Protein Structure and Function A protein has a unique three-dimensional shape, or structure, created by the twisting or folding of one or more polypeptide chains. Protein structure usually arises spontaneously. Depending on the sequence of amino acids, various types of bonds form between parts of the chain as the protein is synthesized in the cell. The unique structure of a protein enables it to recognize and bind to other molecules. *Globular proteins* are roughly spherical; *fibrous proteins* are long fibers.

Primary structure is the genetically coded sequence of amino acids within a protein.

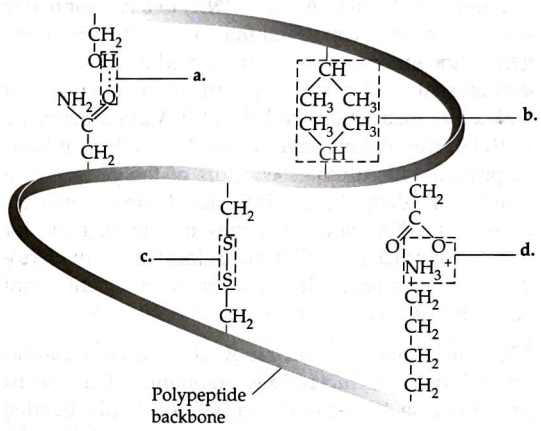
Secondary structure involves regions of coiling or folding of the polypeptide backbone, stabilized by hydrogen bonds between the oxygen (with a partial negative charge) of one peptide bond and the partially positive hydrogen attached to the nitrogen of another peptide bond. An α **helix** is a coil produced by hydrogen bonding between every fourth amino acid. A β **pleated sheet** is held by repeated hydrogen bonds along regions of the polypeptide backbone lying parallel to each other.

Tertiary structure, the three-dimensional shape of a protein, results from interactions between the various side chains (R groups) of the constituent amino acids. The following chemical interactions help produce the stable and unique shape of a protein: **hydrophobic interactions** between nonpolar side groups clumped in the center of the molecule due to their repulsion by water, van der Waals interactions among those nonpolar side chains, hydrogen bonds between polar side chains, and ionic bonds between negatively and positively charged side chains. Strong covalent bonds, called **disulfide bridges**, may occur between the sulfhydryl side groups of cysteine monomers that have been brought close together by the folding of the polypeptide.

Quaternary structure occurs in proteins that are composed of more than one polypeptide. The individual polypeptide subunits are held together in a precise structural arrangement to form a functional protein.

FOCUS QUESTION 3.8

In the following diagram of a portion of a protein, label the types of interactions that are shown. What level of structure are these interactions producing?



In the inherited blood disorder **sickle-cell disease**, a change in one amino acid affects the structure of a hemoglobin molecule, causing red blood cells to deform into a sickle shape that clogs tiny blood vessels.

The bonds and interactions that maintain the three-dimensional shape of a protein may be disrupted by changes in pH, salt concentration, or temperature, causing a protein to unravel. **Denaturation** also occurs if a protein is transferred to an organic solvent; in that case, its hydrophobic regions are on the outside interacting with the nonpolar solvent.

Using the technique of **X-ray crystallography** biochemists have identified the structure of thousands of proteins. These structures can then be related to the specific functions of different regions of a protein.

FOCUS QUESTION 3.9

Now that you have gained experience with concept maps, create your own map to review what you have learned about proteins. Try to include the concepts of structure and function, and look for cross-links on your map. You may want to include the functions of proteins. *One version of a protein concept map is included in the answer section, but remember that the real value is in the thinking process you must go through to create your own map.*

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

Genes are the units of inheritance that determine the primary structure of proteins. **Nucleic acids** are polymers made of nucleotide monomers.

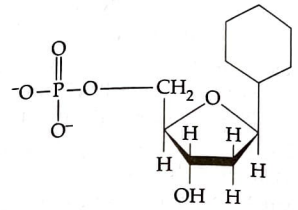
The Roles of Nucleic Acids **DNA, deoxyribonucleic acid**, is the genetic material that is inherited from one generation to the next and is replicated whenever a cell divides so that all cells of an organism contain identical DNA. The instructions coded in DNA are transcribed to **RNA, ribonucleic acid**, which directs the synthesis of proteins, the ultimate enactors of the genetic program. In a eukaryotic cell, DNA resides in the nucleus. *Messenger RNA* (*mRNA*) carries the instructions for protein synthesis to ribosomes located in the cytoplasm. Recent research has revealed other important functions of RNA.

The Components of Nucleic Acids **Polynucleotides** are polymers of **nucleotides**—monomers that consist of a pentose (five-carbon sugar) covalently bonded to a phosphate group and to a nitrogenous (nitrogen-containing) base. A nucleotide may contain more than one phosphate group; without the phosphate group it is called a *nucleoside*.

Nitrogenous bases are either **pyrimidines** or **purines**, which consist respectively of one or two nitrogen-containing rings. Adenine, guanine, and cytosine are present in DNA and RNA. The base thymine is present only in DNA; uracil is only in RNA. In DNA, the sugar is **deoxyribose**; in RNA, it is **ribose**. In a nucleotide, the base attaches to the 1′ carbon and a phosphate group attaches to the 5′ carbon of the sugar.

Nucleotide Polymers Nucleotides are linked together into a polynucleotide by phosphodiester linkages, which join the sugar of one nucleotide with the phosphate of the next. The polymer has two distinct ends: a 5′ end with a phosphate attached to the 5′ carbon of a sugar, and a 3′ end with a hydroxyl group on the 3′ carbon of a sugar. The nitrogenous bases extend from this backbone of repeating sugar-phosphate units. The unique sequence of bases in a gene codes for the specific amino acid sequence of a protein.

FOCUS QUESTION 3.10



a. Label the three parts of this nucleotide. Indicate with an arrow where the phosphate group of the next nucleotide would attach to build a polynucleotide. Number the carbons of the pentose.

b. Is the base of this nucleotide a purine or a pyrimidine? How do you know?

c. Is this a DNA nucleotide or an RNA nucleotide? How do you know?

The Structure of DNA and RNA Molecules DNA molecules consist of two polynucleotides (strands) spiraling in a **double helix**. The two sugar-phosphate backbones run in opposite 5′ to 3′ directions, an arrangement called **antiparallel**. The nitrogenous bases pair and hydrogen-bond together in the inside of the molecule. Adenine pairs only with thymine; guanine always pairs with cytosine. Thus, the sequences of nitrogenous bases on the two strands of DNA are *complementary*. Because of this specific base-pairing property, DNA can precisely replicate itself.

RNA molecules are usually single polynucleotides, although base-pairing within or between RNA molecules is common. For example, the functional shape of *transfer RNA* (*tRNA*), an RNA involved in protein synthesis, involves several regions of complementary base-pairing.

DNA and Proteins as Tape Measures of Evolution Genes form the hereditary link between generations. Closely related members of the same species share many common DNA sequences and proteins. More closely related species have a larger proportion of their DNA and proteins in common. This "molecular

genealogy" provides evidence of evolutionary relationships.

FOCUS QUESTION 3.11

Take the time to create a concept map that summarizes what you have just reviewed about nucleic acids. Compare your map with that of a study partner or explain it to a friend. Refer to Figures 3.26 and 3.27 in your textbook to help you visualize polynucleotides and the three-dimensional structures of DNA and RNA.

Word Roots

carb- = coal (*carboxyl group:* a chemical group present in organic acids, consisting of a single carbon atom double-bonded to an oxygen atom and also bonded to a hydroxyl group)

di- = two; **-sacchar** = sugar (*disaccharide:* a double sugar, consisting of two monosaccharides joined through a dehydration reaction)

glyco- = sweet (*glycogen:* an extensively branched glucose polysaccharide that stores energy in animals)

hydro- = water; **-lyse** = break (*hydrolysis:* a chemical reaction that breaks bonds between two molecules by the addition of water; functions in disassembly of polymers to monomers)

macro- = large (*macromolecule:* a giant molecule formed by the joining of smaller molecules, such as a polysaccharide, a protein, or a nucleic acid)

poly- = many; **meros-** = part (*polymer:* a long molecule consisting of many similar or identical monomers linked together by covalent bonds)

sulf- = sulfur (*sulfhydryl group:* a chemical group consisting of a sulfur atom bonded to a hydrogen atom)

tri- = three (*triacylglycerol:* a lipid consisting of three fatty acids linked to one glycerol molecule; also called a fat or triglyceride)

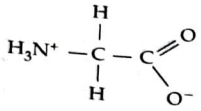
Structure Your Knowledge

1. The diversity of life is amazing. Yet the molecular logic of life is simple: Small molecules common to all organisms are ordered into unique large biological molecules. Explain why carbon is central to the molecular diversity of life. How do carbon skeletons, chemical groups, monomers, and polymers relate to this diversity?

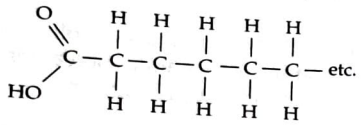
2. Fill in the following table on the important chemical groups of organic compounds.

Chemical Group	Molecular Formula	Names and Characteristics of Compounds Containing Group
	—OH	
		Aldehyde or ketone; polar group
Carboxyl		
	—NH_2	
		Thiols; cross-links stabilize proteins
Phosphate		
	—CH_3	

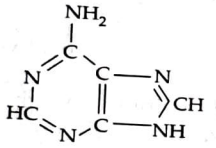
3. Identify the type of monomer or group shown by the formulas a–g. Then match the chemical formulas with their descriptions. Answers may be used more than once.



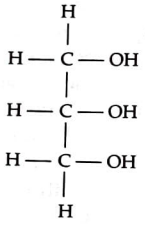
a. _____



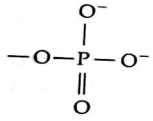
b. _____



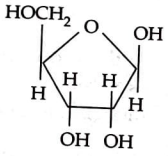
c. _____



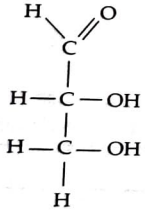
d. _____



e. _____



f. _____



g. _____

_____ 1. molecules that would combine to form a fat

_____ 2. monomer that would be attached to other monomers by a peptide bond

_____ 3. molecules or groups that would combine to form a nucleotide

_____ 4. molecules that are carbohydrates

_____ 5. monomer of a protein

_____ 6. most nonpolar (hydrophobic) molecule

4. Describe the four structural levels that produce the functional shape of a protein.

Test Your Knowledge

MATCHING: *Match the molecule with its class of molecule.*

_____ 1. glycogen
_____ 2. cholesterol
_____ 3. RNA
_____ 4. collagen
_____ 5. hemoglobin
_____ 6. a gene
_____ 7. triacylglycerol
_____ 8. enzyme
_____ 9. cellulose
_____ 10. chitin

A. carbohydrate
B. lipid
C. protein
D. nucleic acid

MULTIPLE CHOICE: *Choose the one best answer.*

1. Carbon's valence of four most directly results from
   a. its tetrahedral shape.
   b. its very slight electronegativity.
   c. its four electrons in the valence shell that can form four covalent bonds.
   d. its ability to form single, double, and triple bonds.
   e. its ability to form chains and rings of carbon atoms.

2. Hydrocarbons are not soluble in water because
   a. they are hydrophilic.
   b. their C—H bonds are nonpolar.
   c. they do not ionize.
   d. they store energy in the many C—H bonds along the carbon backbone.
   e. they are lighter than water.

3. The chemical group that can cause an organic molecule to act as a base is
   a. —COOH.
   b. —OH.
   c. —SH.
   d. $—NH_2$.
   e. $—CH_3$.

4. The chemical group that confers acidic properties to organic molecules is
   a. —COOH.
   b. —OH.
   c. —SH.
   d. $—NH_2$.
   e. $—CH_3$.

5. Polymerization (the formation of polymers) is a process that
   a. creates bonds between glucose monomers in the formation of a polypeptide.
   b. involves the addition of a water molecule.
   c. links the nitrogenous base of one nucleotide with the phosphate of the next.
   d. involves a dehydration reaction.
   e. may involve all of the above.

6. Which of the following statements is *not* true of a hexose?
   a. It may be found in nucleic acids.
   b. It can occur in a ring structure.
   c. It has the formula $C_6H_{12}O_6$.
   d. It has one carbonyl and five hydroxyl groups.
   e. It may be an aldehyde or a ketone sugar.

7. Which of the following statements is *not* true of cellulose?
   a. It is the most abundant organic compound on Earth.
   b. It differs from starch because of the configuration of glucose and the geometry of the glycosidic linkage.
   c. It may be hydrogen-bonded to neighboring cellulose molecules to form microfibrils.
   d. Few organisms have enzymes that hydrolyze its glycosidic linkages.
   e. Its monomers are glucose with nitrogen-containing appendages.

8. Plants store most of their energy for later use as
   a. unsaturated fats.
   b. glycogen.
   c. starch.
   d. sucrose.
   e. cellulose.

9. Maltose is made from joining two glucose molecules in a dehydration reaction. What is the molecular formula for this disaccharide?
   a. $C_6H_{12}O_6$
   b. $C_{10}H_{20}O_{10}$
   c. $C_{12}H_{22}O_{11}$
   d. $C_{12}H_{24}O_{12}$
   e. $C_{12}H_{24}O_{13}$

10. A cow can derive nutrients from cellulose because
    a. it can produce the enzymes that break the β linkages between glucose molecules.
    b. it chews and rechews its cud so that cellulose fibers are finally broken down.
    c. its rumen contains prokaryotes and protists that can hydrolyze the bonds of cellulose.
    d. its intestinal tract contains termites, which harbor microbes that hydrolyze cellulose.
    e. it has enzymes that convert cellulose to starch and then hydrolyze starch to glucose.

11. Which of the following substances is the major component of the cell membrane of a fungus?
    a. cellulose
    b. chitin
    c. cholesterol
    d. phospholipids
    e. unsaturated fatty acids

12. A fatty acid that has the formula $C_{16}H_{32}O_2$ is
    a. saturated.
    b. unsaturated.
    c. branched.
    d. hydrophilic.
    e. part of a steroid molecule.

13. Three molecules of the fatty acid in question 12 are joined to a molecule of glycerol ($C_3H_8O_3$). The resulting molecule has the formula
    a. $C_{48}H_{96}O_6$.
    b. $C_{48}H_{98}O_9$.
    c. $C_{51}H_{102}O_8$.
    d. $C_{51}H_{98}O_6$.
    e. $C_{51}H_{104}O_9$.

14. Which of the following molecules is the most hydrophobic?
    a. cholesterol
    b. nucleotide
    c. chitin
    d. phospholipid
    e. glucose

15. Which of the following molecules provides the most energy (kcal/g) when eaten and digested?
    a. glucose
    b. starch
    c. glycogen
    d. fat
    e. protein

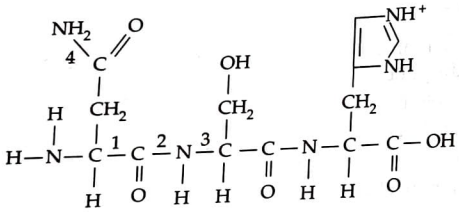
16. Which of the following is *not* one of the many functions performed by proteins?
    a. acting as signals and receptors
    b. acting as an enzymatic catalyst for metabolic reactions
    c. providing protection against disease
    d. serving as contractile components of muscle
    e. forming primary energy storage in plant seeds

17. What happens when a protein denatures?
    a. Its primary structure is disrupted.
    b. Its secondary and tertiary structures are disrupted.
    c. It always flips inside out.
    d. It hydrolyzes into component amino acids.
    e. Its hydrogen bonds, ionic bonds, hydrophobic interactions, disulfide bridges, and peptide bonds are disrupted.

18. The α helix of proteins is
    a. part of the protein's tertiary structure and is stabilized by disulfide bridges.
    b. a double helix.
    c. stabilized by hydrogen bonds and is commonly found in fibrous proteins.
    d. found in some regions of globular proteins and is stabilized by hydrophobic interactions.
    e. a complementary sequence to messenger RNA.

19. β pleated sheets are characterized by
    a. disulfide bridges between cysteine amino acids.
    b. parallel regions of the polypeptide chain held together by hydrophobic interactions.
    c. folds stabilized by hydrogen bonds between segments of the polypeptide backbone.
    d. membrane sheets composed of phospholipids.
    e. hydrogen bonds between adjacent cellulose molecules.

20. What is the *best* description of the following molecule?



    a. chitin
    b. amino acid
    c. tripeptide
    d. nucleotide
    e. protein

21. Which number(s) in the molecule in question 20 refer(s) to a peptide bond?
    a. 1
    b. 2
    c. 3
    d. 4
    e. both 2 and 4

22. What *determines* the sequence of the amino acids in a particular protein?
    a. its primary structure
    b. the sequence of nucleotides in RNA, which was determined by the sequence of nucleotides in the gene for that protein
    c. the sequence of nucleotides in DNA, which was determined by the sequence of nucleotides in RNA
    d. the sequence of RNA nucleotides making up the ribosome
    e. the three-dimensional shape of the protein

23. Both hydrophobic and hydrophilic interactions are important for which of the following types of molecules or structures?
    a. proteins
    b. cell membranes
    c. cellulose in plant cell walls
    d. a and b
    e. a, b, and c

24. How are nucleotide monomers connected to form a polynucleotide?
    a. by hydrogen bonds between complementary nitrogenous base pairs
    b. by ionic attractions between phosphate groups
    c. by disulfide bridges between cysteines
    d. by covalent bonds between the sugar of one nucleotide and the phosphate of the next
    e. by ester linkages between the carboxyl group of one nucleotide and the hydroxyl group on the ribose of the next

25. If the nucleotide sequence of one strand of a DNA helix is 5′GCCTAA3′, what would be the 3′–5′ sequence on the complementary strand?
    a. GCCTAA
    b. CGGAUU
    c. CGGATT
    d. ATTCGG
    e. TAAGCC

26. Monkeys and humans share many of the same DNA sequences and have similar proteins, indicating that
    a. the two groups belong to the same species.
    b. the two groups share a relatively recent common ancestor.
    c. humans evolved from monkeys.
    d. monkeys evolved from humans.
    e. the two groups evolved about the same time.