort.

Biology and Society: Got Lactose?

- Lactose intolerance can be addressed by
  - avoiding foods with lactose or
  - consuming lactase pills along with food.

Figure 3.0

ORGANIC COMPOUNDS

- A cell is mostly water.
- The rest of the cell consists mainly of carbon-based molecules.
- Carbon forms large, complex, and diverse molecules necessary for life’s functions.
- **Organic compounds** are carbon-based molecules.

Carbon Chemistry

- Carbon is a versatile atom.
  - It has four electrons in an outer shell that holds eight electrons.
  - Carbon can share its electrons with other atoms to form up to four covalent bonds.

Carbon Chemistry

- Carbon can use its bonds to
  - attach to other carbons and
  - form an endless diversity of carbon skeletons varying in size and branching pattern.

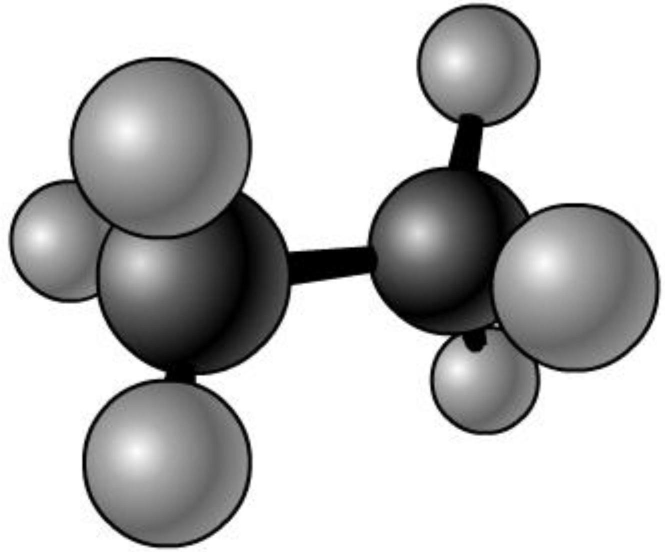
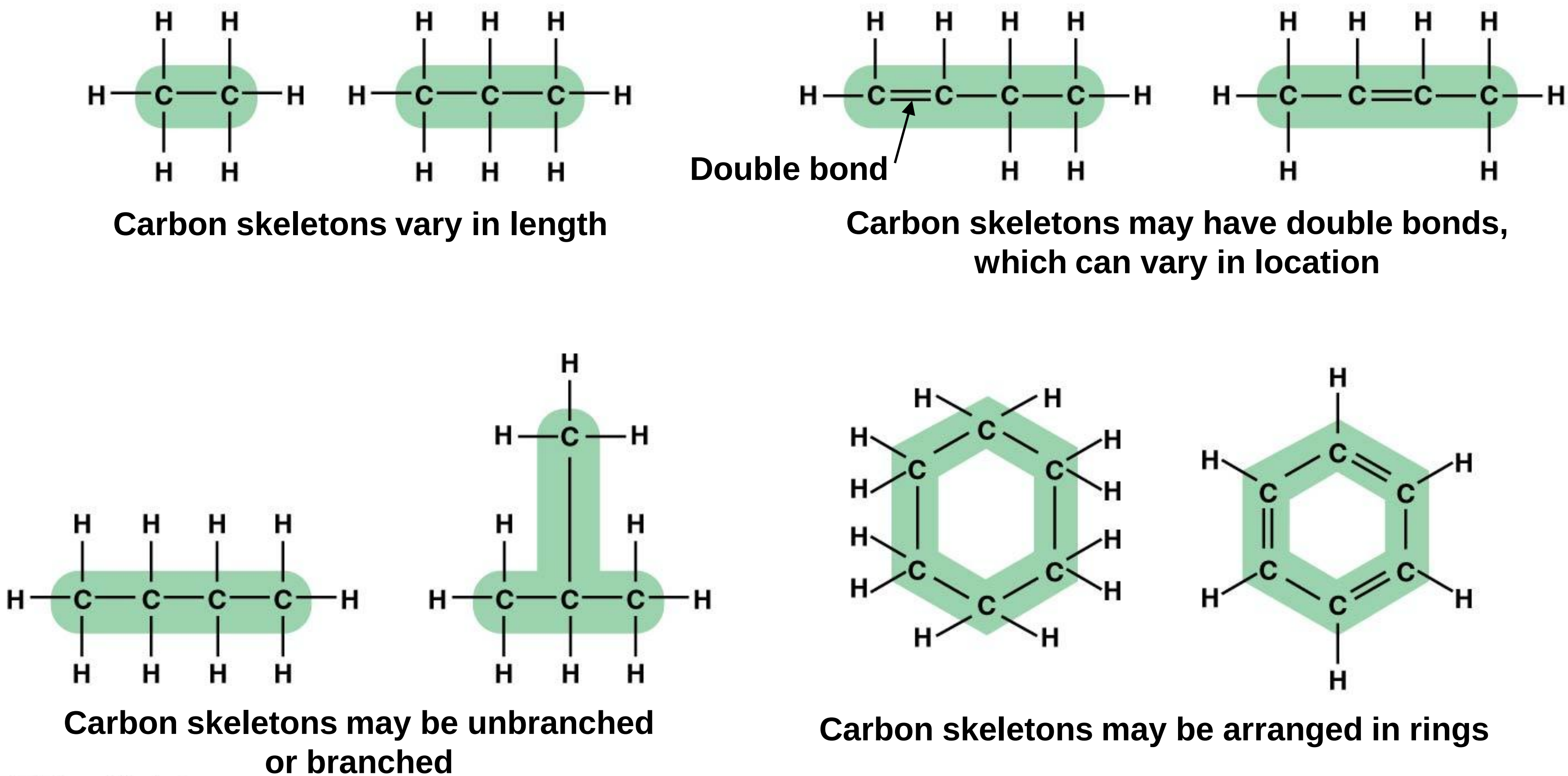


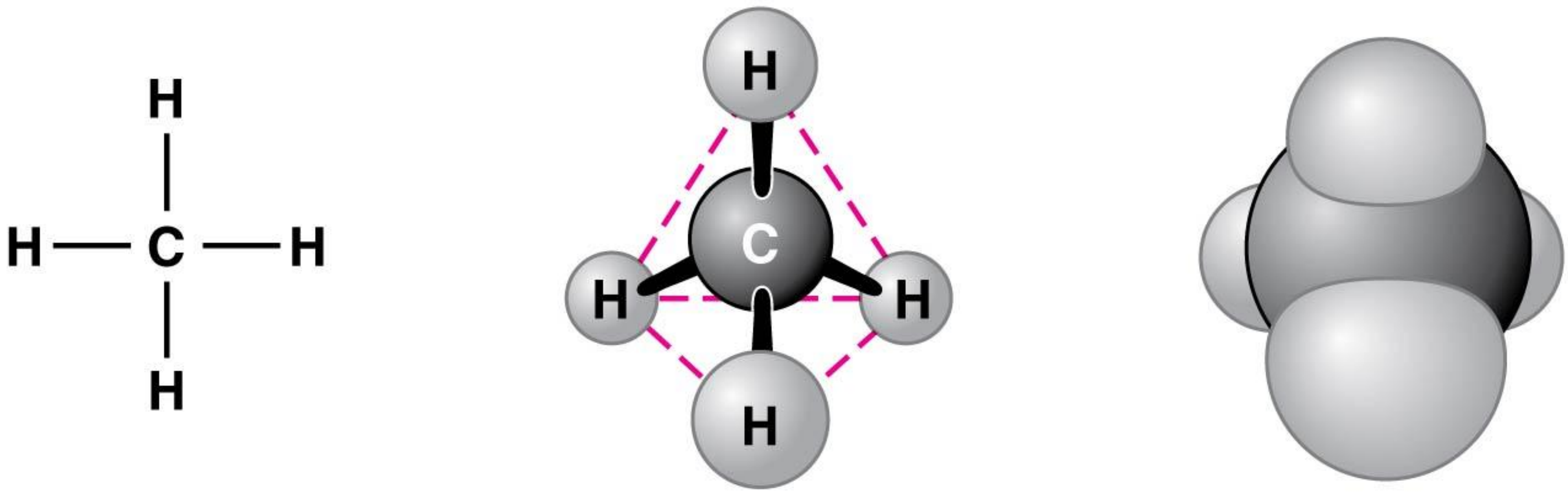
Figure 3.1


Double bond
Carbon skeletons vary in length
Carbon skeletons may have double bonds, which can vary in location
Carbon skeletons may be unbranched or branched
Carbon skeletons may be arranged in rings

Carbon Chemistry

- The simplest organic compounds are **hydrocarbons,** which contain only carbon and hydrogen atoms.
- The simplest hydrocarbon is methane, a single carbon atom bonded to four hydrogen atoms.

Figure 3.2



Structural formula **Ball-and-stick model** **Space-filling model**

Carbon Chemistry

- Larger hydrocarbons form fuels for engines.
- Hydrocarbons of fat molecules are important fuels for our bodies.

Figure 3.3

Octane **Dietary fat**

Carbon Chemistry

- Each type of organic molecule has a unique three-dimensional shape.
- The shapes of organic molecules relate to their functions.
- The unique properties of an organic compound depend on
  - its carbon skeleton and
  - the atoms attached to the skeleton.

Carbon Chemistry

- The groups of atoms that usually participate in chemical reactions are called **functional groups**. Two common examples are
  - hydroxyl groups (-OH) and
  - carboxyl groups (-COOH).
- Many biological molecules have two or more functional groups.

Giant Molecules from Smaller Building Blocks

- On a molecular scale, many of life's molecules are gigantic, earning the name **macromolecules**.
- Three categories of macromolecules are
  1. carbohydrates,
  2. proteins, and
  3. nucleic acids.

Giant Molecules from Smaller Building Blocks

- Most macromolecules are polymers.
- **Polymers** are **made** by stringing together many smaller molecules called **monomers**.
- A **dehydration reaction**
  - links two monomers together and
  - removes a molecule of water.

Giant Molecules from Smaller Building Blocks

- Organisms also have to break down macromolecules.
- Digestion breaks down macromolecules to make monomers available to your cells.

Giant Molecules from Smaller Building Blocks

- **Hydrolysis**
  - breaks bonds between monomers,
  - adds a molecule of water, and
  - reverses the dehydration reaction.

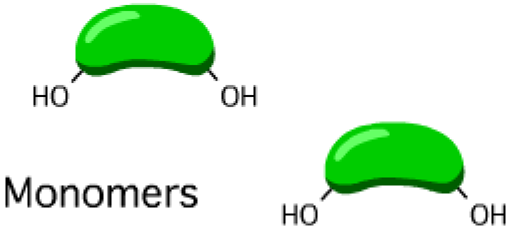

HO
OH
Monomers
HO
OH

Figure 3.UN01

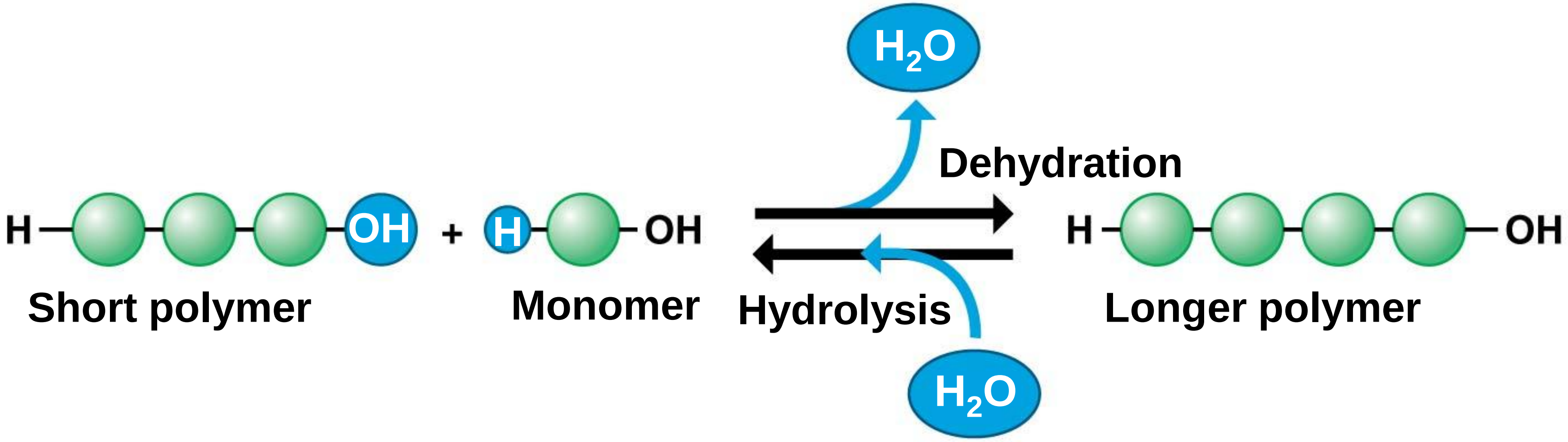
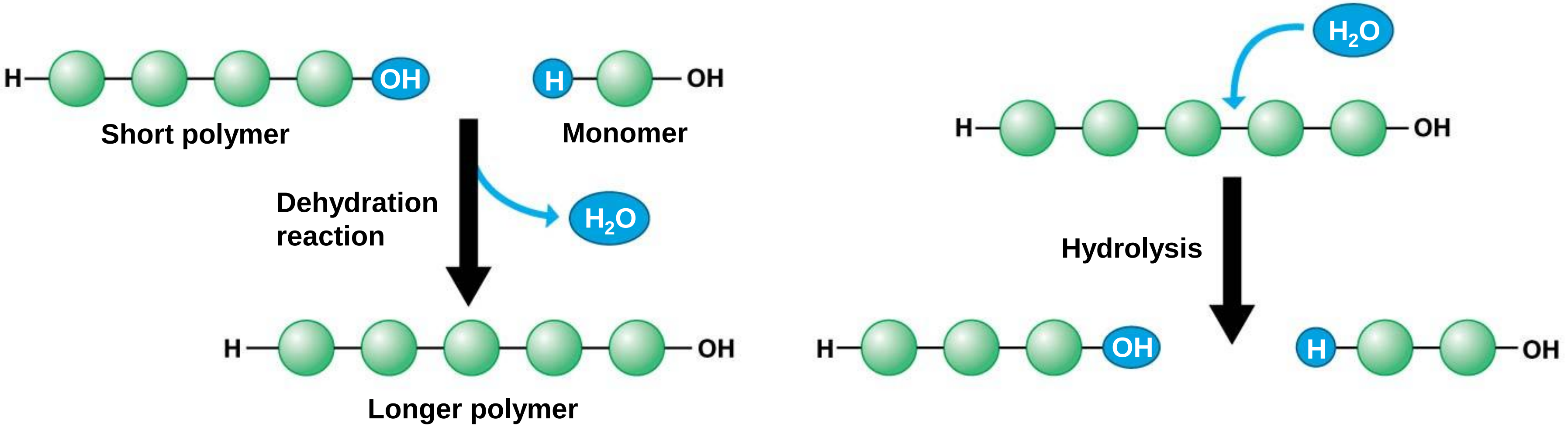


Figure 3.4



(a) Building a polymer chain

(b) Breaking a polymer chain

LARGE BIOLOGICAL MOLECULES

- There are four categories of large biological molecules:
  - carbohydrates,
  - lipids,
  - proteins, and
  - nucleic acids.

Carbohydrates

- **Carbohydrates** include sugars and polymers of sugar. They include
  - small sugar molecules in energy drinks and
  - long starch molecules in spaghetti and French fries.

Carbohydrates

- In animals, carbohydrates are
  - a primary source of dietary energy and
  - raw material for manufacturing other kinds of organic compounds.
- In plants, carbohydrates serve as a building material for much of the plant body.

Monosaccharides

- **Monosaccharides** are
  - simple sugars that cannot be broken down by hydrolysis into smaller sugars and
  - the monomers of carbohydrates.
- Common examples are
  - glucose in sports drinks and
  - fructose found in fruit.

Monosaccharides

- Both glucose and fructose are found in honey.
- Glucose and fructose are **isomers**, molecules that have the same molecular formula but different structures.

Structural isomers

Geometric isomers

Enantiomers

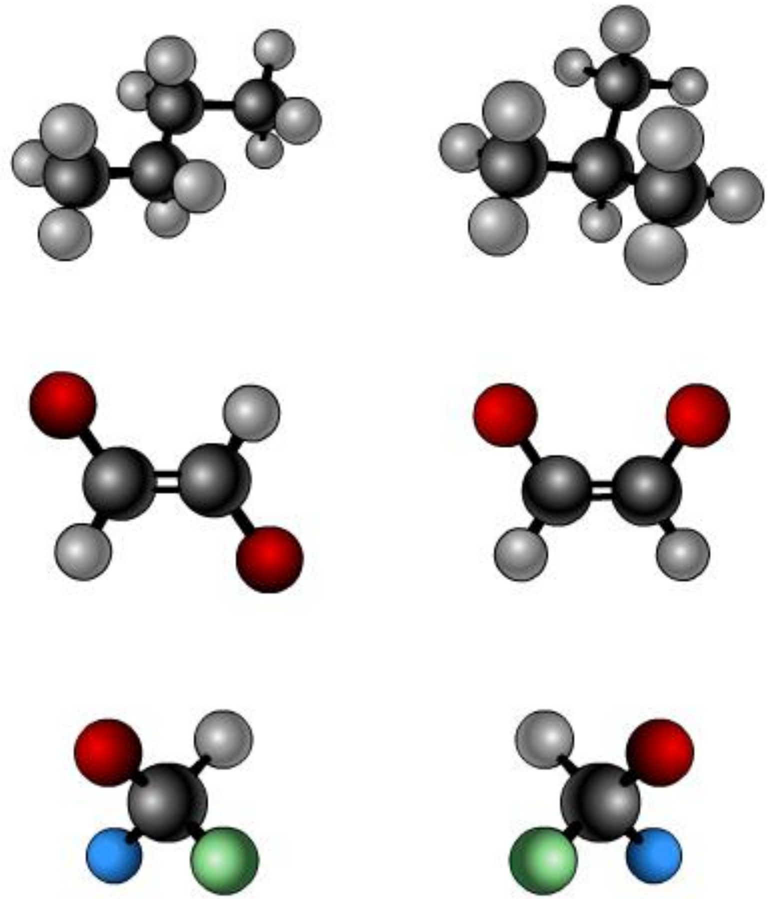


Figure 3.5

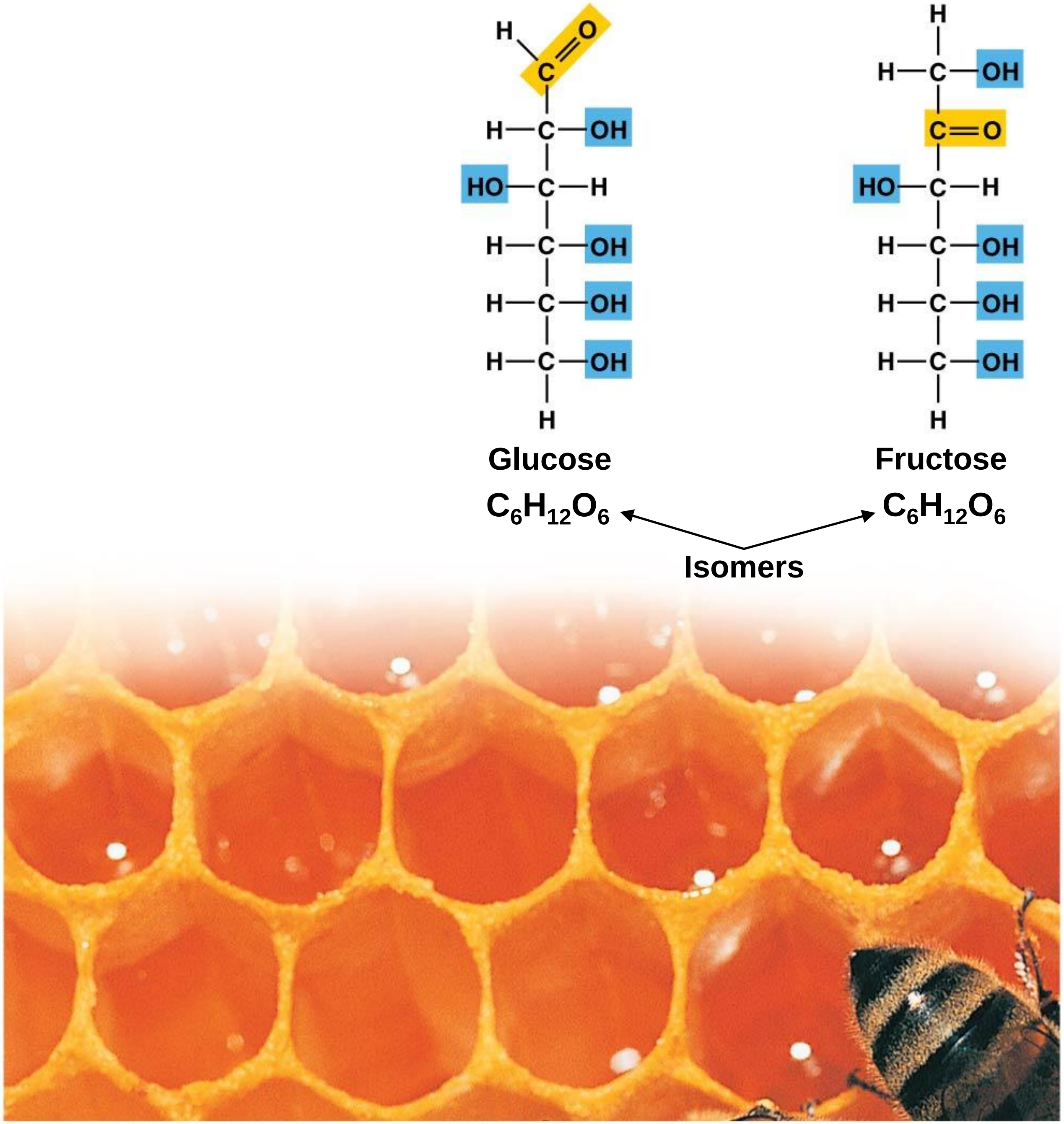
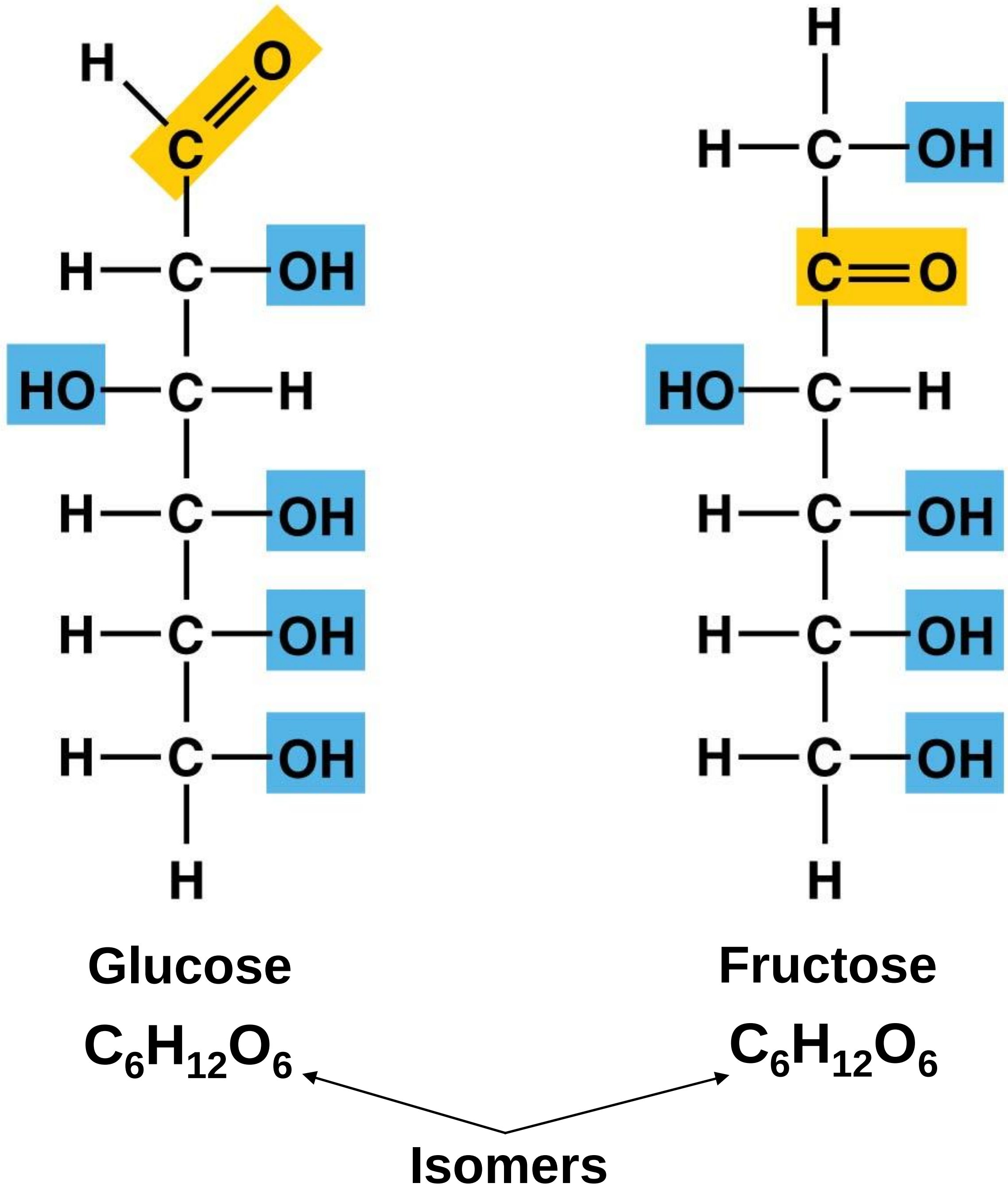


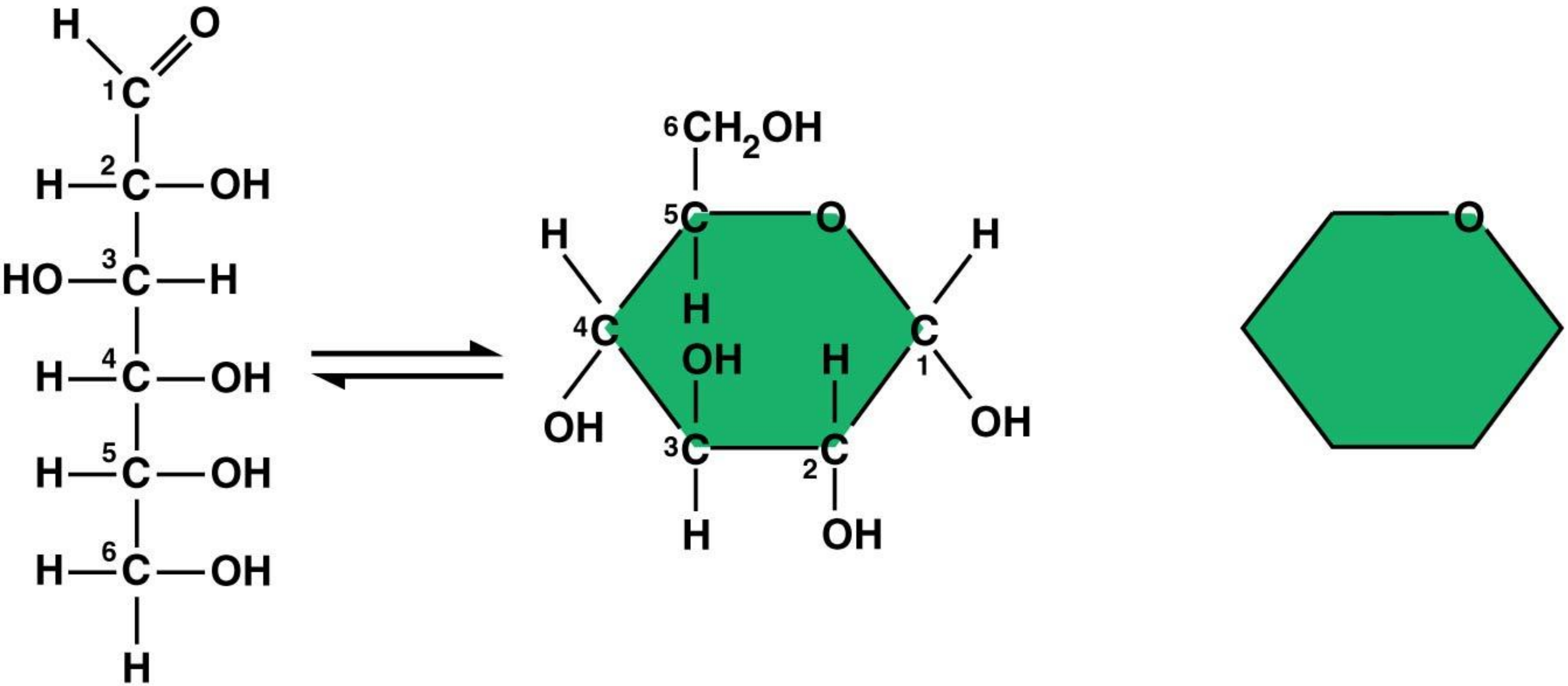
Figure 3.5a



Monosaccharides

- Monosaccharides are the main fuels for cellular work.
- In water, many monosaccharides form rings.

Figure 3.6



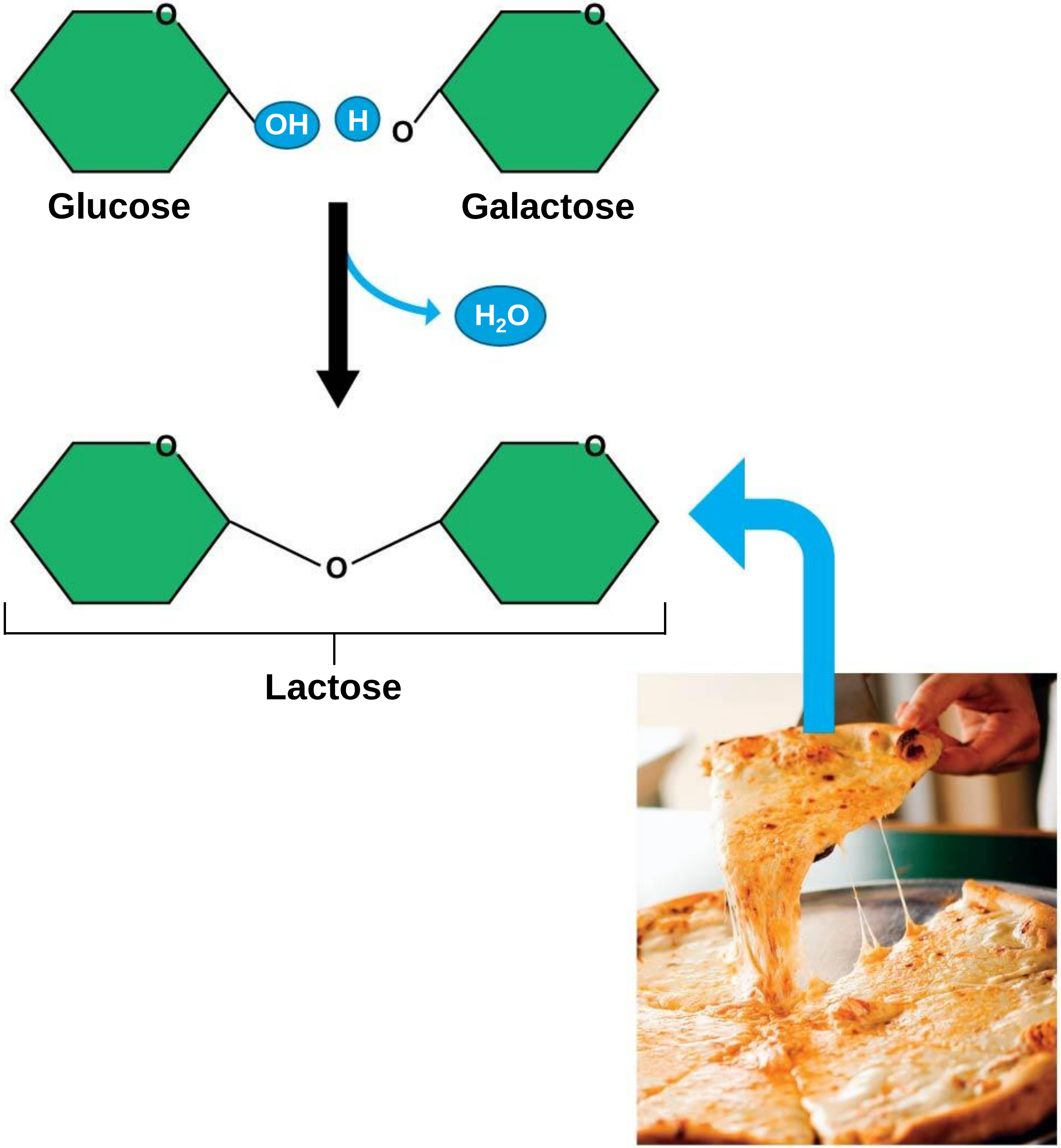
(a) Linear and ring structures

(b) Abbreviated ring structure

Disaccharides

- A **disaccharide** is
  - a double sugar,
  - constructed from two monosaccharides, and
  - formed by a dehydration reaction.

Figure 3.7



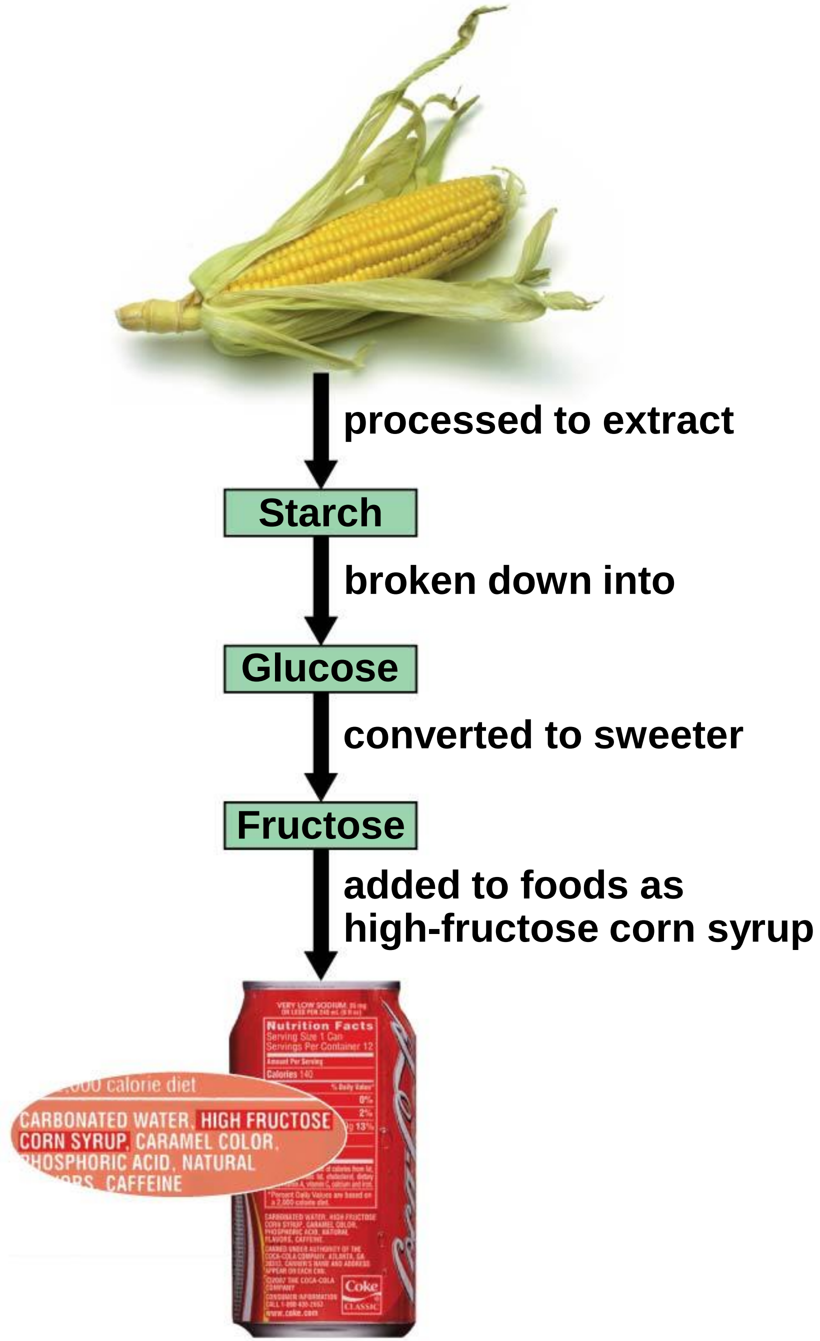
Disaccharides

- Disaccharides include
  - lactose in milk,
  - maltose in beer, malted milk shakes, and malted milk ball candy, and
  - sucrose in table sugar.

Disaccharides

- Sucrose is
  - the main carbohydrate in plant sap and
  - rarely used as a sweetener in processed foods in the United States.
- High-fructose corn syrup is made by a commercial process that converts
  - natural glucose in corn syrup to
  - much sweeter fructose.

Figure 3.8



processed to extract
Starch
broken down into
Glucose
converted to sweeter
Fructose
added to foods as
high-fructose corn syrup
CARBONATED WATER, HIGH FRUCTOSE
CORN SYRUP, CARAMEL COLOR,
Nutrition Facts

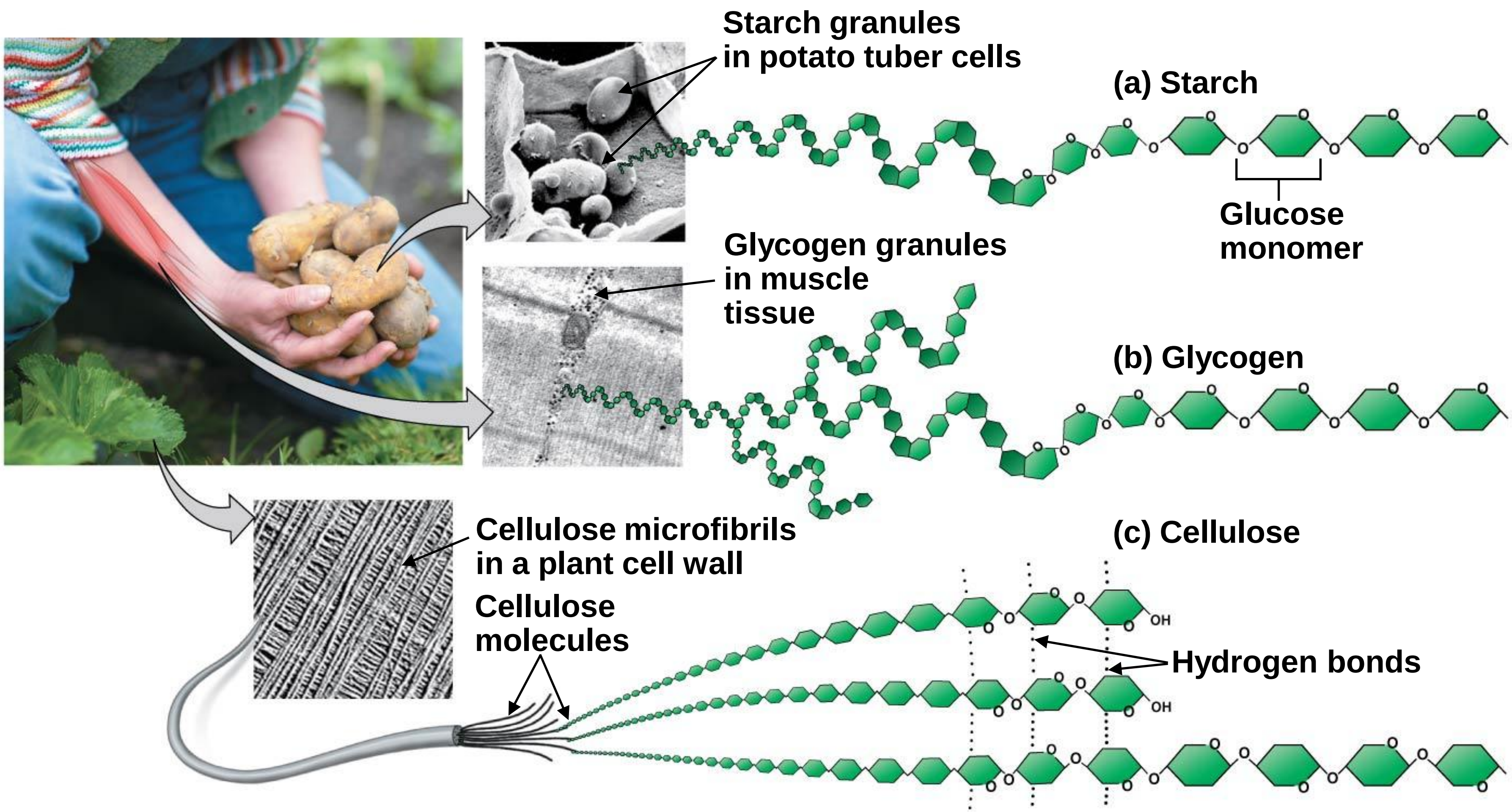
Disaccharides

- The United States is one of the world’s leading markets for sweeteners.
- The average American consumes
  - about 45 kg of sugar (about 100 lb) per year,
  - mainly as sucrose and high-fructose corn syrup.

Polysaccharides

- **Polysaccharides** are
  - complex carbohydrates
  - made of long chains of sugar units—polymers of monosaccharides.

Figure 3.9



Starch granules in potato tuber cells
(a) Starch
Glucose monomer
Glycogen granules in muscle tissue
(b) Glycogen
Cellulose microfibrils in a plant cell wall
Cellulose molecules
(c) Cellulose
Hydrogen bonds
OH

Polysaccharides

- **Starch**
  - is a familiar example of a polysaccharide,
  - is used by plant cells to store energy, and
  - consists of long strings of glucose monomers.
- Potatoes and grains are major sources of starch in our diet.

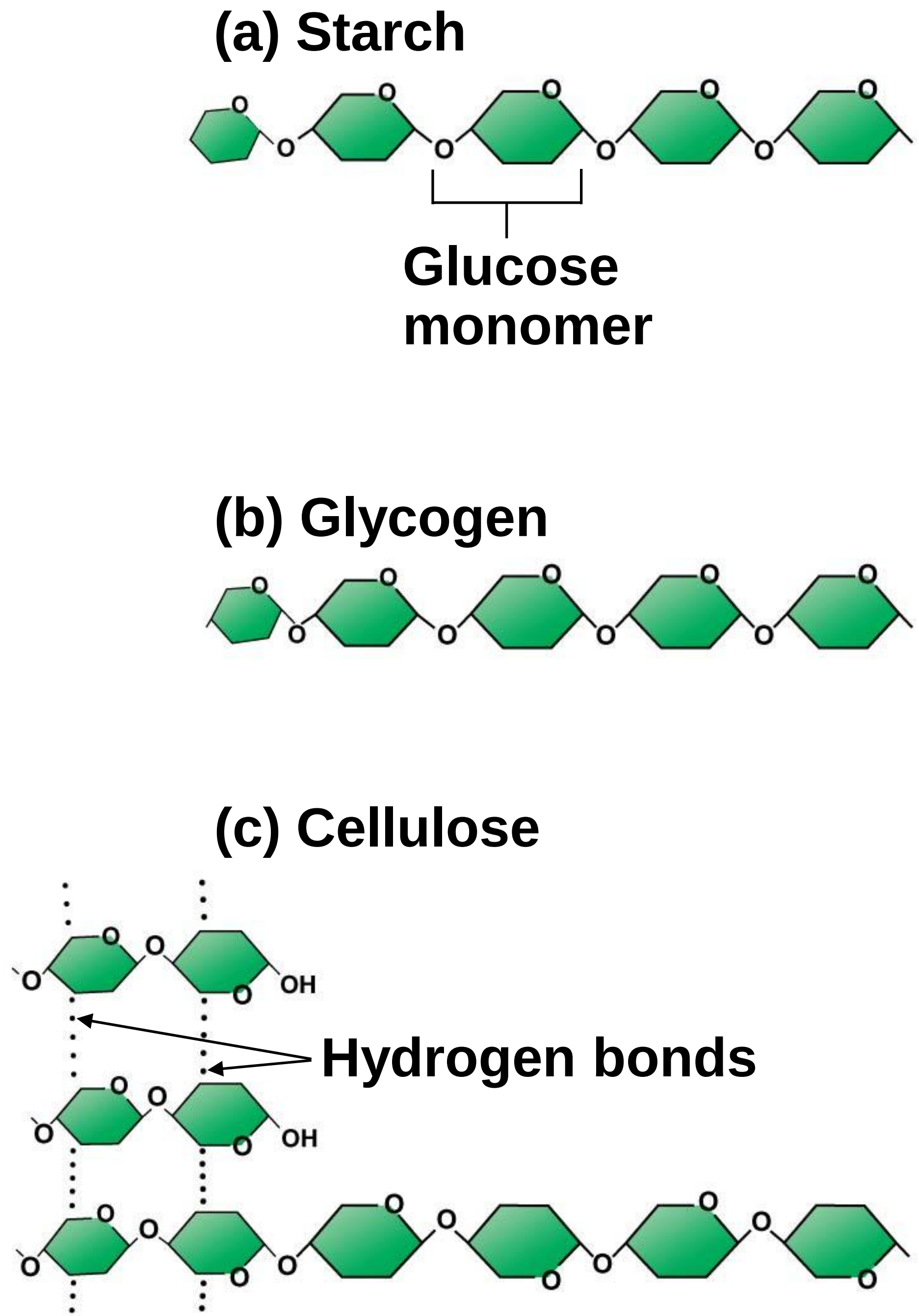
Polysaccharides

- **Glycogen** is
  - used by animals cells to store energy and
  - converted to glucose when it is needed.

Polysaccharides

- **Cellulose**
  - is the most abundant organic compound on Earth,
  - forms cable-like fibrils in the walls that enclose plant cells, and
  - cannot be broken apart by most animals.

Figure 3.9d


(a) Starch
O
Glucose monomer
(b) Glycogen
(c) Cellulose
OH
Hydrogen bonds

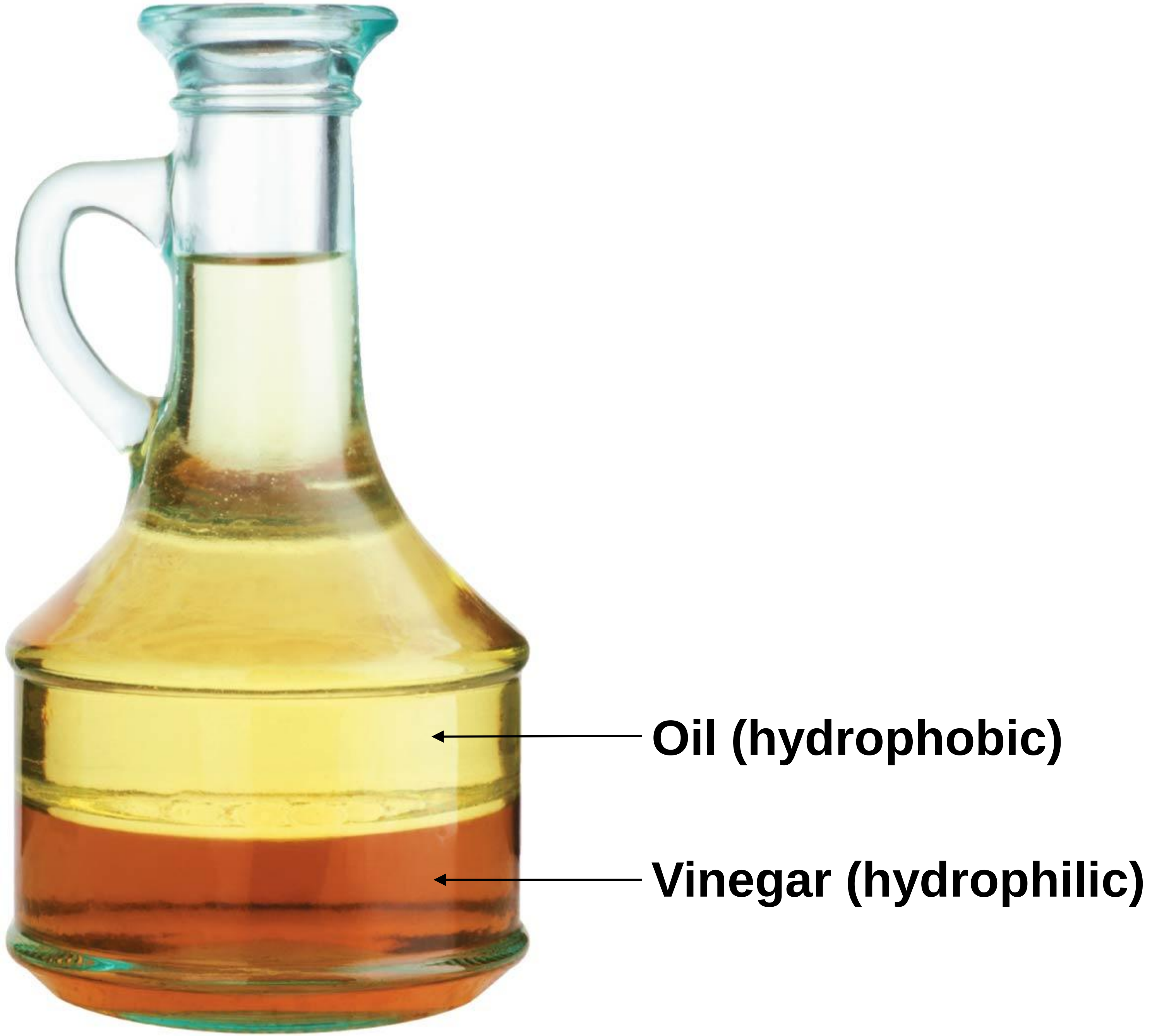
Polysaccharides

- Monosaccharides and disaccharides dissolve readily in water.
- Cellulose does not dissolve in water.
- Almost all carbohydrates are **hydrophilic**, or “water-loving,” adhering water to their surface.

Lipids

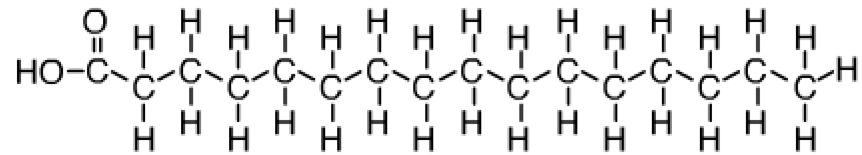
- **Lipids** are
  - neither macromolecules nor polymers and
  - **hydrophobic**, unable to mix with water.

Figure 3.10

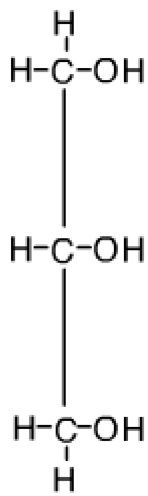


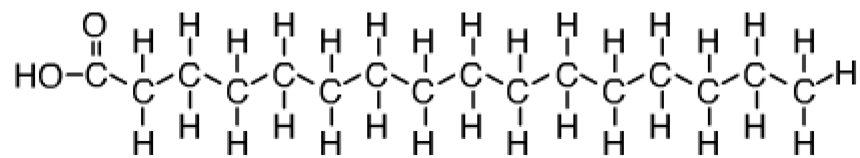
Fats

- A typical **fat**, or **triglyceride,** consists of
  - a glycerol molecule,
  - joined with three fatty acid molecules,
  - via a dehydration reaction.



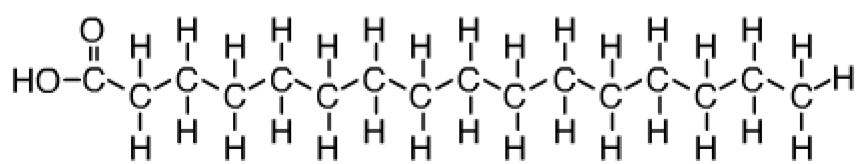
Fatty acid





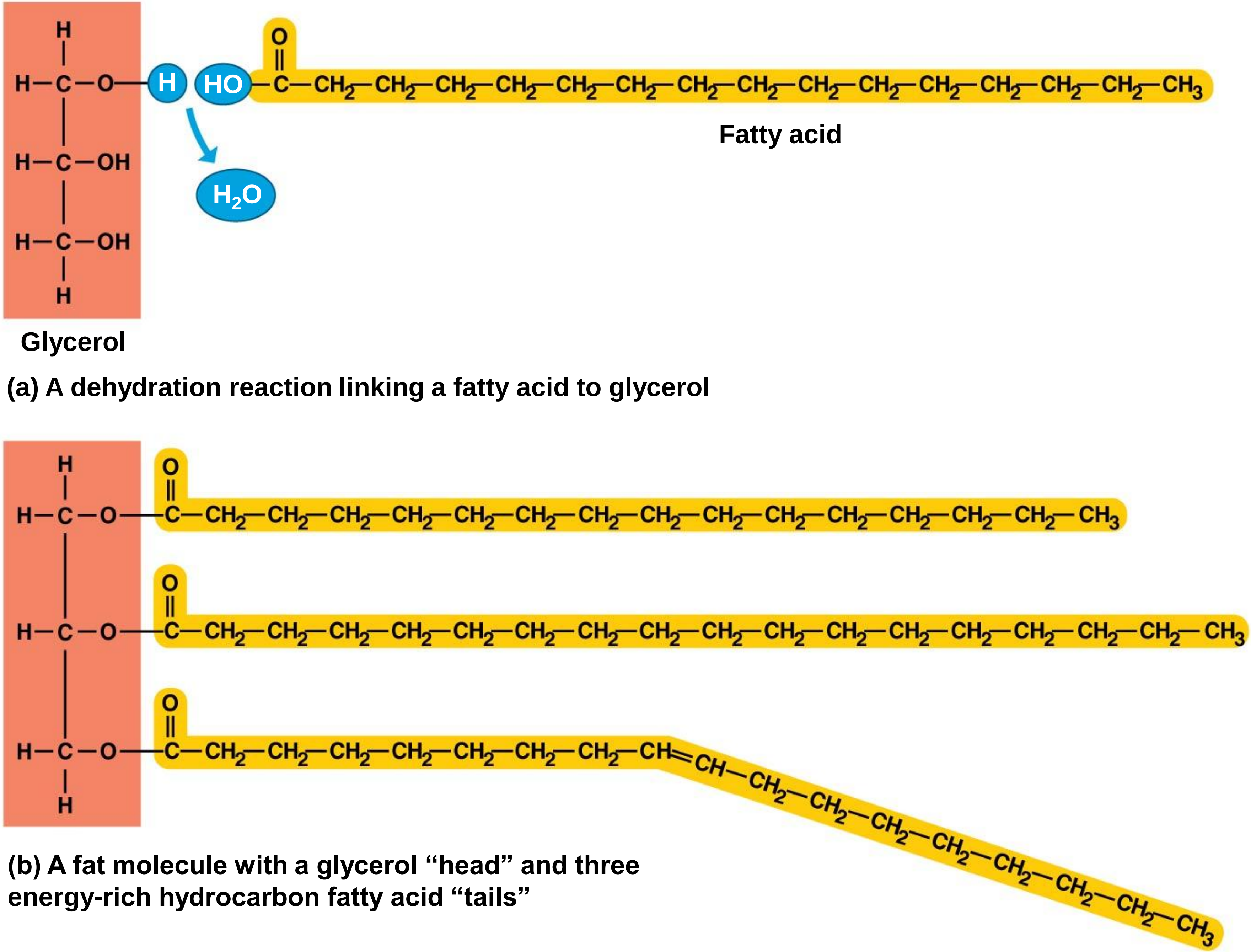
Fatty acid

Glycerol



Fatty acid

Figure 3.11



(a) A dehydration reaction linking a fatty acid to glycerol

(b) A fat molecule with a glycerol “head” and three energy-rich hydrocarbon fatty acid “tails”

Fats

- Fats perform essential functions in the human body including
  - energy storage,
  - cushioning, and
  - insulation.

Fats

- If the carbon skeleton of a fatty acid
  - has fewer than the maximum number of hydrogens, it is **unsaturated**;
  - if it has the maximum number of hydrogens, it is **saturated**.
- A saturated fat has
  - no double bonds and
  - all three of its fatty acids saturated.

Fats

- Most animal fats
  - have a high proportion of saturated fatty acids,
  - can easily stack, tending to be solid at room temperature, and
  - contribute to **atherosclerosis**, in which lipid-containing plaques build up along the inside walls of blood vessels.

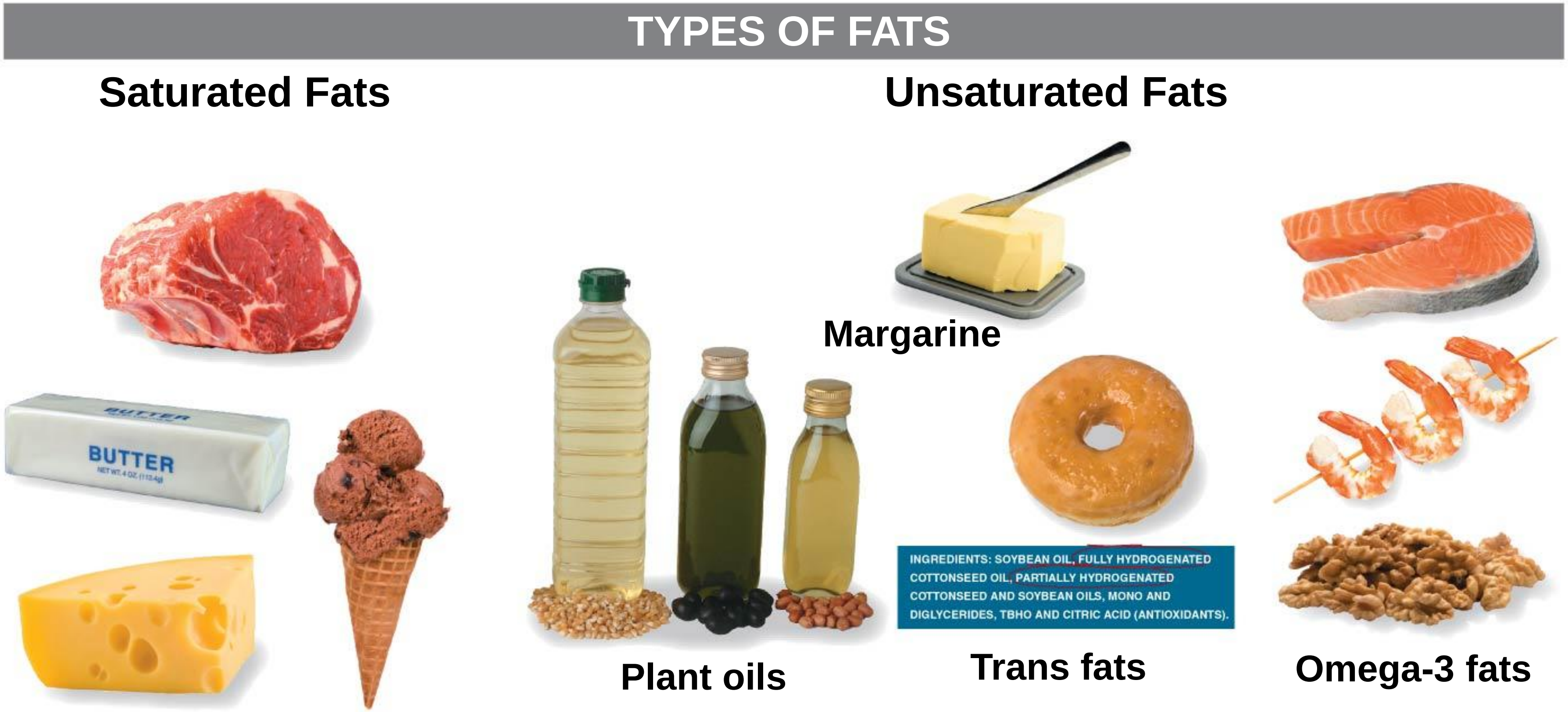
Fats

- Most plant and fish oils tend to be
  - high in unsaturated fatty acids and
  - liquid at room temperature.

Fats

- **Hydrogenation**
  - adds hydrogen,
  - converts unsaturated fats to saturated fats,
  - makes liquid fats solid at room temperature, and
  - creates **trans fat**, a type of unsaturated fat that is particularly bad for your health.

Figure 3.12


TYPES OF FATS
Saturated Fats
Unsaturated Fats
BUTTER
Margarine
INGREDIENTS: SOYBEAN OIL, FULLY HYDROGENATED COTTONSEED OIL, PARTIALLY HYDROGENATED COTTONSEED AND SOYBEAN OILS, MONO AND DIGLYCERIDES, TBHO AND CITRIC ACID (ANTIOXIDANTS).
Plant oils
Trans fats
Omega-3 fats

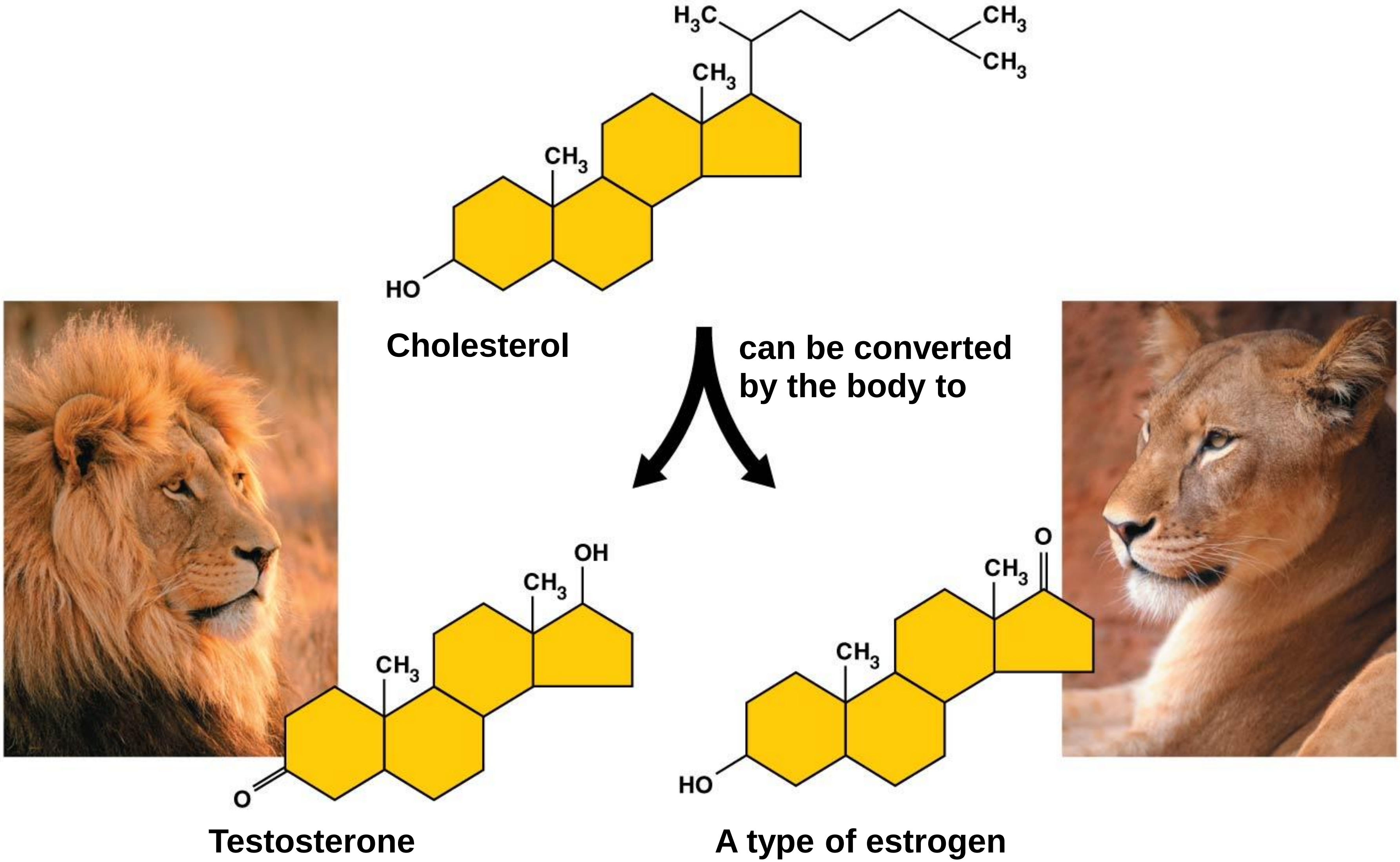
Steroids

- **Steroids** are very different from fats in structure and function.
  - The carbon skeleton is bent to form four fused rings.
  - Steroids vary in the functional groups attached to this set of rings, and these chemical variations affect their function.

Steroids

- Cholesterol is
  - a key component of cell membranes and
  - the "base steroid" from which your body produces other steroids, such as estrogen and testosterone.

Figure 3.13



H_3C
CH_3
CH_3
CH_3
CH_3
HO
Cholesterol
can be converted by the body to
OH
CH_3
CH_3
O
Testosterone
O
CH_3
CH_3
HO
A type of estrogen

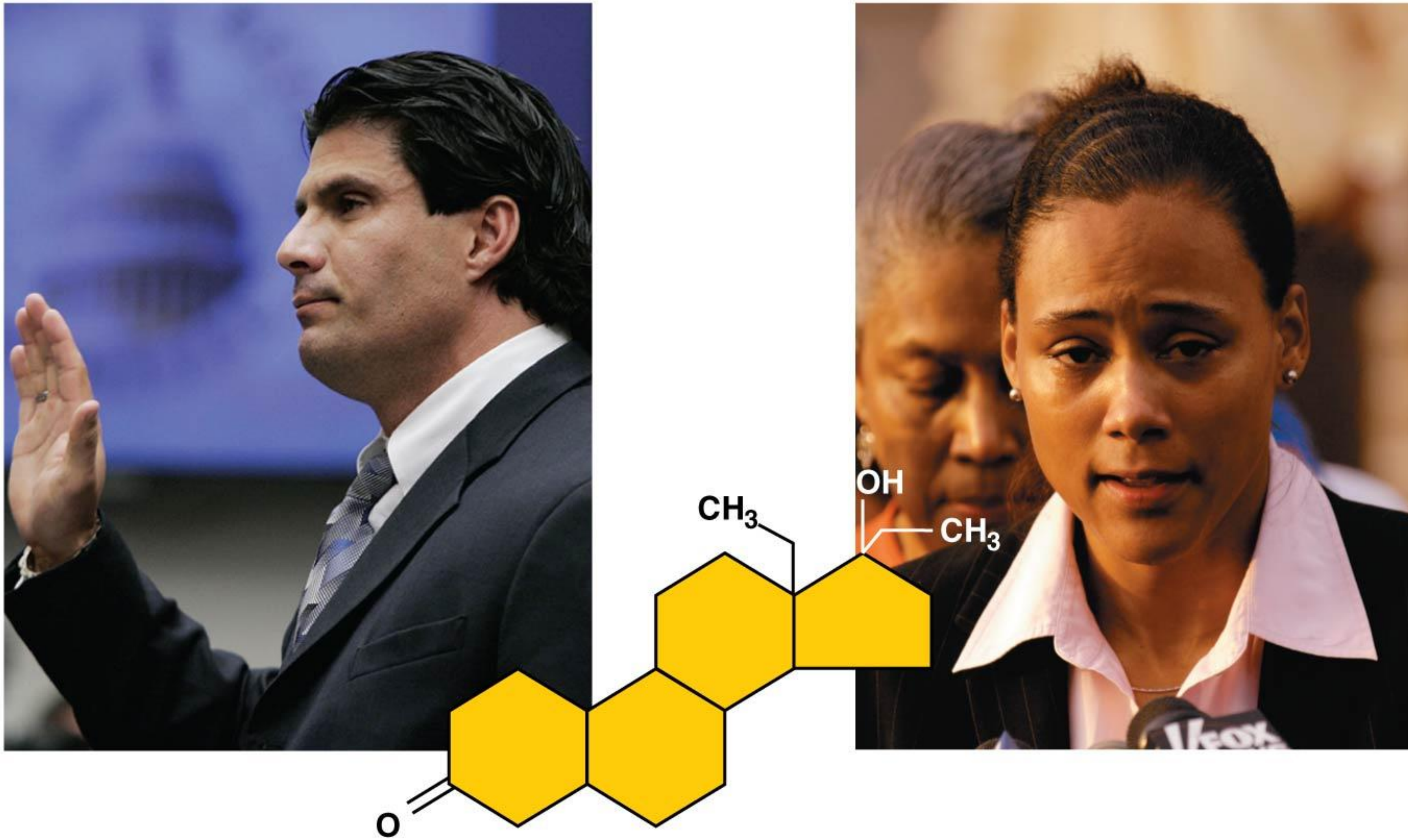
Steroids

- Synthetic anabolic steroids
  - are variants of testosterone,
  - mimic some of its effects,
  - can cause serious physical and mental problems,
  - may be prescribed to treat diseases such as cancer and AIDS, and
  - are abused by athletes to enhance performance.

Steroids

- Most athletic organizations now ban the use of anabolic steroids because of their
  - health hazards and
  - unfairness, by providing an artificial advantage.

Figure 3.14



THG

Proteins

- **Proteins**
  - are polymers constructed from amino acid monomers,
  - account for more than 50% of the dry weight of most cells,
  - perform most of the tasks required for life, and
  - form enzymes, chemicals that change the rate of a chemical reaction without being changed in the process.

Figure 3.15

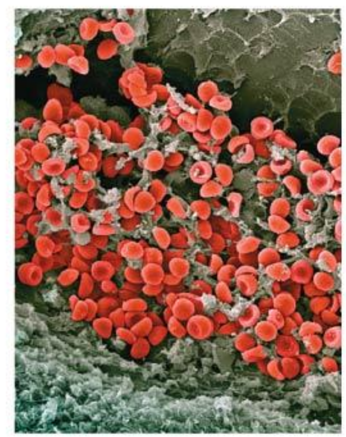
MAJOR TYPES OF PROTEINS

Structural Proteins (provide support)

Storage Proteins (provide amino acids for growth)

Contractile Proteins (help movement)

Transport Proteins (help transport substances)

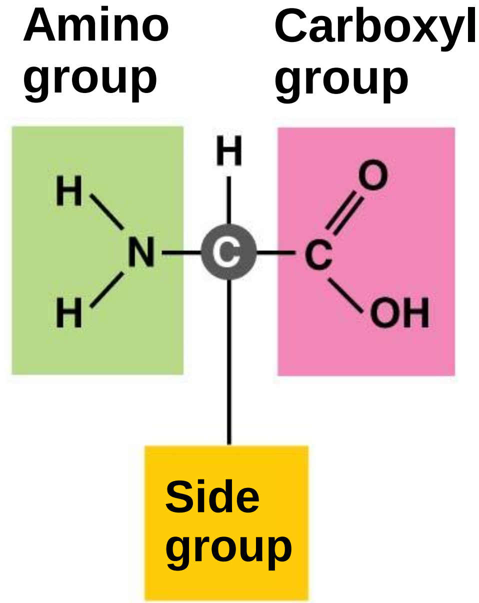


Enzymes (help chemical reactions)

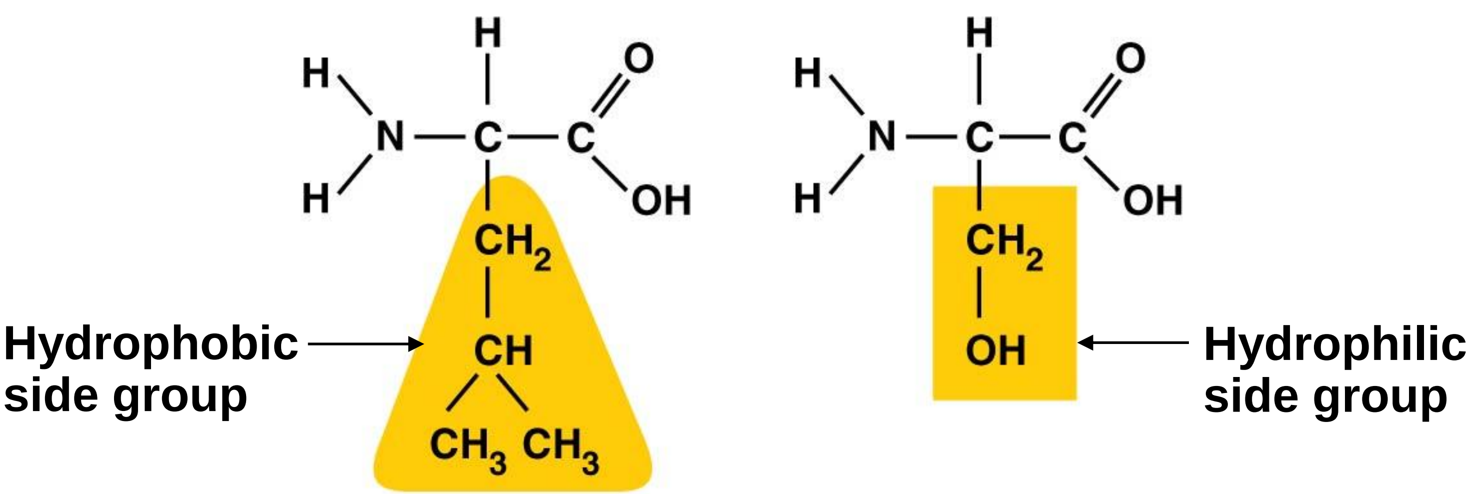
The Monomers of Proteins: Amino Acids

- All proteins are macromolecules constructed from a common set of 20 kinds of amino acids.
- Each **amino acid** consists of a central carbon atom bonded to four covalent partners.
- Three of those attachment groups are common to all amino acids:
  - a carboxyl group (-COOH),
  - an amino group (-NH_2), and
  - a hydrogen atom.

Figure 3.16



The general structure of an amino acid



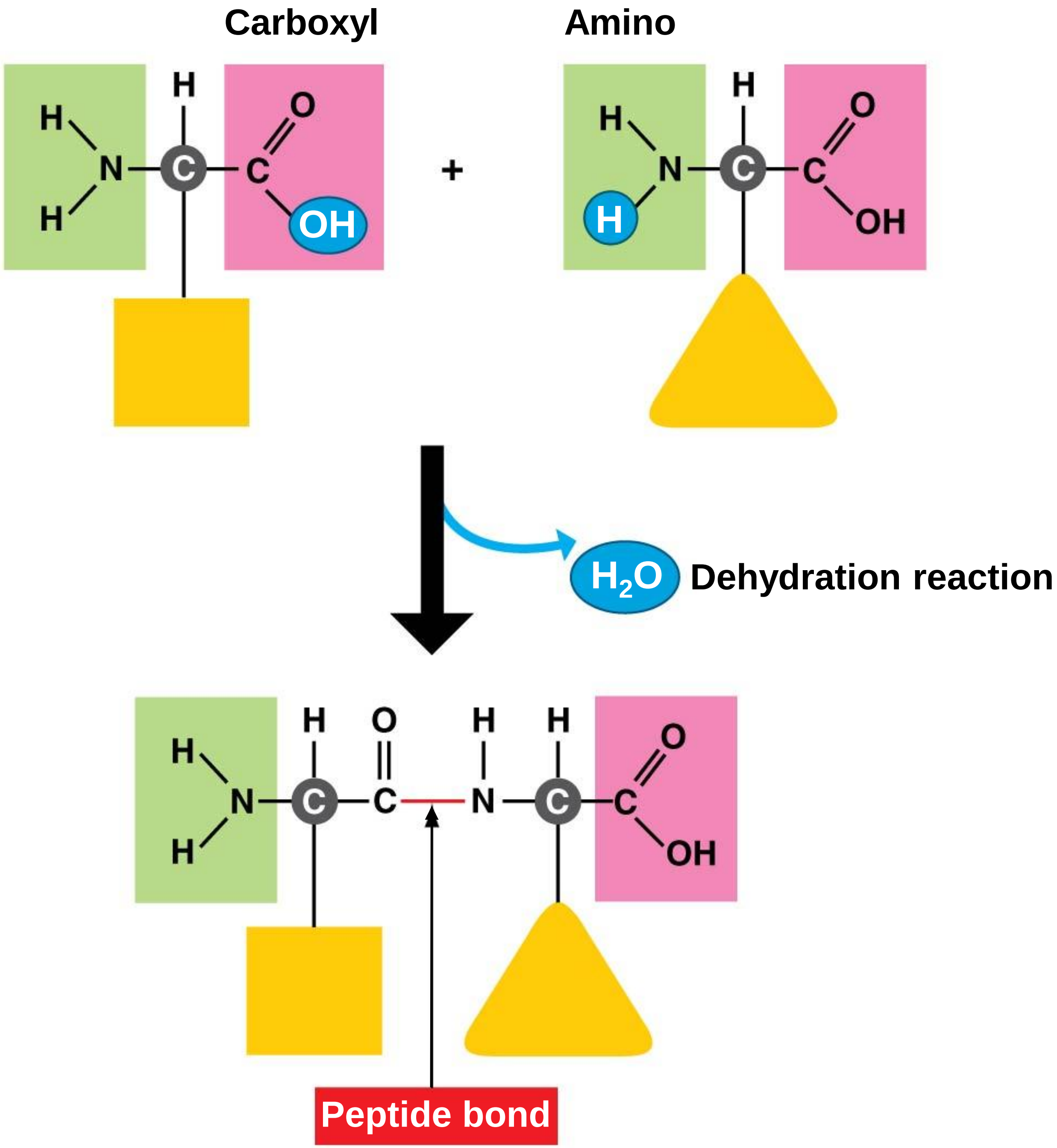
Leucine

Serine

Proteins as Polymers

- Cells link amino acids together
  - by dehydration reactions,
  - forming **peptide bonds,** and
  - creating long chains of amino acids called **polypeptides**.

Figure 3.17-2


Carboxyl
Amino
H
H
N
C
C
O
OH
H
+
H
H
N
C
C
O
OH
H
H_2O
Dehydration reaction
H
H
N
C
H
C
O
N
H
C
H
C
O
OH
Peptide bond

Proteins as Polymers

- Your body has tens of thousands of different kinds of protein.
- Proteins differ in their arrangement of amino acids.
- The specific sequence of amino acids in a protein is its **primary structure**.

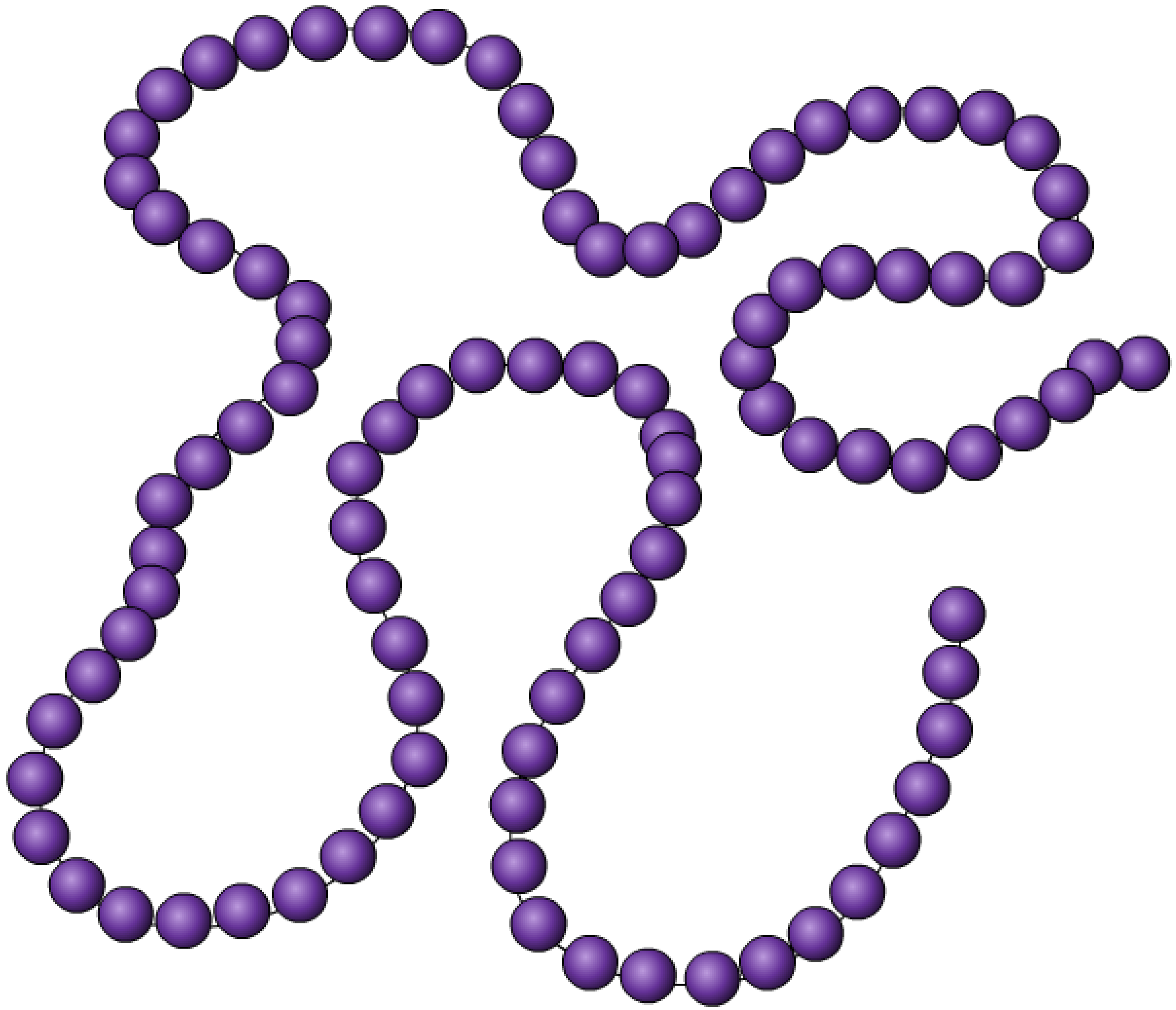
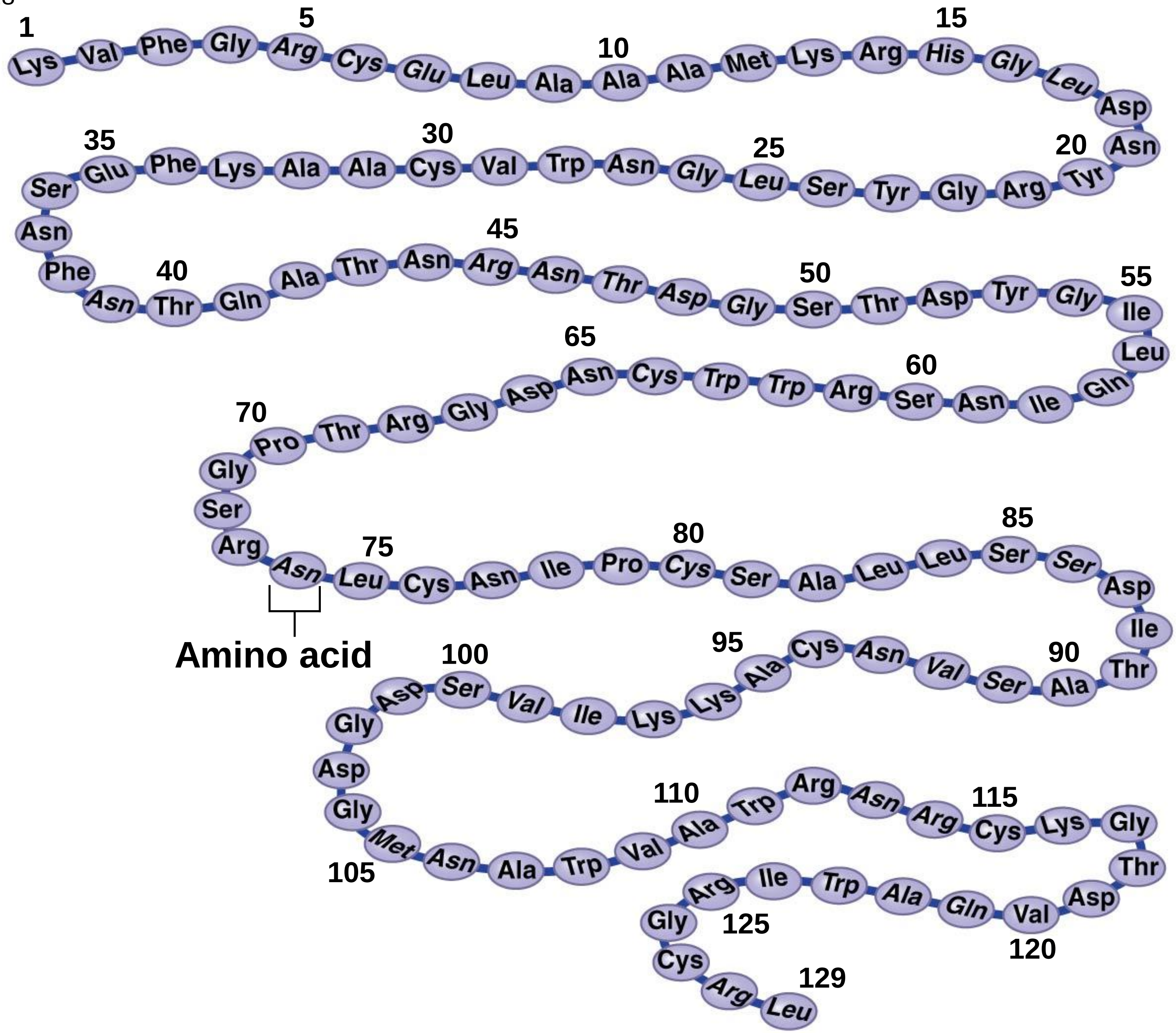


Figure 3.18

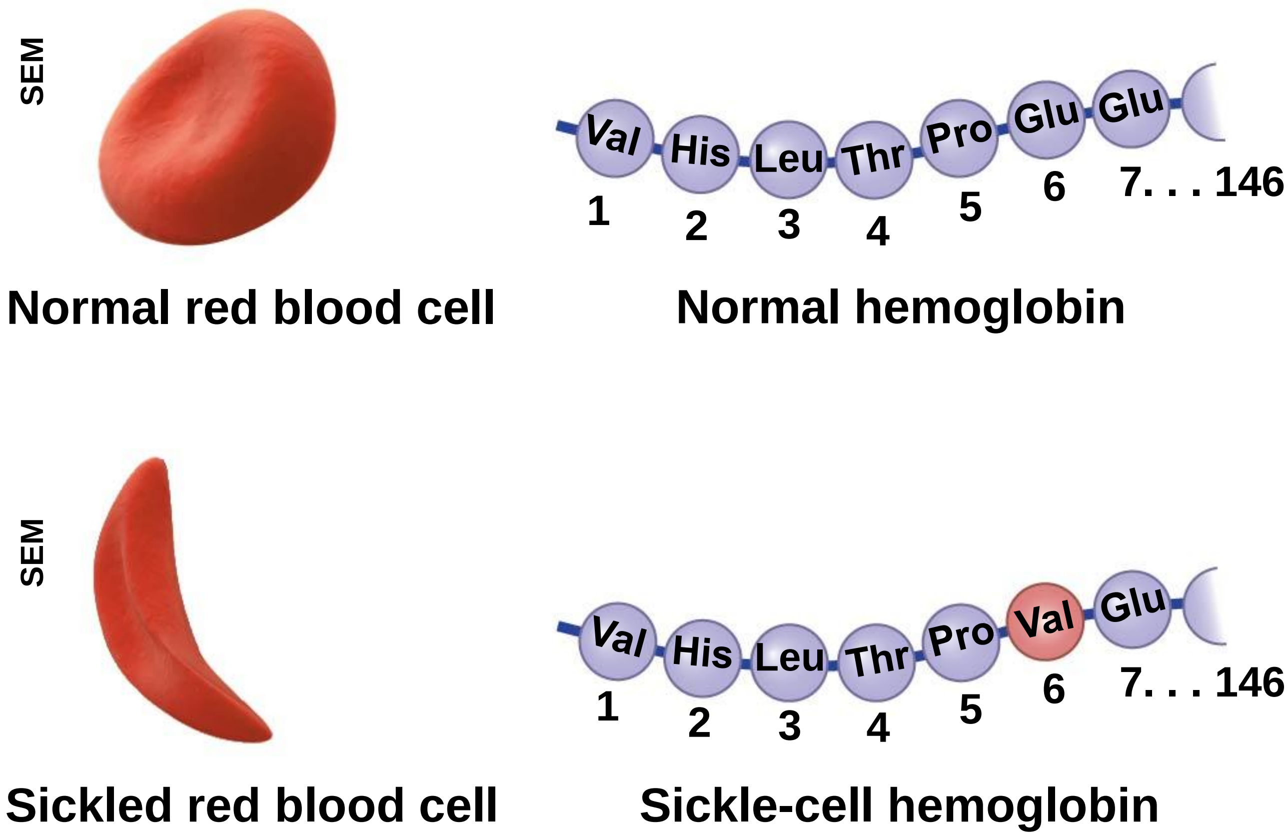


1
Lys Val Phe Gly Arg Cys Glu Leu Ala Ala Ala Met Lys Arg His Gly Leu Asp Asn Tyr Arg Gly Tyr Ser Leu Gly Asn Trp Val Cys Ala Ala Lys Phe Glu Ser Asn Phe Asn Thr Gln Ala Thr Asn Arg Asn Thr Asp Gly Ser Thr Asp Tyr Gly Ile Leu Gln Ile Asn Ser Arg Trp Trp Cys Asn Asp Gly Arg Thr Pro Gly Ser Arg Asn Leu Cys Asn Ile Pro Cys Ser Ala Leu Leu Ser Ser Asp Ile Thr Ala Ser Val Asn Cys Ala Lys Lys Ile Val Ser Asp Gly Asp Gly Met Asn Ala Trp Val Ala Trp Arg Asn Arg Cys Lys Gly Thr Asp Val Gln Ala Trp Ile Arg Gly Cys Arg Leu
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
129
Amino acid

Proteins as Polymers

- A slight change in the primary structure of a protein affects its ability to function.
- The substitution of one amino acid for another in hemoglobin causes sickle-cell disease, an inherited blood disorder.

Figure 3.19


SEM
Val His Leu Thr Pro Glu Glu
1 2 3 4 5 6 7. . . 146
Normal red blood cell
Normal hemoglobin
SEM
Val His Leu Thr Pro Val Glu
1 2 3 4 5 6 7. . . 146
Sickled red blood cell
Sickle-cell hemoglobin

Protein Shape

- A functional protein consists of
  - one or more polypeptide chains,
  - precisely twisted, folded, and coiled into a molecule of unique shape.

Protein Shape

- Proteins consisting of one polypeptide have three levels of structure.
- Proteins consisting of more than one polypeptide chain have a fourth level, quaternary structure.

Figure 3.20-4

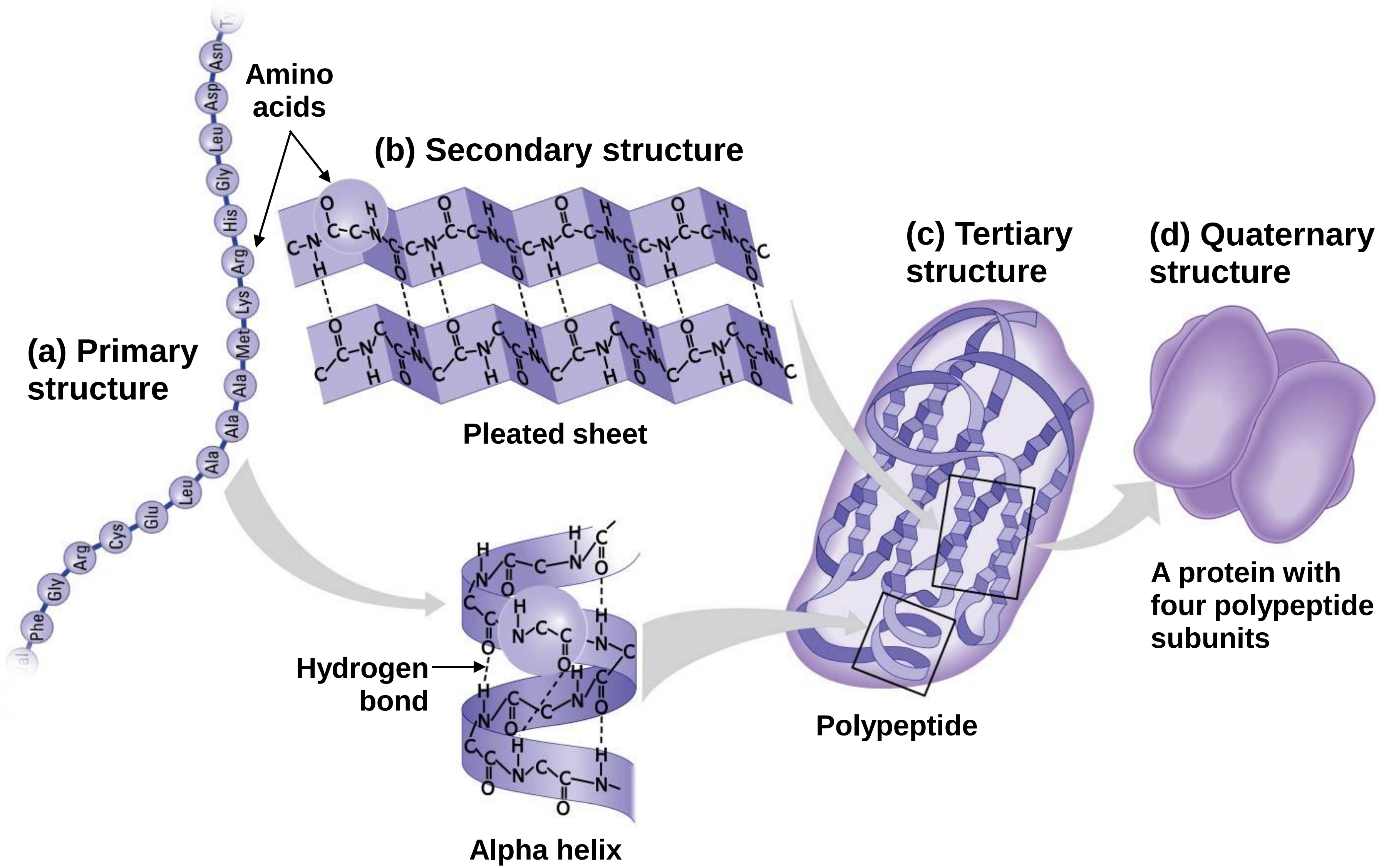
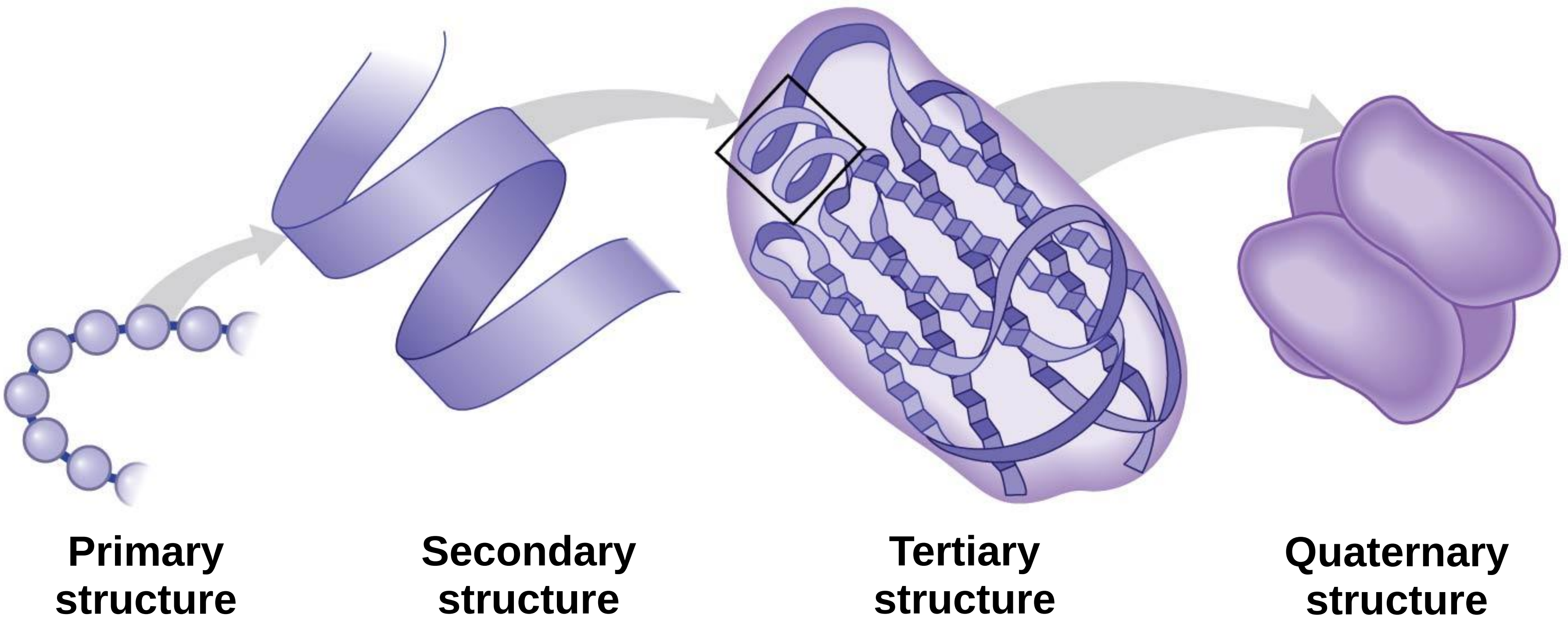

Amino acids
(a) Primary structure
(b) Secondary structure
Pleated sheet
Hydrogen bond
Alpha helix
(c) Tertiary structure
Polypeptide
(d) Quaternary structure
A protein with four polypeptide subunits
Asn
Asp
Leu
Gly
His
Arg
Lys
Met
Ala
Ala
Ala
Leu
Glu
Cys
Arg
Gly
Phe

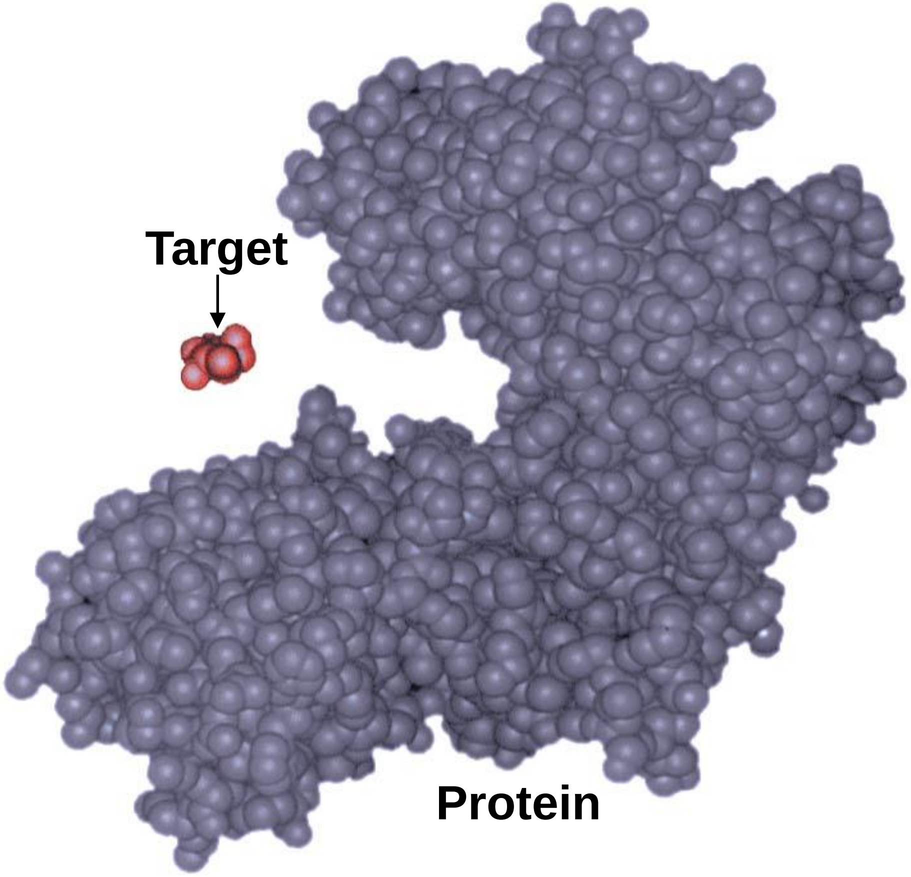
Figure 3.UN03



Protein Shape

- A protein's three-dimensional shape
  - typically recognizes and binds to another molecule and
  - enables the protein to carry out its specific function in a cell.

Figure 3.21



What Determines Protein Shape?

- A protein’s shape is sensitive to the surrounding environment.
- An unfavorable change in temperature and/or pH can cause **denaturation** of a protein, in which it unravels and loses its shape.
- High fevers (above 104°F) in humans can cause some proteins to denature.

What Determines Protein Shape?

- Misfolded proteins are associated with
  - Alzheimer’s disease,
  - mad cow disease, and
  - Parkinson’s disease.

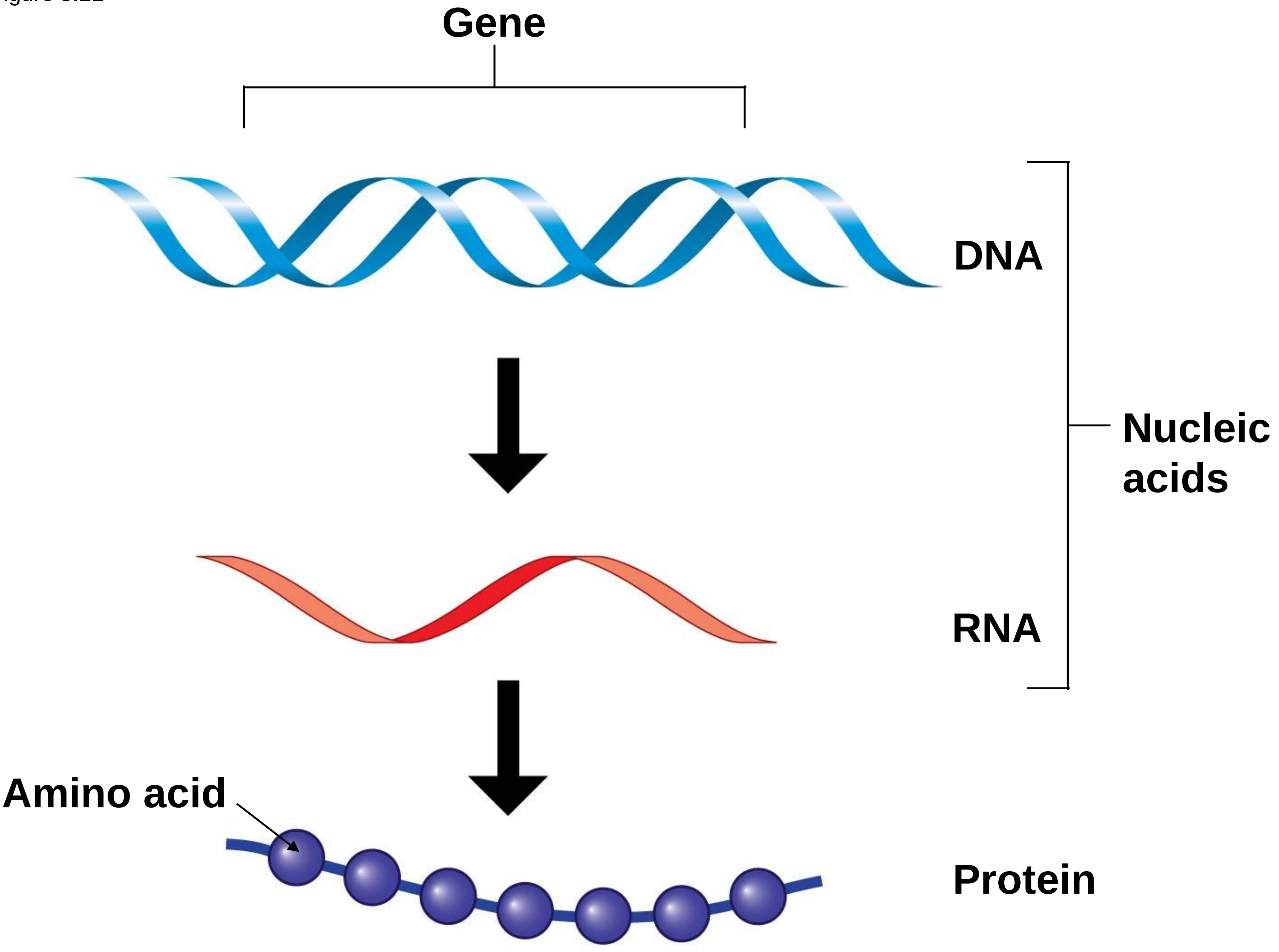
Nucleic Acids

- Nucleic acids are macromolecules that
  - store information,
  - provide the directions for building proteins, and
  - include **DNA** and **RNA**.

Nucleic Acids

- DNA resides in cells in long fibers called chromosomes.
- A **gene** is a specific stretch of DNA that programs the amino acid sequence of a polypeptide.
- The chemical code of DNA must be translated from “nucleic acid language” to “protein language.”

Figure 3.22

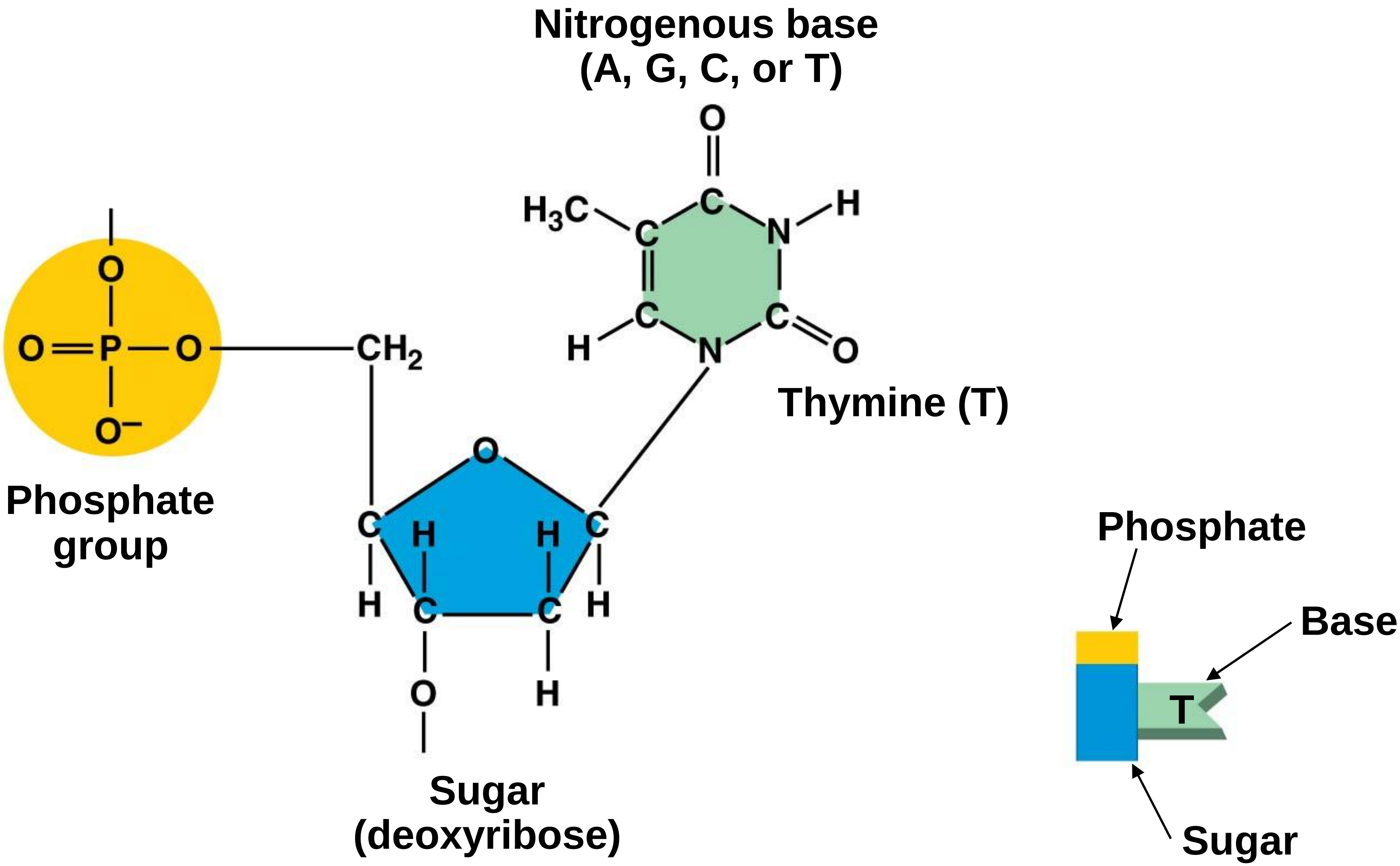


Nucleic Acids

- Nucleic acids are polymers made from monomers called **nucleotides**.
- Each nucleotide has three parts:

  1. a five-carbon sugar,
  2. a phosphate group, and
  3. a nitrogen-containing base.

Figure 3.23



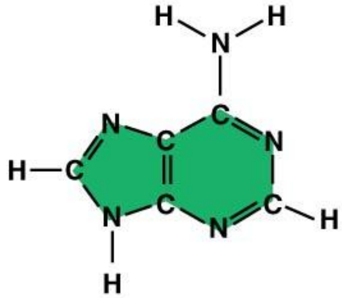
(a) Atomic structure

(b) Symbol used in this book

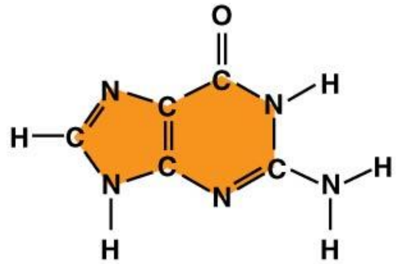
Nucleic Acids

- Each DNA nucleotide has one of four possible nitrogenous bases:
  - adenine (A),
  - guanine (G),
  - thymine (T), or
  - cytosine (C).

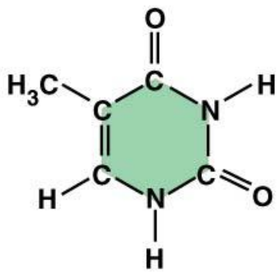
Figure 3.24



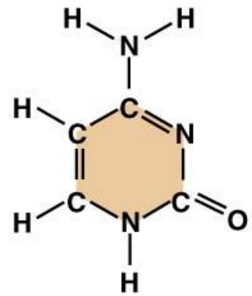
Adenine (A)



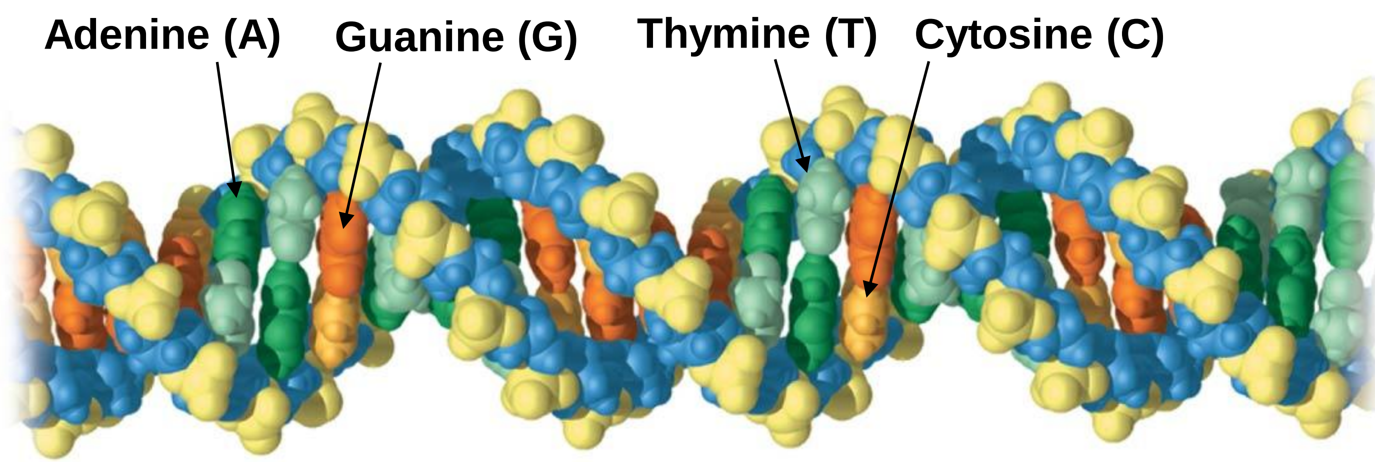
Guanine (G)



Thymine (T)



Cytosine (C)



Space-filling model of DNA

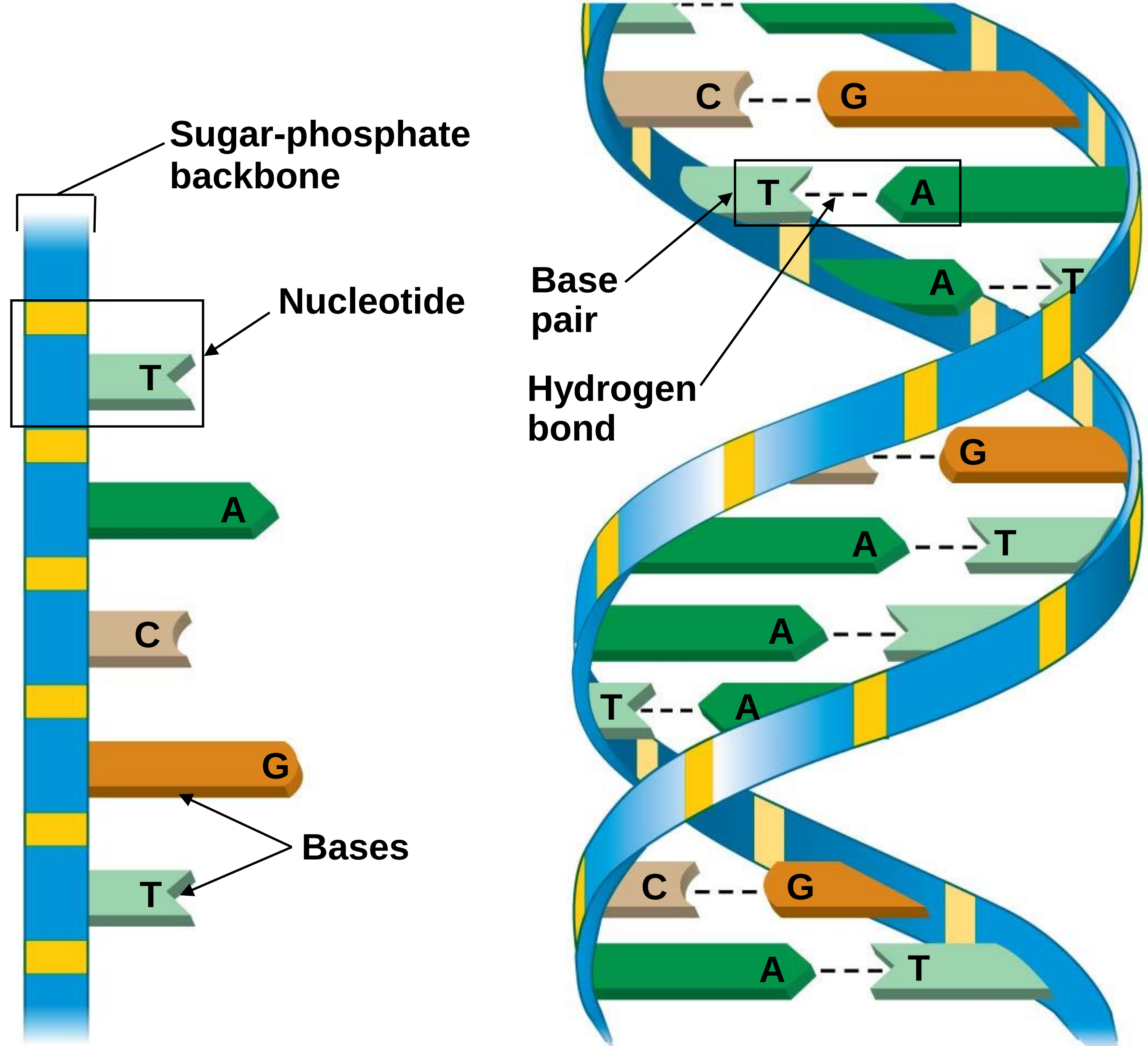
Nucleic Acids

- Dehydration reactions
  - link nucleotide monomers into long chains called polynucleotides,
  - form covalent bonds between the sugar of one nucleotide and the phosphate of the next, and
  - form a **sugar-phosphate backbone.**
- Nitrogenous bases hang off the sugar-phosphate backbone.

Nucleic Acids

- Two strands of DNA join together to form a **double helix**.
- Bases along one DNA strand hydrogen-bond to bases along the other strand.
- The functional groups hanging off the base determine which bases pair up:
  - A only pairs with T and
  - G can only pair with C.

Figure 3.25



(a) DNA strand (polynucleotide)

(b) Double helix (two polynucleotide strands)

Nucleic Acids

- RNA, ribonucleic acid, is different from DNA.
  - RNA uses the sugar ribose and the base uracil (U) instead of thymine (T).
  - RNA is usually single-stranded, but DNA usually exists as a double helix.

Figure 3.26

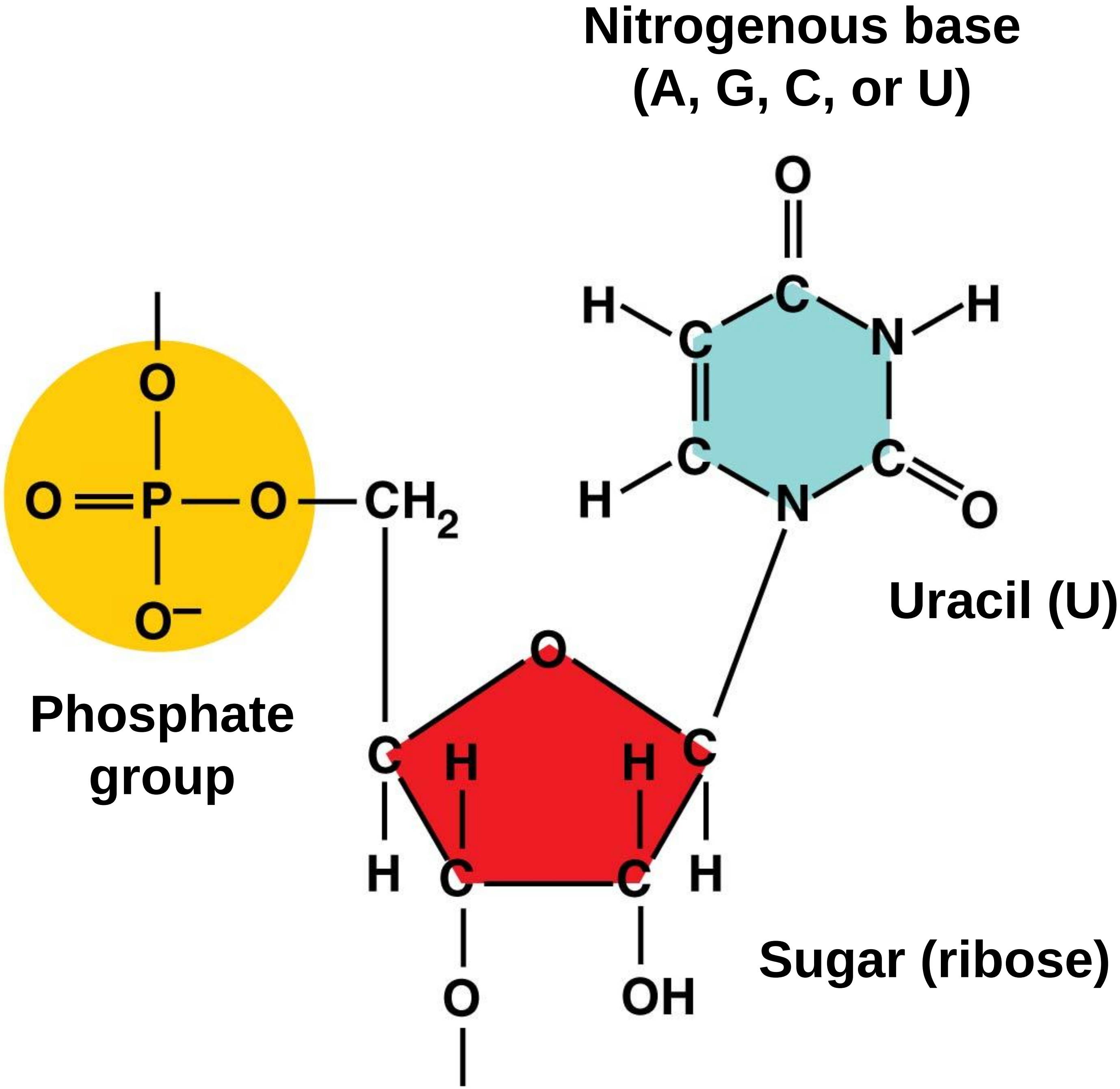

Nitrogenous base
(A, G, C, or U)
Phosphate group
Uracil (U)
Sugar (ribose)

Figure 3.UN04

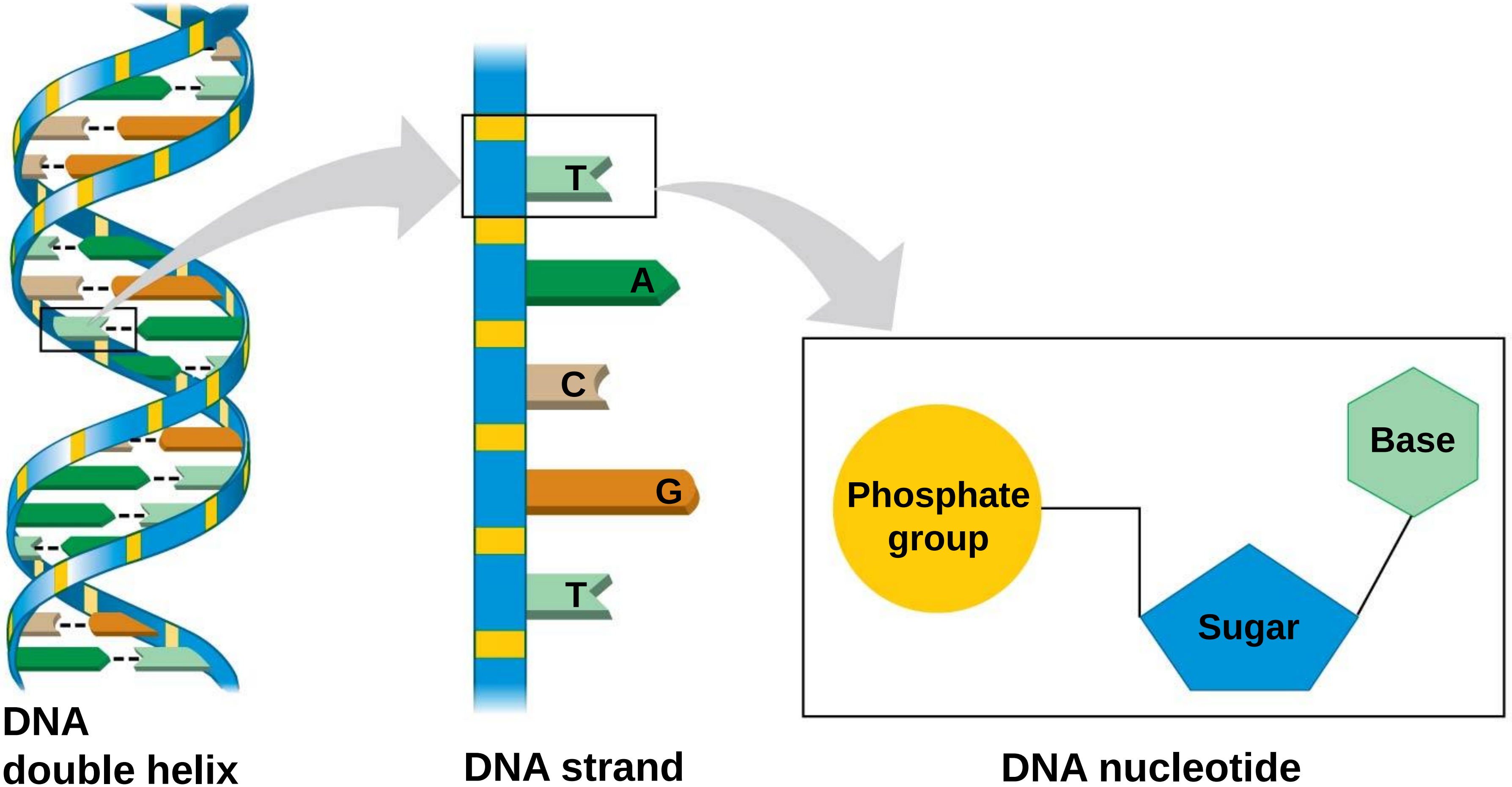
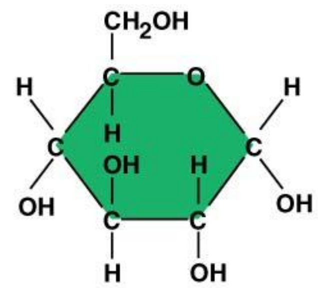
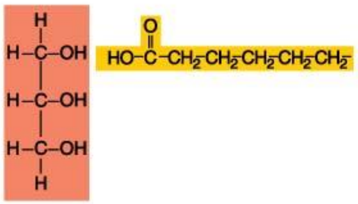
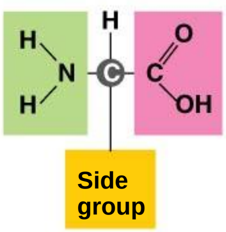
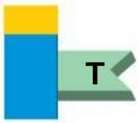


Figure 3.UN02

Large biological molecules	Functions	Components	Examples
Carbohydrates	Dietary energy; storage; plant structure	 Monosaccharide	Monosaccharides: glucose, fructose; Disaccharides: lactose, sucrose; Polysaccharides: starch, cellulose
Lipids	Long-term energy storage (fats); hormones (steroids)	 Components of a triglyceride	Fats (triglycerides); steroids (testosterone, estrogen)
Proteins	Enzymes, structure, storage, contraction, transport, etc.	 Amino acid	Lactase (an enzyme); hemoglobin (a transport protein)
Nucleic acids	Information storage	 Nucleotide	DNA, RNA

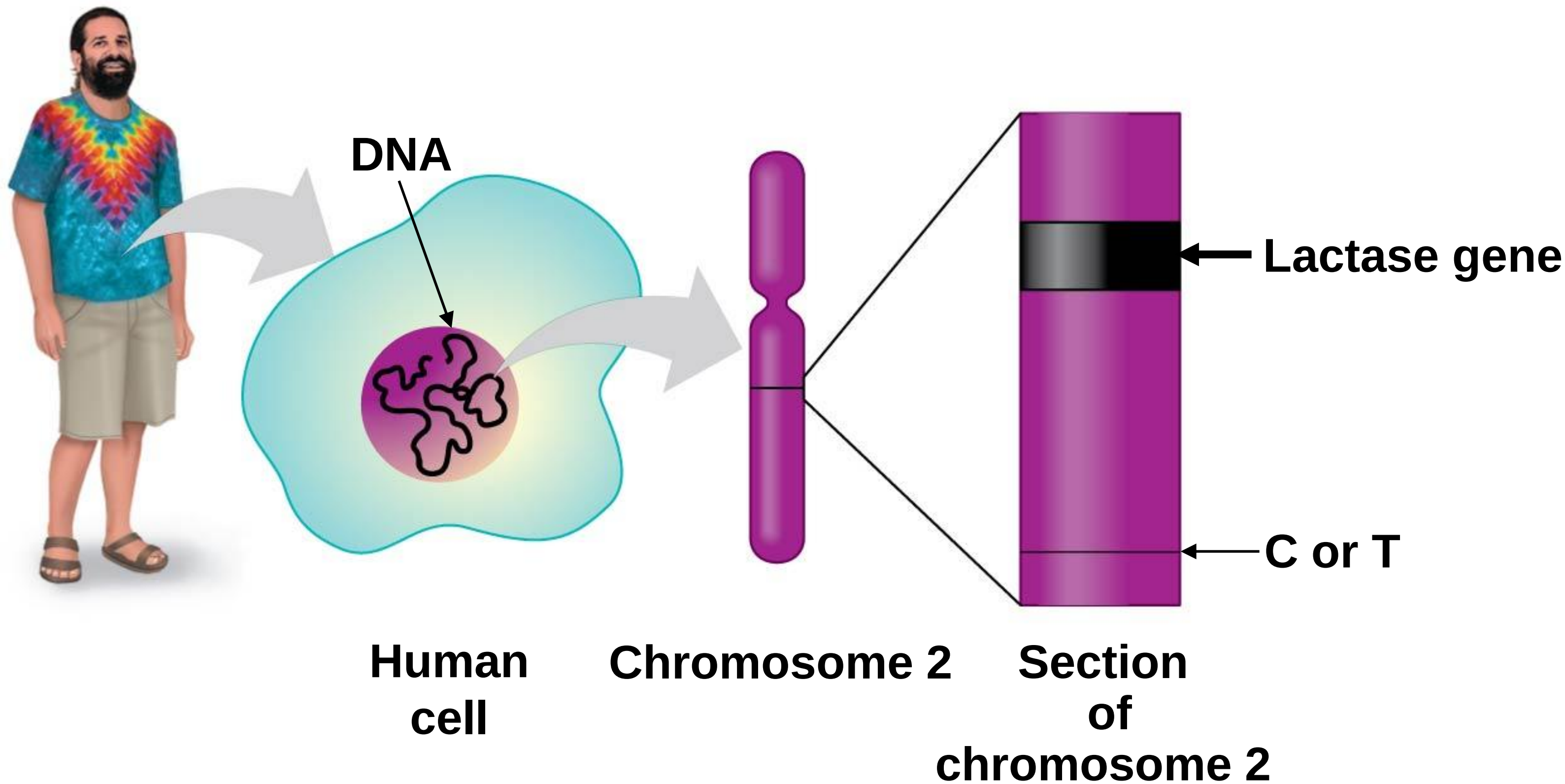
The Process of Science:
Does Lactose Intolerance Have a Genetic Basis?

- **Observation**: Most lactose-intolerant people have a normal version of the lactase gene.
- **Question**: What is the genetic basis for lactose intolerance?
- **Hypothesis**: Lactose-intolerant people have a mutation but not within the lactase gene.

The Process of Science: Does Lactose Intolerance Have a Genetic Basis?

- **Prediction**: A mutation would be found near the lactase gene.
- **Experiment**: Genes of 196 lactose-intolerant people were examined.
- **Results**: Researchers found a 100% correlation between lactose intolerance and a nucleotide at a site approximately 14,000 nucleotides away from the lactase gene.

Figure 3.27


DNA
Lactase gene
C or T
Human cell
Chromosome 2
Section of chromosome 2

Evolution Connection: The Evolution of Lactose Intolerance in Humans

- Most people are lactose-intolerant as adults.
- Lactose intolerance is found in
  - 80% of African Americans and Native Americans,
  - 90% of Asian Americans, but
  - only 10% of Americans of northern European descent.

Evolution Connection: The Evolution of Lactose Intolerance in Humans

- Lactose tolerance appears to have evolved in northern European cultures that relied upon dairy products.
- Ethnic groups in East Africa that rely upon dairy products are also lactose tolerant but due to different mutations.

Figure 3.28