Chapter 5

The Structure and Function of Large Biological Molecules

Key Concepts

5.1 Macromolecules are polymers, built from monomers

5.2 Carbohydrates serve as fuel and building materials

5.3 Lipids are a diverse group of hydrophobic molecules

5.4 Proteins include a diversity of structures, resulting in a wide range of functions

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

5.6 Genomics and proteomics have transformed biological inquiry and applications

Framework

A small number of monomers or subunits join to form a huge variety of large molecules with diverse structures and functions. The following table briefly summarizes the four classes of biological molecules.

Class	Monomers or Components	Functions
Carbohydrates	Monosaccharides	Energy source, raw materials, energy storage, structural compounds
Lipids	Glycerol and fatty acids → fats; phospholipids; steroids	Energy storage (fats), membrane components (phospholipids), hormones (steroids)
Proteins	Amino acids	Enzymes, transport, movement, receptors, defense, structure, storage, hormones
Nucleic acids	Nucleotides	Heredity, various functions in gene expression

Chapter Review

The most important biological molecules include lipids and the huge **macromolecules** of carbohydrates, proteins, and nucleic acids. These molecules have emergent properties that arise from their complex and unique structures.

5.1 Macromolecules are polymers, built from monomers

Polymers are chainlike molecules formed from the linking together of many similar or identical small molecules, called **monomers.** The macromolecules of carbohydrates, proteins, and nucleic acids are polymers.

The Synthesis and Breakdown of Polymers Monomers are joined by a **dehydration reaction,** in which one monomer provides a hydroxyl group (—OH) and the other contributes a hydrogen (—H) to release a water molecule. In **hydrolysis,** the bond between monomers is broken by the addition of water. The hydroxyl group of a water molecule is joined to one monomer while the hydrogen is bonded with the other. **Enzymes** catalyze both dehydration reactions and hydrolysis.

The Diversity of Polymers Polymers are constructed from about 40 to 50 common monomers and a few rarer molecules. The seemingly endless variety of macromolecules arises from the essentially infinite number of possibilities in the sequencing of these basic building blocks.

INTERACTIVE QUESTION 5.1

Monomers are linked into polymers by ________ ________, which involve the ________ of a water molecule.

Polymers are broken down to monomers by ________, which involves the ________ of a water molecule.

5.2 Carbohydrates serve as fuel and building materials

Carbohydrates include sugars and their polymers.

Sugars **Monosaccharides** have the general formula of $(CH_2O)_n$. The number (n) of these units forming a sugar varies, with hexoses ($C_6H_{12}O_6$), trioses, and pentoses being most common. Sugar molecules also vary in the location of their carbonyl group and the spatial arrangement of parts around asymmetric carbons.

INTERACTIVE QUESTION 5.2

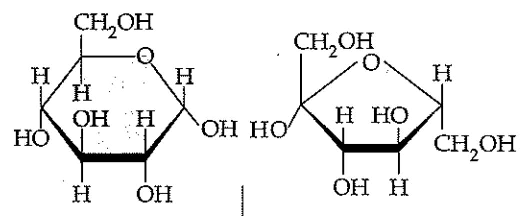
Fill in the blanks to review monosaccharides.

You can recognize a monosaccharide by its multiple (a) ________ groups and its one (b) ________ group, whose location determines whether the sugar is a(n) (c) ________ or a(n) (d) ________. In aqueous solutions, most five- and six-carbon sugars form (e) ________. The names for most sugars end in (f) ________.

Glucose is broken down to yield energy in cellular respiration. Monosaccharides also serve as the raw materials for the synthesis of other organic molecules. Two monosaccharides are joined by a **glycosidic linkage** to form a **disaccharide.**

INTERACTIVE QUESTION 5.3

Number the carbons in the following glucose and fructose molecules (Each unlabeled corner of the ring represents a carbon. In glucose, carbon 1 is to the right of the O in the ring; in fructose, carbon 1 extends up from the ring on the left side.) Circle the atoms that will be removed by a dehydration reaction. Then draw the resulting sucrose molecule with its 1–2 glycosidic linkage.



Glucose

Fructose

Sucrose

Polysaccharides **Polysaccharides** are storage or structural macromolecules. **Starch,** a storage molecule in plants, is a polymer made of glucose molecules joined by 1–4 glycosidic linkages that give starch a helical shape. Amylose is an unbranched polymer; amylopectin is a more complex branched form of starch. Animals use **glycogen,** a highly branched polymer of glucose, as their energy storage molecule.

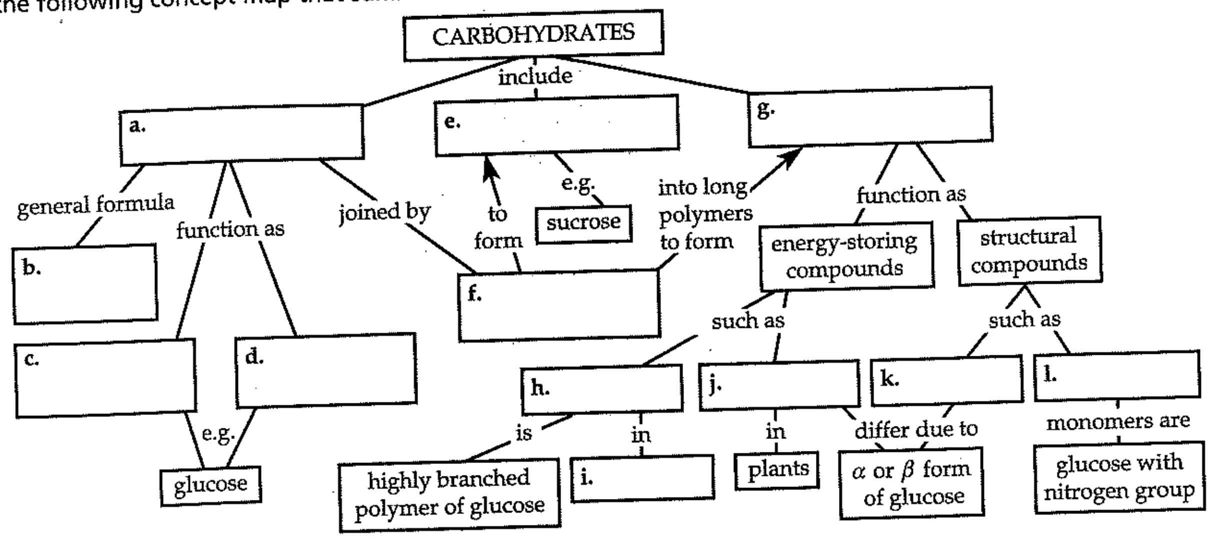
Cellulose, the major component of plant cell walls, is the most abundant organic compound on Earth. It differs from starch by the configuration of the ring form of glucose (beta instead of alpha) and the resulting geometry of the glycosidic bonds. In a plant cell wall, hydrogen bonds between hydroxyl groups hold the parallel, straight cellulose molecules together to form strong microfibrils.

Enzymes that digest the α linkages of starch are unable to hydrolyze the β linkages of cellulose. Only a few organisms (some prokaryotes, protists, and fungi) have enzymes that can digest cellulose.

Chitin is a structural polysaccharide formed from glucose monomers with a nitrogen-containing group. Chitin is found in the exoskeleton of arthropods and the cell walls of many fungi.

INTERACTIVE QUESTION 5.4

Fill in the following concept map that summarizes this section on carbohydrates.



5.3 Lipids are a diverse group of hydrophobic molecules

Fats, phospholipids, and steroids are part of a diverse assemblage of biological molecules that are grouped together as **lipids** based on their hydrophobic behavior. Lipids do not form polymers.

Fats **Fats** are composed of **fatty acids** attached to glycerol, a three-carbon alcohol. A fatty acid consists of a long hydrocarbon chain with a carboxyl group at one end. The nonpolar hydrocarbons make a fat hydrophobic.

A **triacylglycerol,** or fat (or *triglyceride*), consists of three fatty acids, each linked to glycerol by an ester linkage, a bond between a hydroxyl and a carboxyl group.

Fatty acids with double bonds in their carbon chains are called **unsaturated fatty acids.** The *cis* double bond creates a kink in the hydrocarbon chain and prevents fat molecules with unsaturated fatty acids from packing closely together and becoming solidified at room temperature. The fats of plants and fish are generally unsaturated and are called oils. **Saturated fatty acids** have no double bonds in their carbon chains. Most animal fats are saturated and solid at room temperature. Diets rich in saturated fats and in **trans fats** made in the process of hydrogenating vegetable oils have been linked to cardiovascular disease.

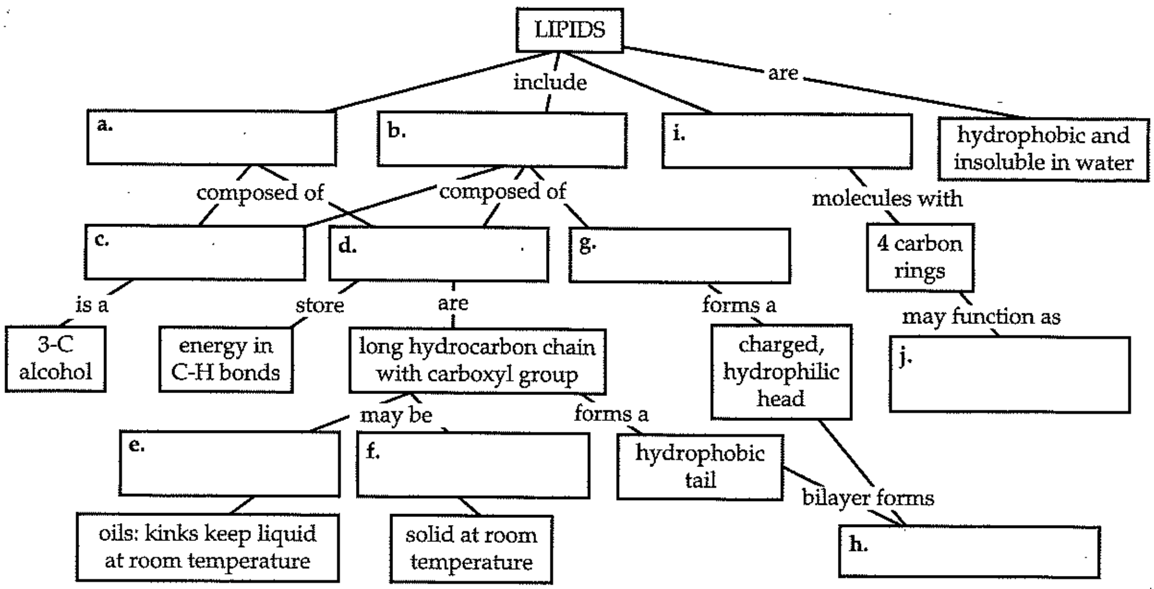
Fats are excellent energy storage molecules, containing twice the energy reserves of carbohydrates such as starch. Adipose tissue, made of fat storage cells, also cushions organs and insulates the body.

Phospholipids **Phospholipids** consist of a glycerol linked to two fatty acids and a negatively charged phosphate group, to which other small molecules are attached. The phosphate head of this molecule is hydrophilic and water soluble, whereas the two fatty acid chains are hydrophobic. The unique structure of phospholipids makes them ideal constituents of cell membranes. The hydrophilic heads face the aqueous environment on either side of a membrane; the hydrophobic tails associate in the center of the phospholipid bilayer, shielded from water.

Steroids **Steroids** are a class of lipids distinguished by four connected carbon rings with various chemical groups attached. **Cholesterol** is a common component of animal cell membranes and a precursor for other steroids, including many hormones.

INTERACTIVE QUESTION 5.5

Fill in this concept map to help you organize your understanding of lipids.



5.4 Proteins include a diversity of structures, resulting in a wide range of functions

Proteins are central to almost every function of life. Most enzymes, which function as **catalysts** that selectively speed up the chemical reactions of a cell, are proteins. A **polypeptide** is a polymer of amino acids, connected by peptide bonds. A **protein** is a functional molecule that consists of one or more polypeptides, each folded into a specific three-dimensional shape.

Amino Acid Monomers **Amino acids** are composed of an asymmetric carbon (called the *alpha [α] carbon*) bonded to four partners: an amino group, a carboxyl group, a hydrogen atom, and a variable side chain called the R group. At the pH in a cell, the amino and carboxyl groups are usually ionized. The R group confers the unique physical and chemical properties of each amino acid. Side chains may be either nonpolar and thus hydrophobic, or polar or charged (acidic or basic) and thus hydrophilic.

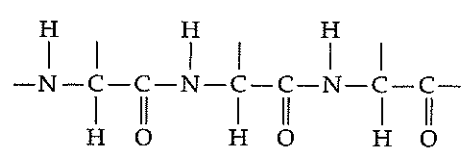
Polypeptides (Amino Acid Polymers) A **peptide bond** links the carboxyl group of one amino acid with the amino group of another. A string of amino acids making up a polypeptide has an amino end (N-terminus) and a carboxyl end (C-terminus).

INTERACTIVE QUESTION 5.6

a. Draw the amino acids alanine (R group: $—CH_3$) and serine (R group: $—CH_2OH$) and then show how a dehydration reaction will form a peptide bond between them.

b. Which of these amino acids has a polar R group? a nonpolar R group?

c. What does the following molecule segment represent? (Note the N—C—C—N—C—C sequence.) What would be attached at each of the three vertical bond lines?



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. 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. *Globular proteins* are roughly spherical; *fibrous proteins* are long fibers. The unique structure of a protein enables it to recognize and bind to other molecules.

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

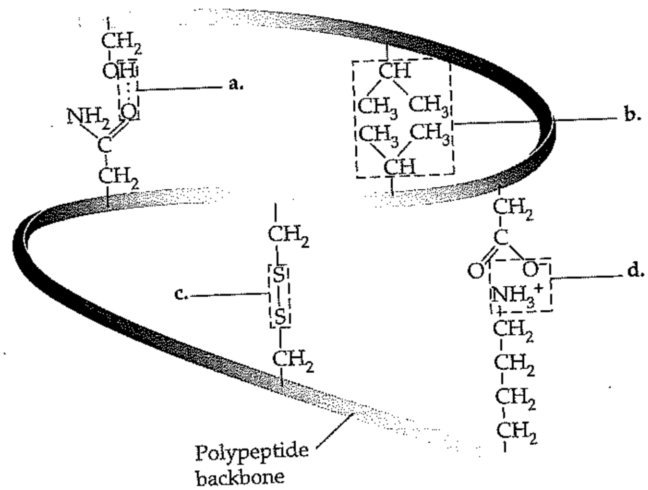
Secondary structure involves regions of coiling or folding of the polypeptide backbone, stabilized by hydrogen bonds between the oxygen (with a partial negative charge) of one peptide bond and the partially positive hydrogen attached to the nitrogen of another peptide bond. An **α helix** is a coil produced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

Tertiary structure, the overall 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 non-polar 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.

INTERACTIVE QUESTION 5.7

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 a nonpolar solvent; in that case, its hydrophilic regions cluster on the inside while its hydrophobic regions are on the outside interacting with the nonpolar solvent.

The primary structure (sequence of amino acids) determines where the interactions and bonds that maintain a protein's shape can form. Within a cell, **chaperonins,** or chaperone proteins, assist newly made polypeptides during the folding process, perhaps by providing a sheltered environment.

Using the techniques of **X-ray crystallography,** nuclear magnetic resonance (NMR) spectroscopy, and bioinformatics, biochemists have identified the structure of more than 25,000 proteins. These structures can then be related to the specific functions of different regions of a protein.

INTERACTIVE QUESTION 5.8

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. Because proteins are complex, you may want to make several smaller maps to organize your knowledge. *One version of a large 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.*

5.5 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.

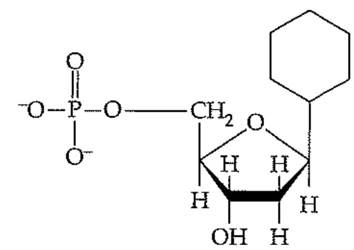
The Roles of Nucleic Acids **DNA, deoxyribonucleic acid,** is the genetic material that is inherited from one generation to the next and is replicated whenever a cell divides so that all cells of an organism contain identical DNA. In the process known as **gene expression,** the instructions coded in DNA are transcribed to **RNA, ribonucleic acid,** which then 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.

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 a nitrogenous (nitrogen-containing) base. A nucleotide may contain more than one phosphate group; without the phosphate group it is called a *nucleoside.*

There are two families of nitrogenous bases. **Pyrimidines,** including cytosine (C), thymine (T), and uracil (U), are characterized by six-membered rings of carbon and nitrogen atoms. **Purines,** adenine (A) and guanine (G), contain two rings of carbon and nitrogen atoms. Adenine, guanine, and cytosine are present in DNA and RNA. Thymine is only in DNA; uracil is only in RNA. In DNA, the sugar is **deoxyribose;** in RNA, it is **ribose.** The nitrogenous 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 *sugar–phosphate backbone.* The unique sequence of bases in a gene codes for the specific amino acid sequence of a protein.

INTERACTIVE QUESTION 5.9



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 Structures of DNA and RNA Molecules DNA molecules consist of two polynucleotides (strands) spiralling in a **double helix.** The two sugar–phosphate backbones run in opposite 5′ → 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 replicate itself and precisely copy the genes of inheritance.

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.

INTERACTIVE QUESTION 5.10

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 5.24 and 5.25 in your textbook to help you visualize polynucleotides and the three-dimensional structures of DNA and RNA.

5.6 Genomics and proteomics have transformed biological inquiry and applications

The first techniques for *DNA sequencing* were developed in the 1970s. The Human Genome Project succeeded in sequencing the entire human *genome* in the early 2000s. Continuing increases in the speed of sequencing and decreases in its cost have spurred the development of *bioinformatics*, the use of computer software and computational tools to analyze large data sets.

Biologists can now analyze and compare whole genomes of different species (an approach called **genomics**) and large sets of proteins (**proteomics**). These new approaches have contributed to the fields of evolution, medical science, paleontology, community ecology, and conservation biology.

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 additional evidence in assessing evolutionary relationships.

Word Roots

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

glyco- = sweet (*glycogen:* an extensively branched glucose-storage polysaccharide found in the liver and muscle of animals)

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

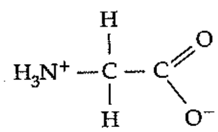
macro- = large (*macromolecule:* a giant molecule formed by the joining of smaller molecules, such as a polysaccharide, a protein, or a nucleic acid)

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

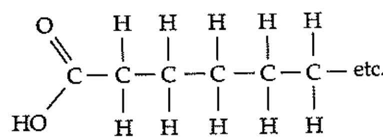
tri- = three (*triacylglycerol:* a lipid consisting of three fatty acids linked to one glycerol molecule; also called a fat or triglyceride)

Structure Your Knowledge

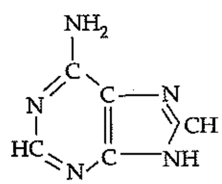
1. Describe the four structural levels in the functional shape of a protein.
2. Identify the type of monomer or group shown by the formulas a–g. Then match the chemical formulas with their descriptions. Answers may be used more than once.



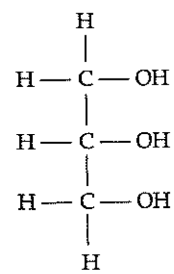
a. ____________________



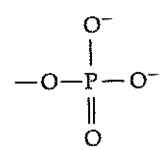
b. ____________________



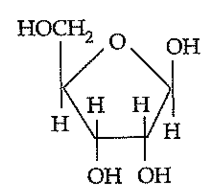
c. ____________________



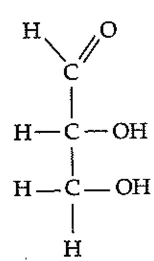
d. ____________________



e. ____________________



f. ____________________



g. ____________________

______ 1. molecules that would combine to form a fat
______ 2. molecule 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. molecule that is a purine
______ 6. monomer of a protein
______ 7. groups that would be joined by phosphodiester bonds
______ 8. most nonpolar (hydrophobic) molecule

Test Your Knowledge

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

______ 1. glycogen	A. carbohydrate
______ 2. cholesterol	B. lipid
______ 3. RNA	C. protein
______ 4. collagen	D. nucleic acid
______ 5. hemoglobin	
______ 6. a gene	
______ 7. triacylglycerol	
______ 8. enzyme	
______ 9. cellulose	
______ 10. chitin	

MULTIPLE CHOICE: *Choose the one best answer.*

1. Polymerization (the formation of polymers) is a process that
- **a.** creates bonds between R groups in the formation of a polypeptide.
- **b.** involves the removal of a water molecule in a dehydration reaction.
- **c.** links the nitrogenous base of one nucleotide with the phosphate of the next.
- **d.** may involve all of the above.

2. Which of the following statements is *not* true of a pentose?
- **a.** It can be found in nucleic acids.
- **b.** It can occur in a ring structure.
- **c.** It has the formula $C_5H_{10}O_5$.
- **d.** It has one carbonyl and five hydroxyl groups.

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

4. Plants store most of their energy for later use as
- **a.** unsaturated fats.
- **b.** starch.
- **c.** sucrose.
- **d.** cellulose.

5. 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.** $C_{12}H_{24}O_{12}$

6. Which of the following substances is the major component of the cell membrane of a fungus?
- **a.** cellulose
- **b.** chitin
- **c.** cholesterol
- **d.** phospholipids

7. A fatty acid that has the formula $C_{16}H_{32}O_2$ is
- **a.** saturated.
- **b.** unsaturated.
- **c.** branched.
- **d.** a trans fat.

8. Three molecules of the fatty acid in question 7 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.** $C_{51}H_{98}O_6$.

9. What are trans fats?
- **a.** hydrogenated fish oils that have been identified with health risks
- **b.** fats made from cholesterol that are components of plaques in the walls of blood vessels
- **c.** fats that are derived from animal sources and are associated with cardiovascular disease
- **d.** fats that contain *trans* double bonds and may contribute to atherosclerosis

10. Which of the following molecules is the most hydrophobic?
- **a.** cholesterol
- **b.** nucleotide
- **c.** chitin
- **d.** phospholipid

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

12. 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. serving as contractile components of muscle

d. performing primary energy storage in plant seeds

13. What happens when a protein denatures?

a. Its primary structure is disrupted.

b. Its secondary and tertiary structures are disrupted.

c. It flips inside out.

d. Its hydrogen bonds, ionic bonds, hydrophobic interactions, disulfide bridges, and peptide bonds are disrupted.

14. The α helix of proteins is

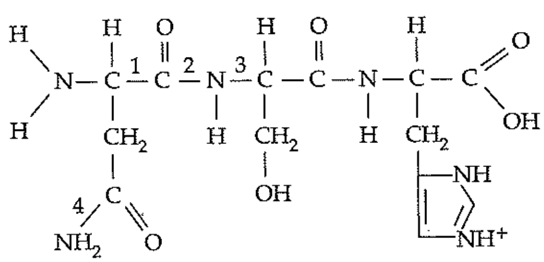
a. part of a protein's tertiary structure and is stabilized by disulfide bridges.

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.

15. What is the best description of the following molecule?



a. chitin **c.** tripeptide

b. amino acid **d.** protein

16. Which number(s) in the molecule in question 15 refer(s) to a peptide bond?

a. 1 **c.** 3

b. 2 **d.** 2 and 4

17. 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

18. 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. both **a** and **b**

19. How are nucleotide monomers connected to form a polynucleotide?

a. by covalent bonds between the sugar of one nucleotide and the phosphate of the next

b. by hydrolysis, the removal of a water molecule and formation of a covalent bond between monomers

c. by hydrogen bonds between complementary nitrogenous base pairs

d. by ester linkages between the carboxyl group of one nucleotide and the hydroxyl group on the ribose of the next

20. 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 **c.** CGGATT

b. CGGAUU **d.** ATTCGG

21. 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. the two groups evolved at about the same time.

22. Which of the following questions is *least* likely to be answered using genomics or proteomics?

a. Are certain proteins more abundant and active in cancer cells than in other body cells?

b. Did Neanderthals and *Homo sapiens* interbreed?

c. How do chaperonins help polypeptides fold into their three-dimensional protein shape?

d. Are some products for sale in fish markets from endangered species whose harvest is illegal?