Chapter 3

The Molecules of Life

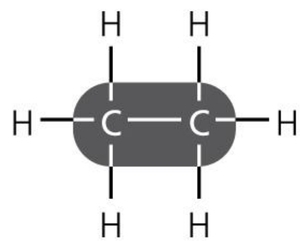
Organic Compounds

- 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.

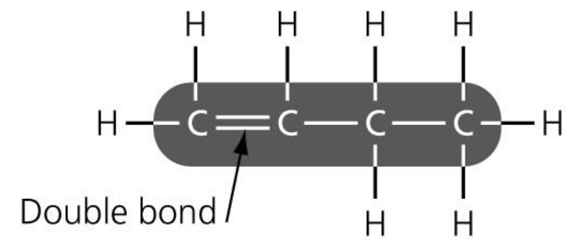
Carbon Chemistry

- Carbon is a versatile molecule.
  - Carbon can share electrons with other atoms in four covalent bonds.
  - There is a tremendous diversity of carbon skeletons varying in size and branching pattern.
- The carbon atoms of organic compounds can also bond with other elements, most commonly hydrogen, oxygen, and nitrogen.

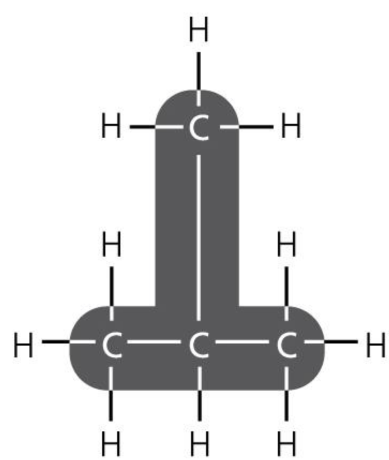
Variations in carbon skeletons



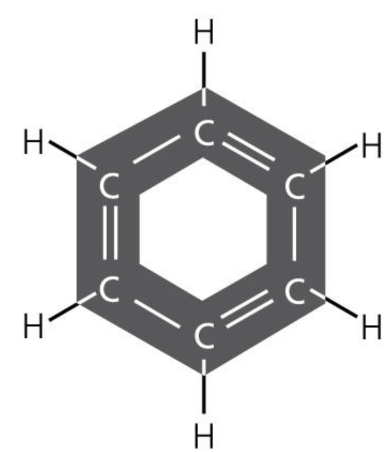
Carbon skeletons vary in length



Carbon skeletons may have double bonds, which can vary in location



Carbon skeletons may be unbranched or branched

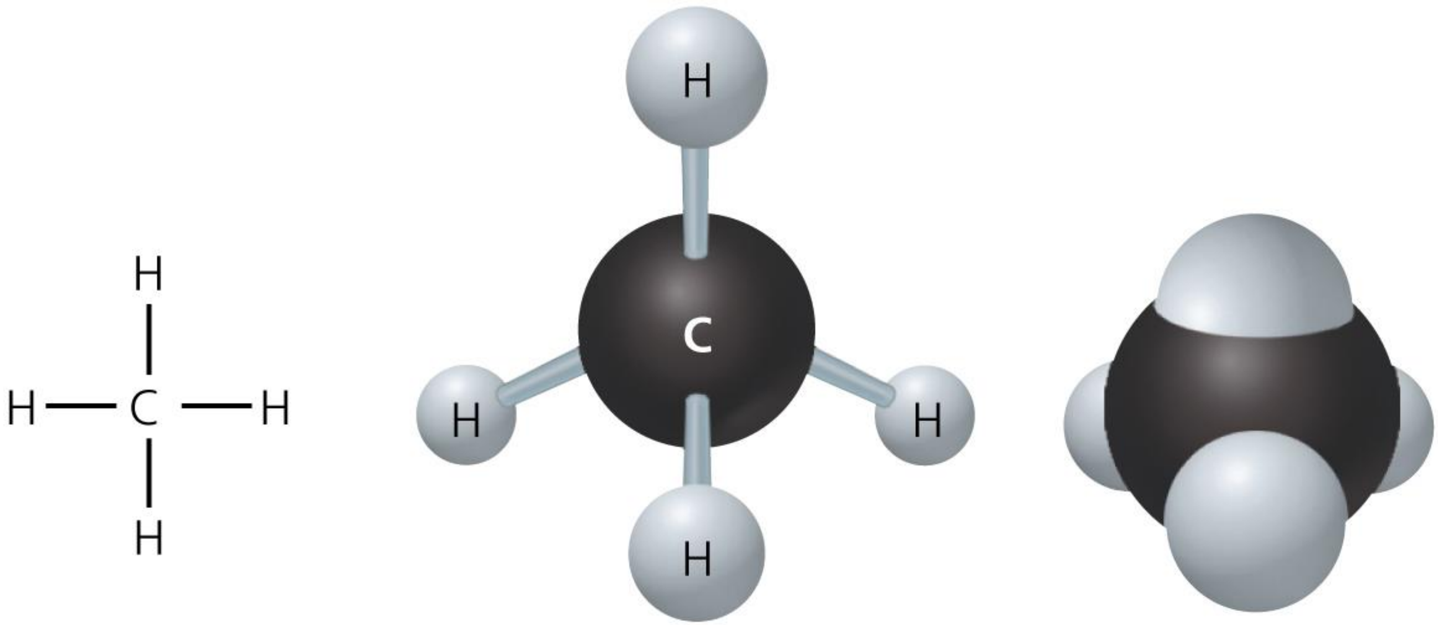


Carbon skeletons may be arranged in rings

Carbon Chemistry (Cont.)

- One of the simplest organic compounds is methane (CH_4), with a single carbon atom bonded to four hydrogen atoms.
- Larger organic compounds are the main molecules in gasoline and are important fuels in your body.

Three representations of methane, a simple organic compound



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

Hydrocarbons as fuel

Octane

Dietary fat

Carbon Chemistry (Cont.)

- The unique properties of an organic compound depend on
  - its carbon skeleton and
  - the atoms attached to the skeleton.
- In an organic compound, the groups of atoms directly involved in chemical reactions are called **functional groups**.
- Many biological molecules have two or more functional groups.

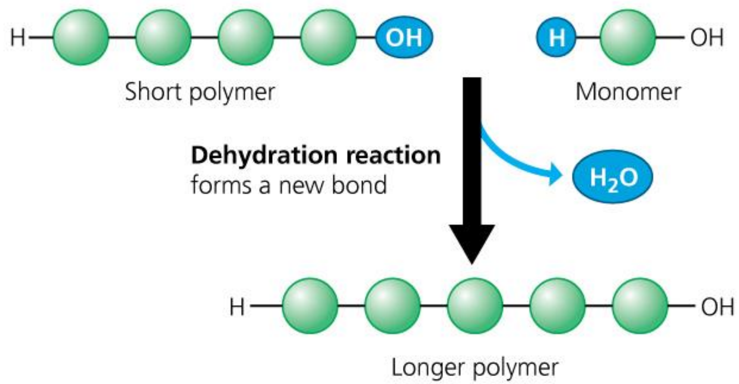
Giant Molecules from Smaller Building Blocks

- 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.

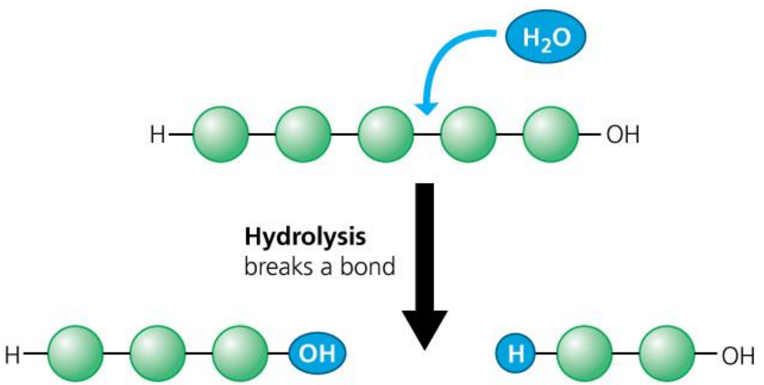
Giant Molecules from Smaller Building Blocks (Cont.)

- Macromolecules are **polymers**, large molecules made by stringing together many smaller molecules called **monomers**.
- A **dehydration reaction**
  - links two monomers together and
  - removes a molecule of water.
- The breakdown of polymers occurs by **hydrolysis**, by adding water to them, a process that is essentially the reverse of a dehydration reaction.

Synthesis and breakdown of polymers



(a) Building a polymer chain. A polymer grows in length when an incoming monomer and the monomer at the end of the polymer each contribute atoms to form a water molecule. The monomers replace the lost covalent bonds with a bond between each other.



(b) Breaking a polymer chain. Hydrolysis reverses the process by adding a water molecule, which breaks the bond between two monomers, creating two smaller molecules from one bigger one.

Large Biological Molecules

- Four categories of large biological molecules are found in all living creatures:
  1. carbohydrates,
  2. lipids,
  3. proteins, and
  4. nucleic acids.

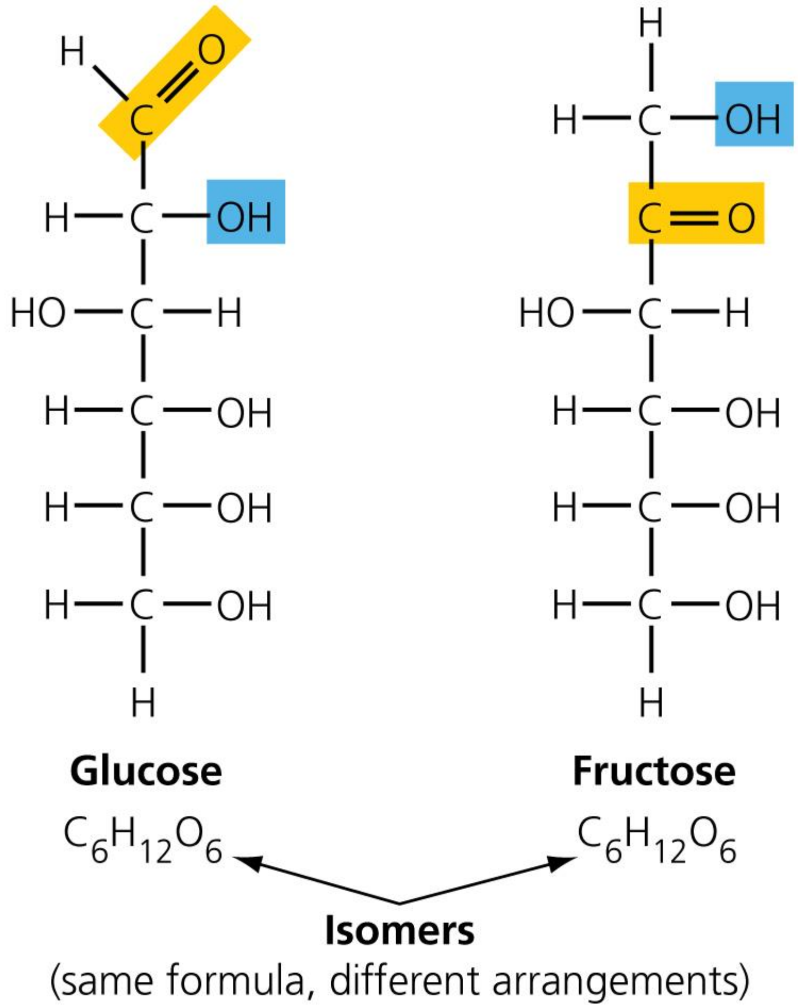
Carbohydrates

- **Carbohydrates** include sugars and polymers of sugar.
- 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

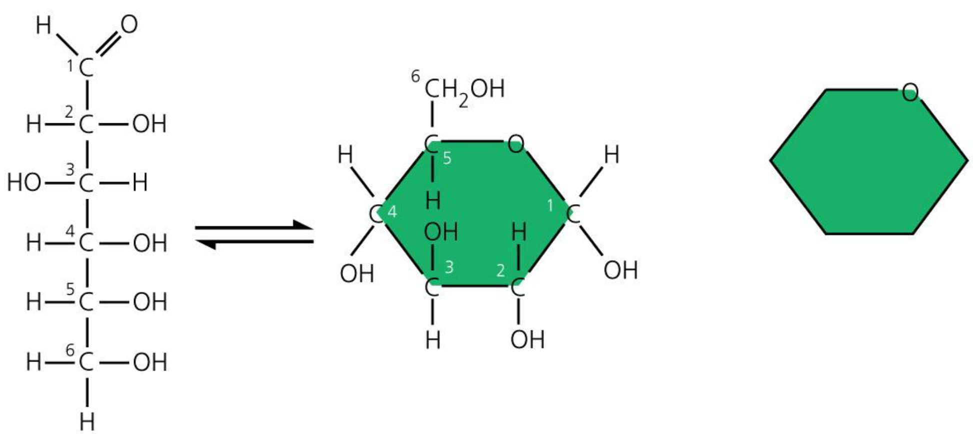
- **Monosaccharides**
  - are the monomers of carbohydrates and
  - cannot be broken down into smaller sugars.
- Common examples are glucose in sports drinks and fructose found in fruit.
  - Both of these simple sugars are also in honey.
  - Glucose and fructose are **isomers**, molecules that have the same molecular formula but different structures.

Monosaccharides (simple sugars)



Monosaccharides

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



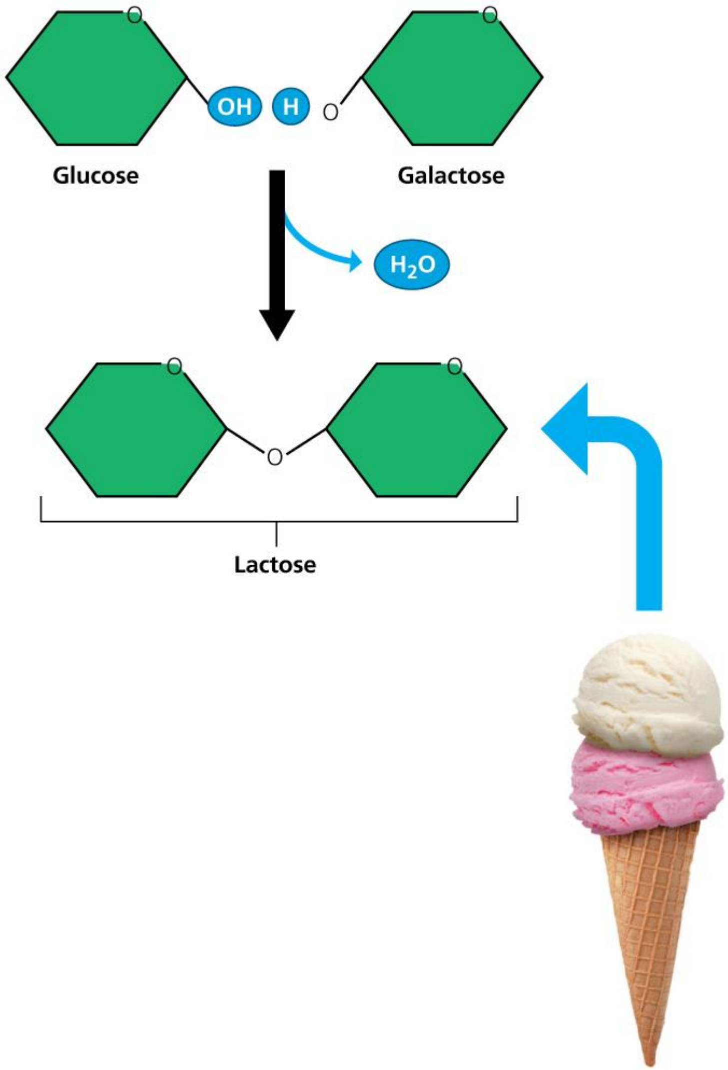
(a) Linear and ring structures. The carbon atoms are numbered so you can relate the linear and ring versions of the molecule. As the double arrows indicate, ring formation is a reversible process, but at any instant in an aqueous solution, most glucose molecules are rings.

(b) Abbreviated ring structure. In this book, we'll use this abbreviated ring symbol for glucose. Each unmarked corner represents a carbon and its attached atoms.

Disaccharides

- A **disaccharide** is constructed from two monosaccharides by a dehydration reaction. Disaccharides include
  - lactose in milk,
  - maltose in malted milk shakes, and
  - sucrose in table sugar. Sucrose is the main carbohydrate in plant sap.
- High-fructose corn syrup (HFCS) is made by a commercial process that converts natural glucose in corn syrup to much sweeter fructose.

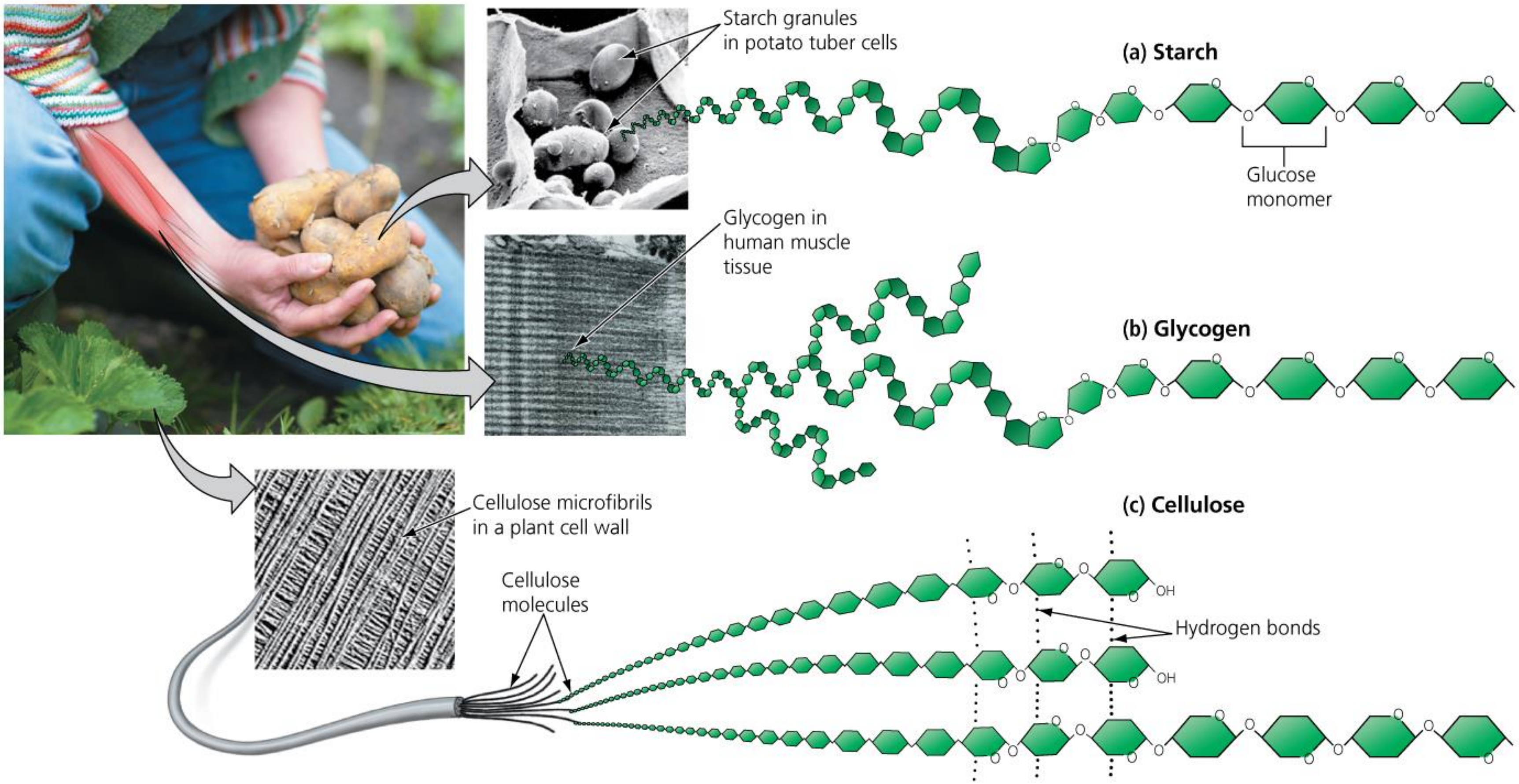
Disaccharide (double sugar) formation



Polysaccharides

- **Polysaccharides**
  - are complex carbohydrates and
  - are made of long chains of sugars—polymers of monosaccharides.
- **Starch**
  - is a familiar example of a polysaccharide,
  - consists of long strings of glucose monomers, and
  - is used by plant cells to store energy.

Three common polysaccharides



Polysaccharides

- **Glycogen**
  - is used by animal cells to store energy and
  - is broken down to release glucose when you need energy.
- **Cellulose**
  - is the most abundant organic compound on Earth,
  - forms cable-like fibrils in the tough walls that enclose plant cells, and
  - cannot be broken by any enzyme produced by animals.

Lipids

- Almost all carbohydrates are **hydrophilic** (“water-loving”) molecules that dissolve readily in water.
- **Lipids** are **hydrophobic**, unable to mix with water.
- Lipids also differ from carbohydrates, proteins, and nucleic acids in that neither are they huge macromolecules nor are they necessarily polymers built from repeating monomers.
- Lipids are a diverse group of molecules made from different molecular building blocks.

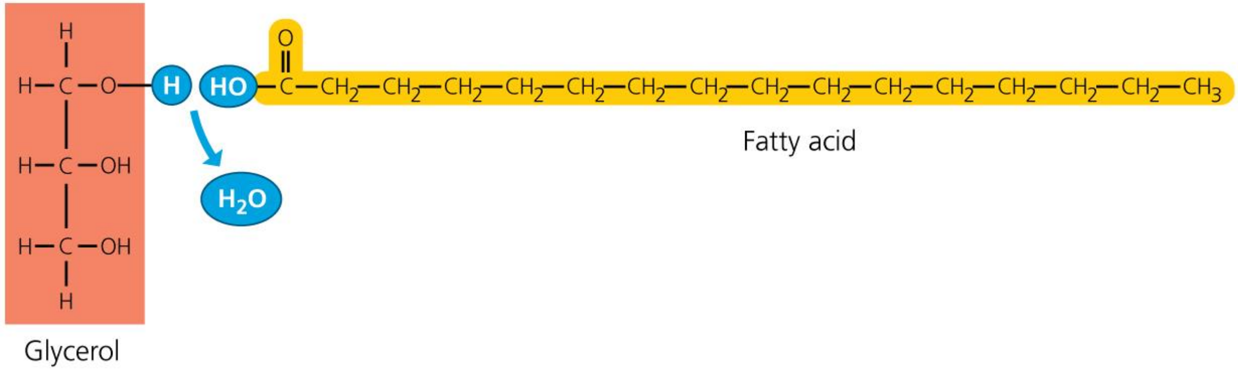
The separation of hydrophobic (oil) and hydrophilic (vinegar) components in salad dressing

Fats

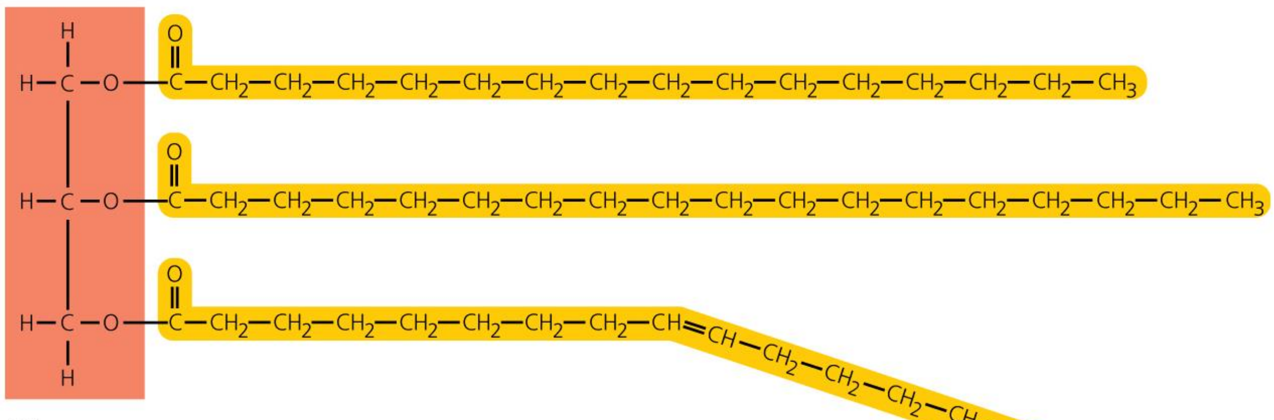
- A typical **fat**, or **triglyceride**, consists of a glycerol molecule joined with three fatty acid molecules via a dehydration reaction.

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

The synthesis and structure of a triglyceride molecule



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

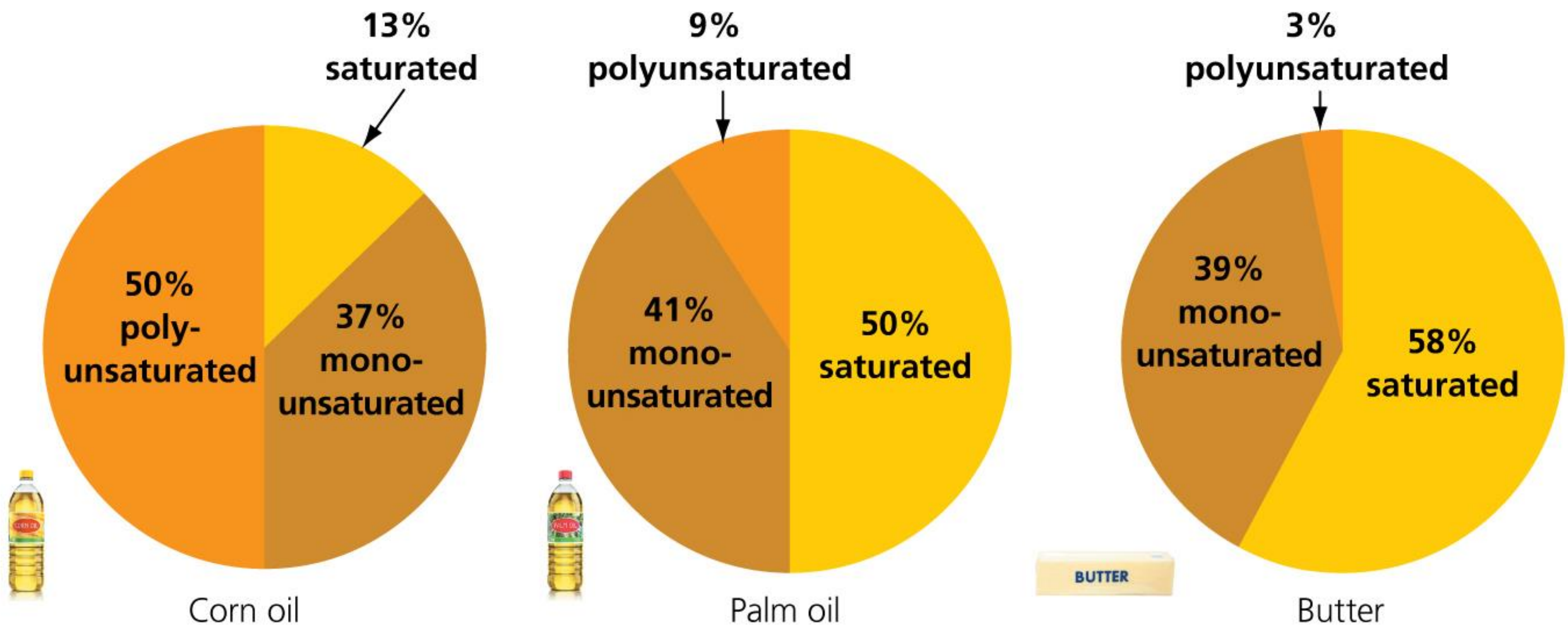


(b) A fat molecule with a glycerol "head" and three energy-rich hydrocarbon fatty acid "tails"

Fats (Cont.)

- If the carbon skeleton of a fatty acid has fewer than the maximum number of hydrogens at the double bond, it is **unsaturated**.
- If it has the maximum number of hydrogens, it is **saturated**.
- A saturated fat has all three of its fatty acids saturated.

Relative amounts of different fats



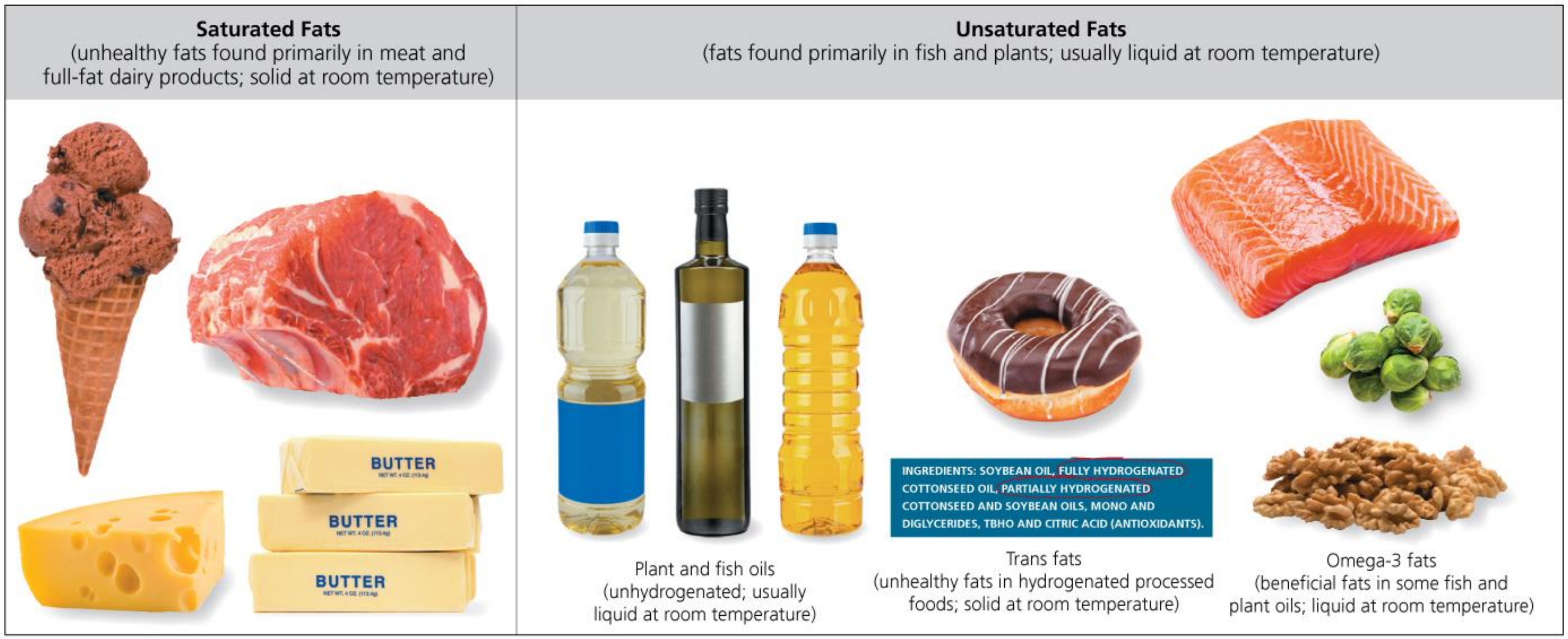
Fats (Cont.)

- Most animal fats
  - have a relatively high proportion of saturated fatty acids,
  - can easily stack, tending to be solid at room temperature, and
  - contribute to atherosclerosis.
- Most plant and fish fats tend to be
  - high in unsaturated fatty acids and
  - liquid at room temperature.

Fats (Cont.)

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

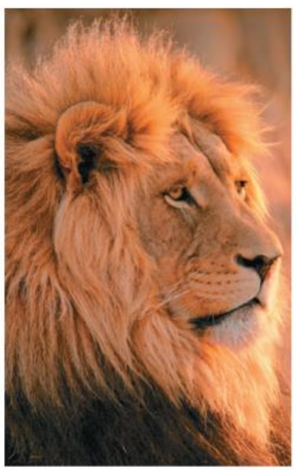
Types of fats

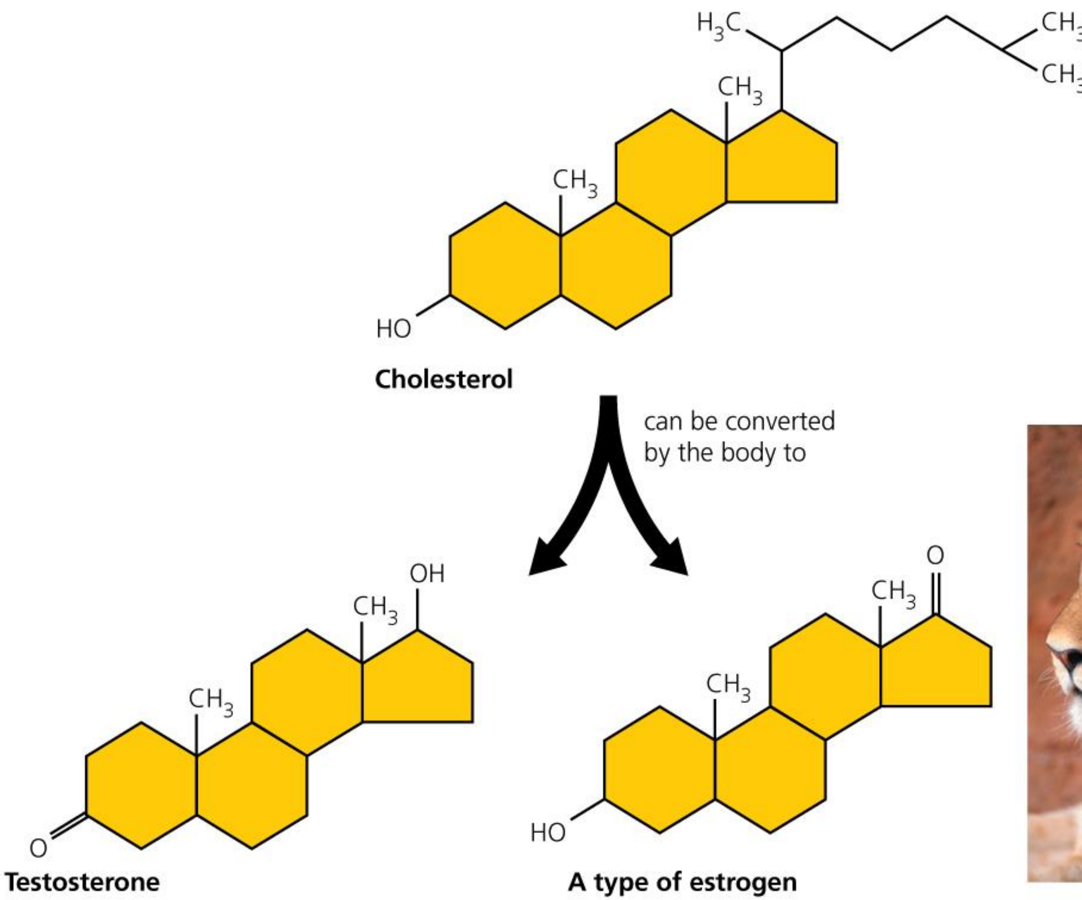


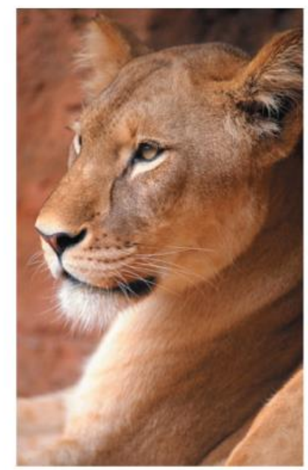
Steroids

- **Steroids** are very different from fats in structure and function.
  - The carbon skeleton has four fused rings.
  - Steroids vary in the functional groups attached to this set of rings, and these chemical variations affect their function.
- Cholesterol is
  - a key component of cell membranes and
  - the “base steroid” from which your body produces other steroids, such as estrogen and testosterone.

Examples of steroids







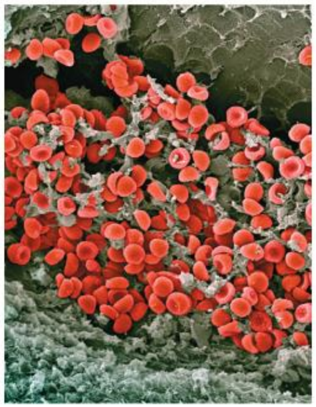
Steroids (Cont.)

- Synthetic anabolic steroids
  - are variants of testosterone,
  - mimic some of its effects,
  - may be prescribed to treat diseases such as cancer and AIDS,
  - are abused by athletes to build up their muscles quickly, and
  - can cause serious physical and mental problems.
- Most athletic organizations ban the use of anabolic steroids.

Proteins

- **Proteins**
  - are polymers of amino acid monomers,
  - account for more than 50% of the dry weight of most cells, and
  - are instrumental in almost everything cells do.

Some of the varied roles played by proteins

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)
				
Structural proteins form hair, ligaments, and horns.	Seeds and eggs are rich in storage proteins.	Contractile proteins enable muscles to contract.	The protein hemoglobin within red blood cells transports oxygen.	Some cleaning products use enzymes to help break down molecules.

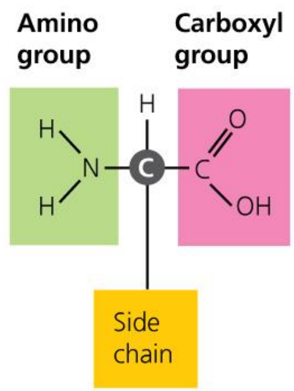
The Monomers of Proteins: Amino Acids

- All proteins are made by stringing together a common set of 20 kinds of amino acids.
- Every **amino acid** consists of a central carbon atom bonded to four covalent partners.
- Three of those attachment groups are common to all amino acids:
    1. a carboxyl group (–COOH),
    2. an amino group ($–NH_2$), and
    3. a hydrogen atom.

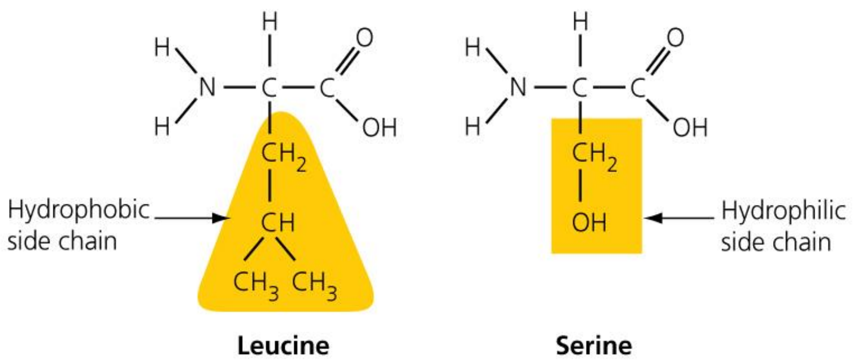
The Monomers of Proteins: Amino Acids (Cont.)

- Each type of amino acid has a unique side chain, which gives that amino acid its special chemical properties.

Amino acids



(a) The general structure of an amino acid.

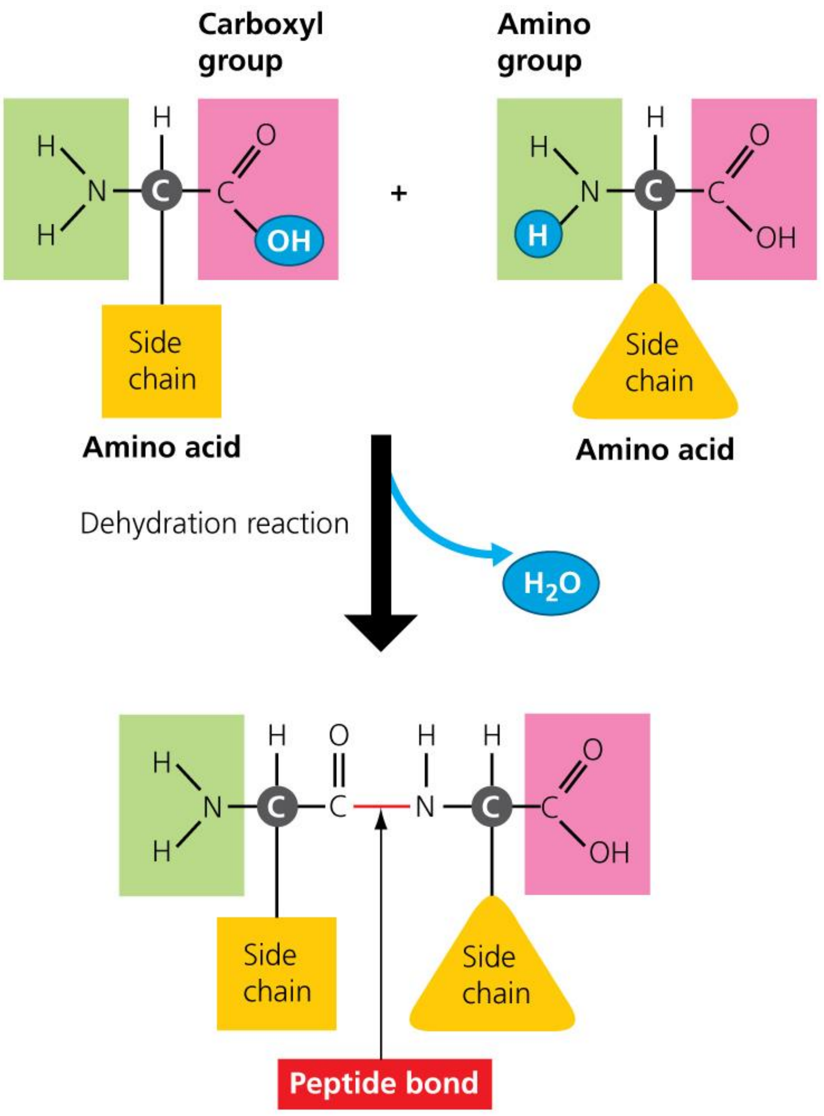


(b) Examples of amino acids with hydrophobic and hydrophilic side chains. The side chain of the amino acid leucine is hydrophobic. In contrast, the side chain of the amino acid serine has a hydroxyl group (–OH), which is hydrophilic.

Structure/Function: Protein Shape

- Cells link amino acids together by dehydration reactions,
  - forming **peptide bonds**, and
  - creating long chains of amino acids called **polypeptides**.
- A functional protein is one or more polypeptide chains precisely twisted, folded, and coiled into a molecule of unique shape.

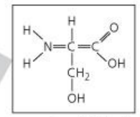
Joining amino acids



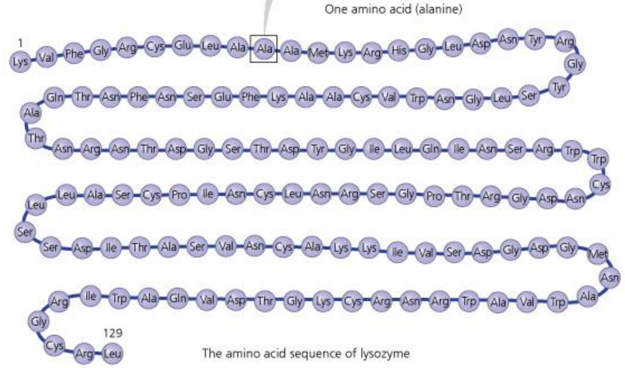
Structure/Function: Protein Shape

- Proteins use 20 different “letters” (amino acids) to create polypeptides hundreds or thousands of amino acids in length.
  - The amino acid sequence of each polypeptide determines the three-dimensional structure.
  - A protein’s three-dimensional structure enables the molecule to carry out its specific function.
  - Nearly all proteins work by recognizing and binding to some other molecule.

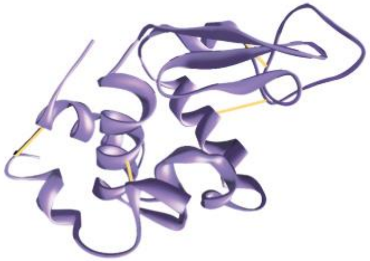
The structure of a protein



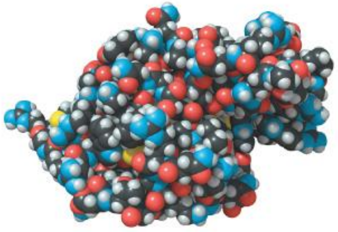
One amino acid (alanine)



The amino acid sequence of lysozyme



Here you can see how the polypeptide folds into a compact shape.

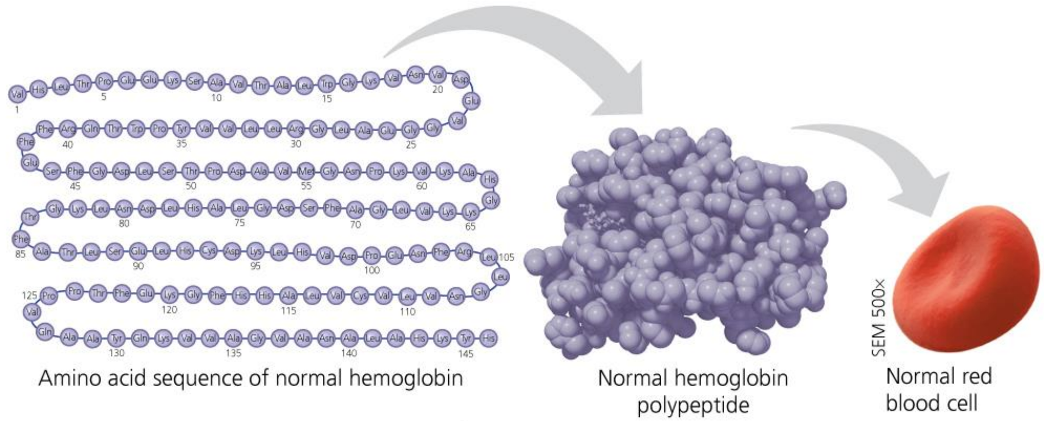


This model allows you to see the details of the protein's structure.

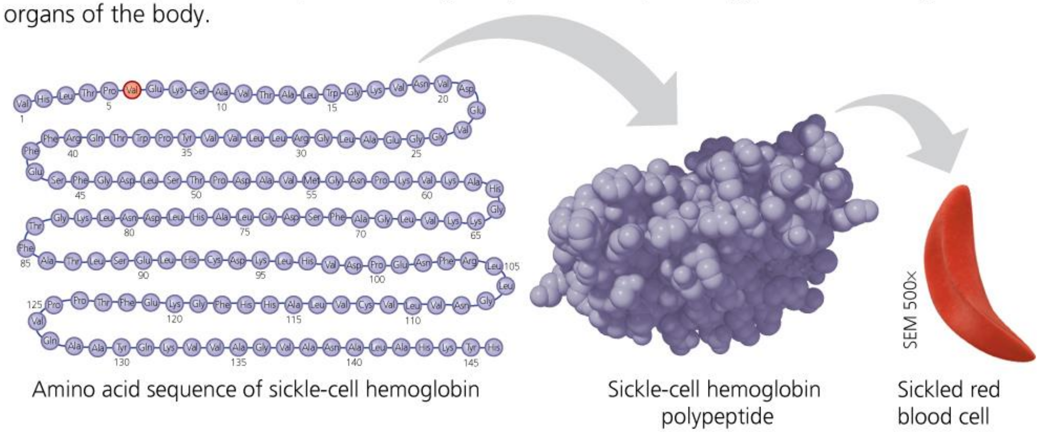
Structure/Function: Protein Shape (Cont.)

- A slight change in the amino acid sequence can affect a protein’s ability to function.
- The substitution of one amino acid for another at a particular position in hemoglobin, the blood protein that carries oxygen, causes sickle-cell disease, an inherited blood disorder.

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



(a) Normal hemoglobin. Red blood cells of humans are normally disk-shaped. Each cell contains millions of molecules of the protein hemoglobin, which transports oxygen from the lungs to other organs of the body.

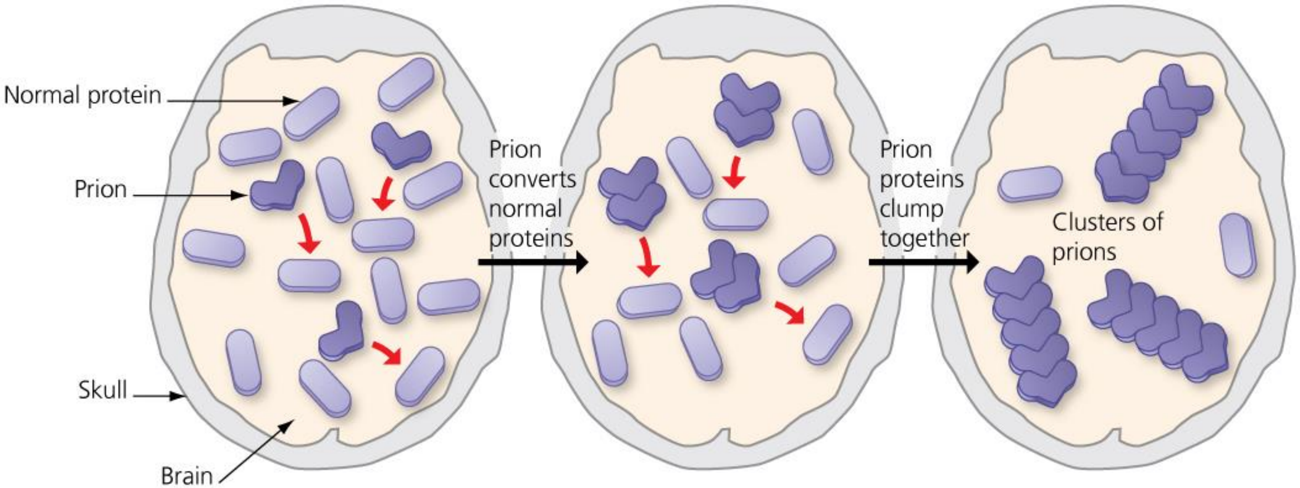


(b) Sickle-cell hemoglobin. A slight change in the amino acid sequence of hemoglobin causes sickle-cell disease. The inherited substitution of one amino acid—valine in place of the amino acid glutamic acid—occurs at the sixth position of the polymer. Such abnormal hemoglobin molecules tend to crystallize, deforming some cells into a sickle shape. Someone with the disease suffers from dangerous episodes when the angular cells clog tiny blood vessels, impeding blood flow.

Structure/Function: Protein Shape (Cont.)

- One difference in structure is enough to cause the protein to fold into a different shape, which alters its function, which in turn causes disease.
- Misfolded proteins are associated with many diseases, including some severe nervous system disorders.
- The diseases shown in **Figure 3.21** are all caused by prions, misfolded versions of normal brain proteins.

How an improperly folded protein can lead to brain disease



Prions cause fatal weight loss in several animals, including deer, elk, and moose. They also cause mad cow disease.

Structure/Function: Protein Shape (Cont.)

- A protein’s shape is sensitive to the environment.
- An unfavorable change in temperature, pH, or some other factor can cause a protein to unravel.

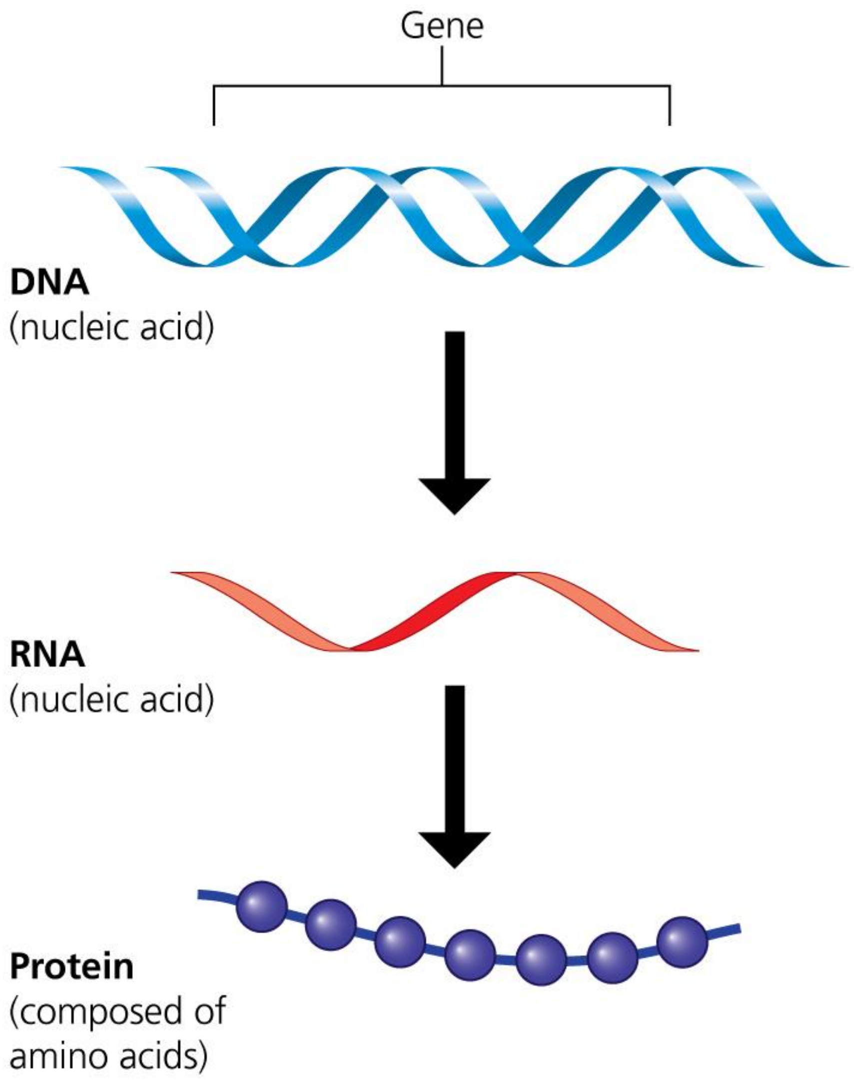
Nucleic Acids

- **Nucleic acids** are macromolecules that
  - store information and
  - provide the instructions for building proteins.
- They consist of two types:
  - **DNA** (deoxyribonucleic acid and
  - **RNA** (ribonucleic acid).

Nucleic Acids (Cont.)

- The genetic material that humans and all other organisms inherit from their parents consists of giant molecules of DNA.
- The DNA resides in the cell as one or more very long fibers called chromosomes.
- A **gene** is a unit of inheritance encoded in a specific stretch of DNA that programs the amino acid sequence of a polypeptide.

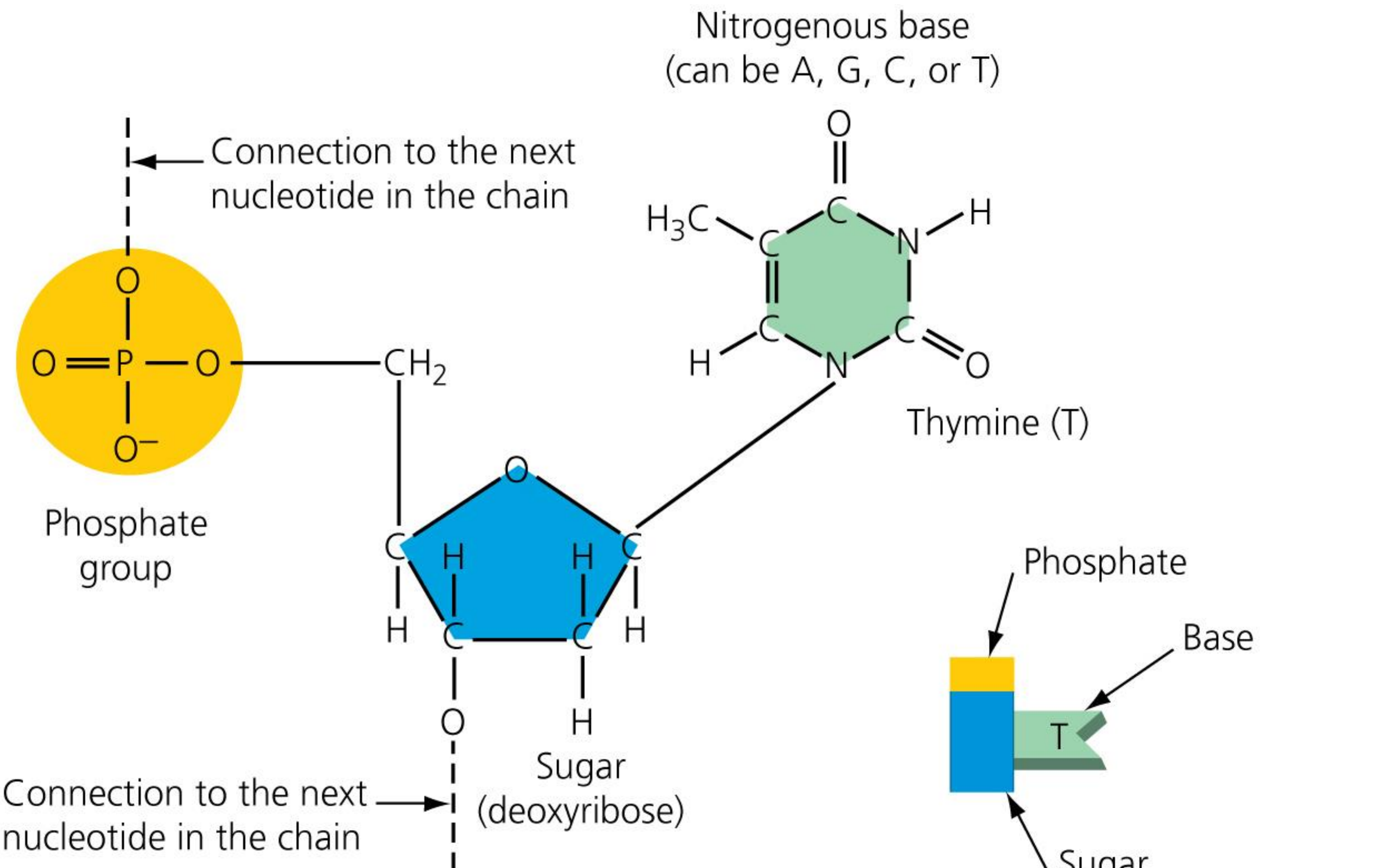
Building a protein



Nucleic Acids (Cont.)

- 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.

A DNA nucleotide



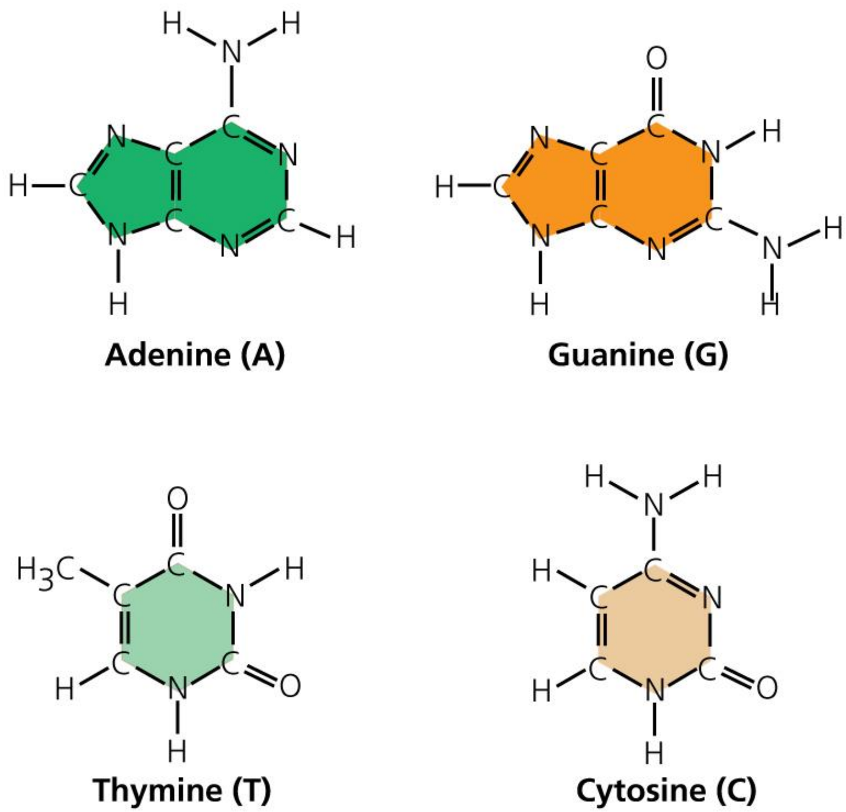
(a) Atomic structure

(b) Symbol used in this book

Nucleic Acids (Cont.)

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

The nitrogenous bases of DNA

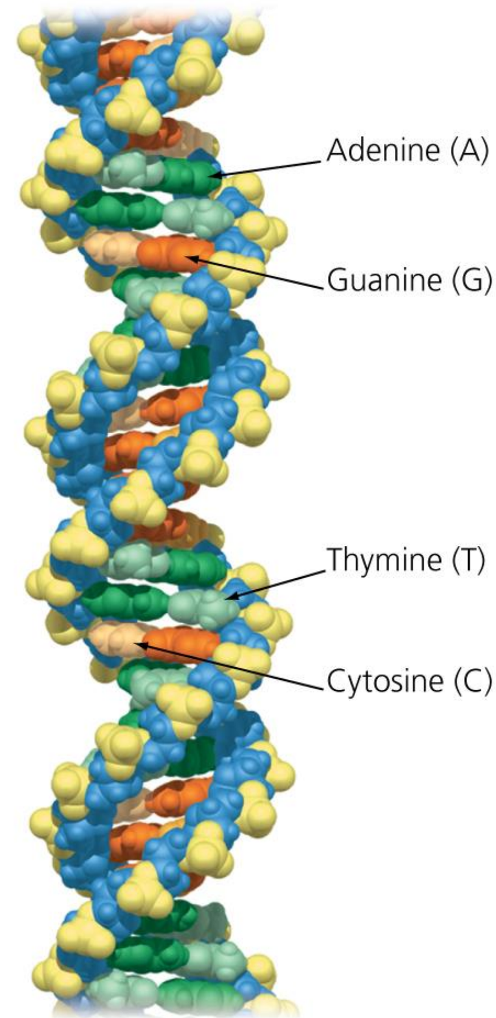


Adenine (A)

Guanine (G)

Thymine (T)

Cytosine (C)



Space-filling model of DNA
(showing the four bases in four different colors)

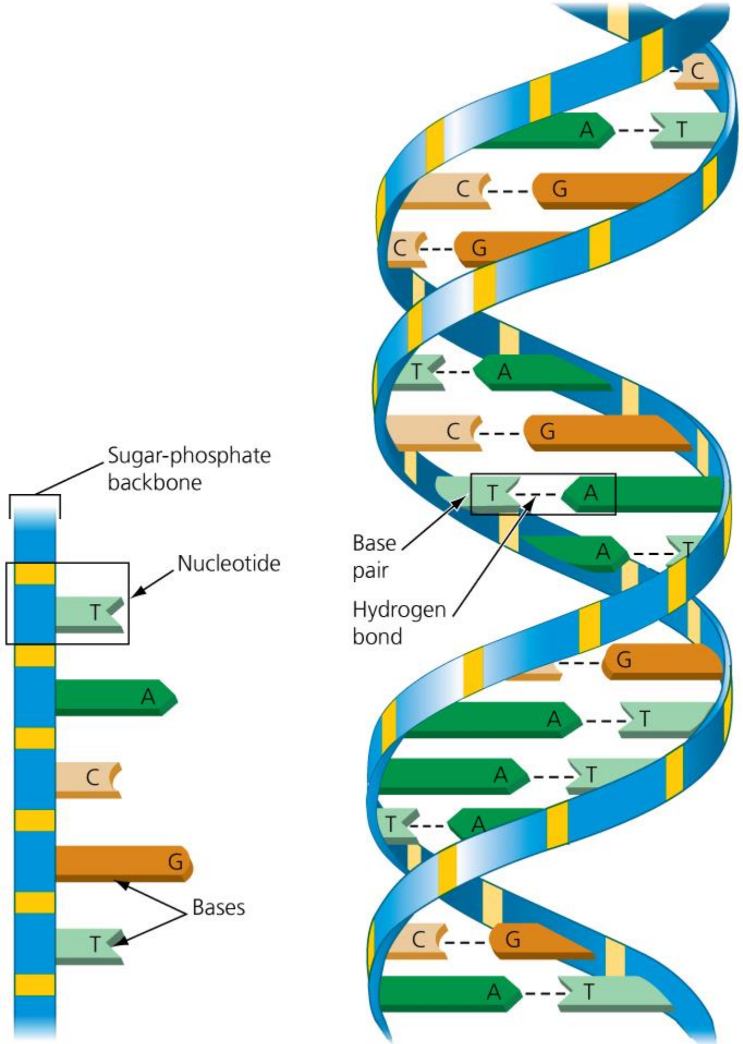
Nucleic Acids (Cont.)

- 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**.
- Bases (A, T, C, or G) hang off the backbone like appendages.

Nucleic Acids (Cont.)

- A molecule of cellular DNA is double-stranded, with two polynucleotide strands coiled around each other 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.

The structure of DNA



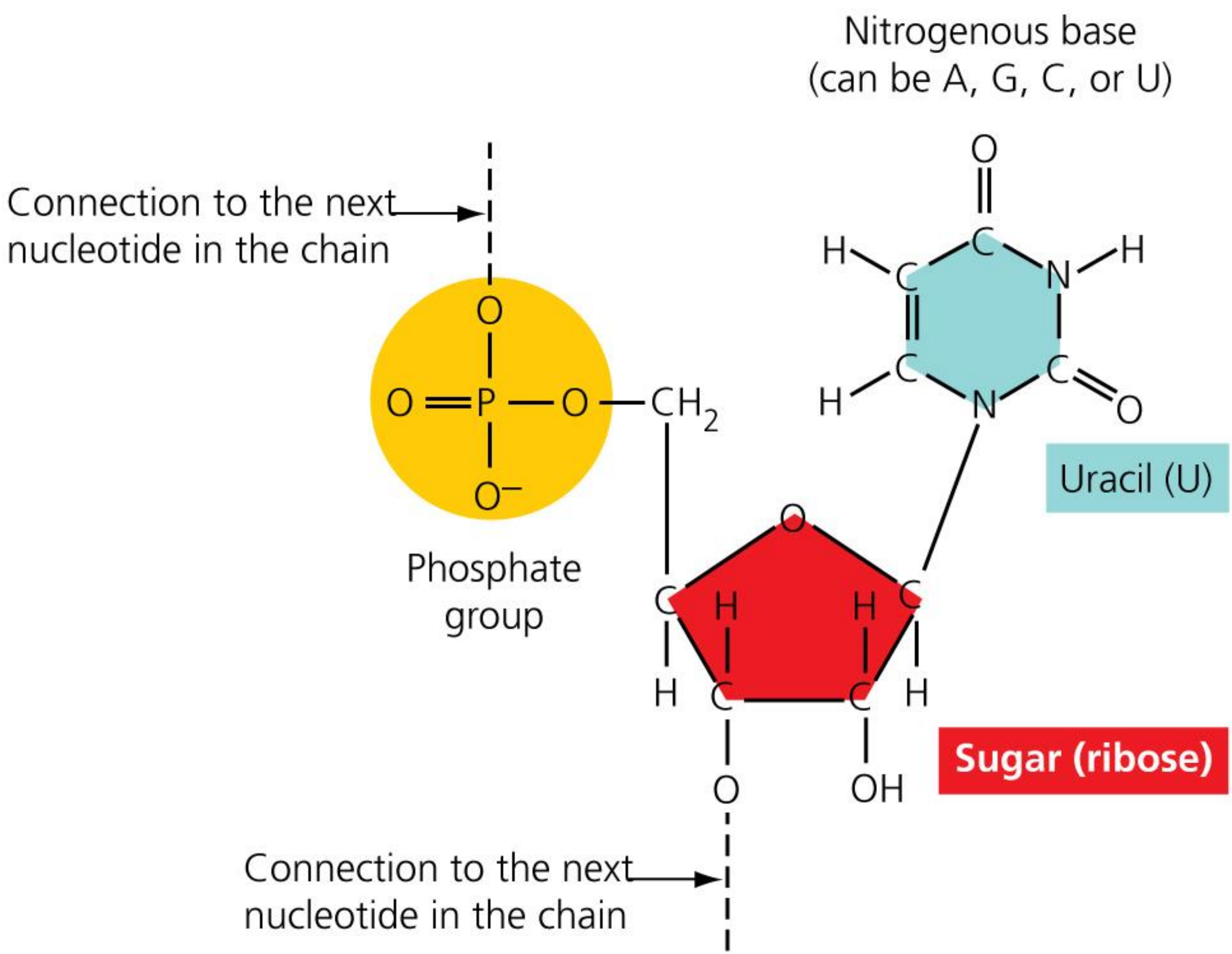
(a) **DNA strand** (polynucleotide)

(b) **Double helix** (two polynucleotide strands)

Nucleic Acids (Cont.)

- Both DNA and RNA are polymers of nucleotides and both are made of nucleotides consisting of a sugar, a phosphate, and a base.
- But there are differences between DNA and RNA.
  1. As its name *ribonucleic acid* denotes, the RNA sugar is ribose rather than deoxyribose in DNA.
  2. Instead of the base thymine, RNA has a similar but distinct base called uracil (U).
  3. RNA is usually found in single-stranded form, whereas DNA usually exists as a double helix.

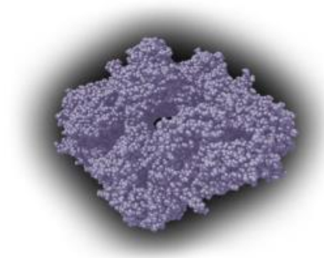
An RNA nucleotide



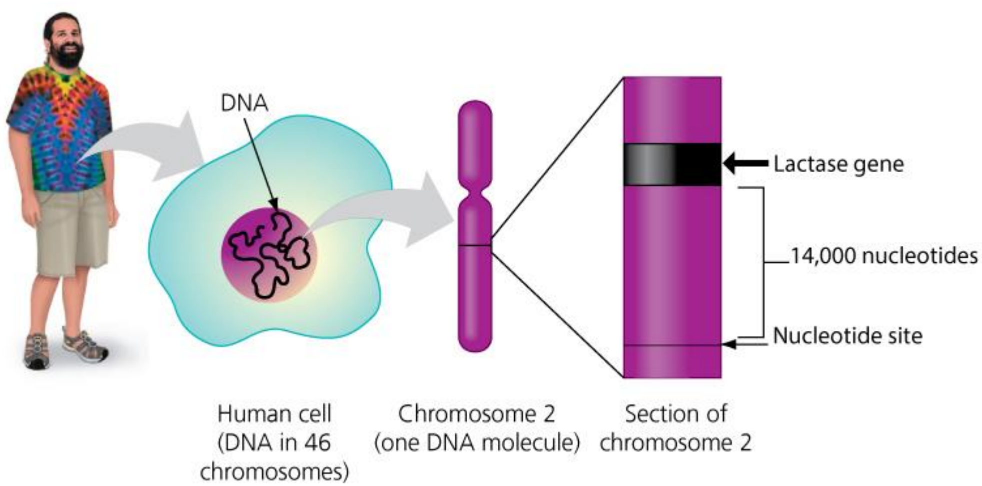
Biology and Society: Got Lactose?

- Lactose is the main sugar found in milk.
- Lactose intolerance is the inability to properly digest lactose.
- Lactose intolerance can be addressed by
  - avoiding lactose-containing foods or
  - consuming lactase pills along with food.

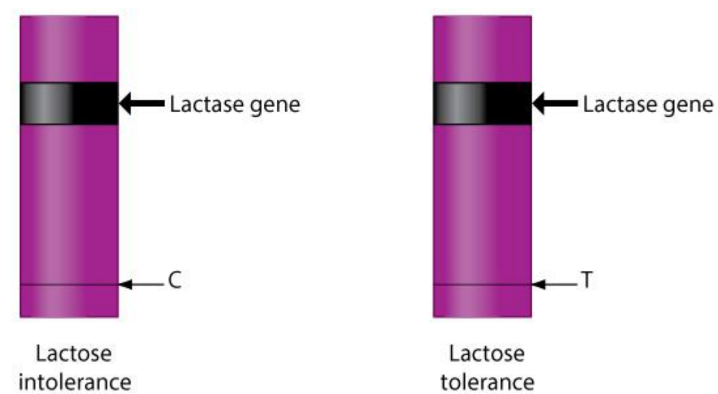
A genetic cause of lactose intolerance



(a) Lactase enzyme



(b) Locations of the lactase gene and the nucleotide site



(c) The nucleotide difference determining lactose intolerance or lactose tolerance.