Proteins and Nucleic Acids

1.5

Spiderwebs, egg white, and even horses' hooves are made of protein. A **protein** is a polymer that has many subunits folded into a three-dimensional structure that specifies its function. The importance of proteins in nature is evident in their name, which comes from the Greek word *proteois*, meaning "first place." Proteins are the most diverse group of molecules in living systems, in terms of their structure and function. They are the real workers of the cell, carrying out vital structural and functional roles.

Nucleic acids are another important type of molecule. They are necessary for protein production in cells. Nucleic acids carry our genetic information, which is passed on from our parents and makes us who we are. Genetic information passes from one type of nucleic acid, DNA, into another type of nucleic acid, RNA. RNA chemical information is then translated for the synthesis of proteins (Chapter 7). The close relationship between DNA, RNA, and proteins keeps our cells functioning properly.

protein a large molecule that consists of many amino acid subunits that are joined together by peptide bonds folded into a specific three-dimensional shape

nucleic acid a blueprint for proteins that are synthesized in cells; stores hereditary information

Amino Acids

All proteins are polymers that are composed of amino acid monomers. An **amino acid** has a central carbon atom attached to an amino group ($-NH_2$), a carboxyl group ($-COOH$), and a hydrogen atom. In solution, the amino group bonds to an H^+, while the carboxyl group releases an H^+ (**Figure 1**). Attached to the central carbon atom is a variable side group, called an R group, which gives each amino acid its distinct characteristics.

amino acid a molecule that contains a carboxyl group and an amino group; serves as the monomer subunit of proteins

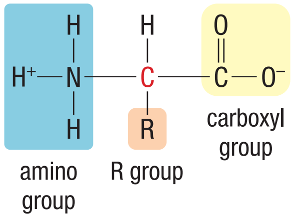

Figure 1 Every amino acid has a central carbon atom with a carboxyl group at one end and an amino group at the other end, as well as a hydrogen atom and an R group.

There are 20 different amino acid side groups, or R groups, ranging from a single hydrogen atom to complex carbon chains or rings (**Figure 2**, next page). The one exception to this organization is the amino acid proline, which has a ring structure that includes the nitrogen and central carbon atoms. Differences in these side groups give the amino acids their individual properties. Side groups may be polar or nonpolar. Among the polar side groups, some carry a positive or negative charge and others act as acids or bases.

Many of the amino acid side groups contain a reactive functional group, such as $-NH_2$, $-OH$, $-COOH$, or $-SH$, which may interact with atoms located elsewhere in the same protein or with molecules and ions located outside the protein. With few exceptions, all proteins in living things are an assembly of various numbers and combinations of 20 different amino acids. Eight of these amino acids are considered essential for humans because they can only be obtained from our diet. The rest can be synthesized by the cells. There are also other amino acids, which include some neurotransmitters.

Proteins

Proteins are by far the most complex molecules in living organisms. There are thousands of different proteins in your body and around you, performing thousands of tasks. The strands of hair on your head, and the tendons and ligaments that connect your muscles and bones, contain structural proteins.

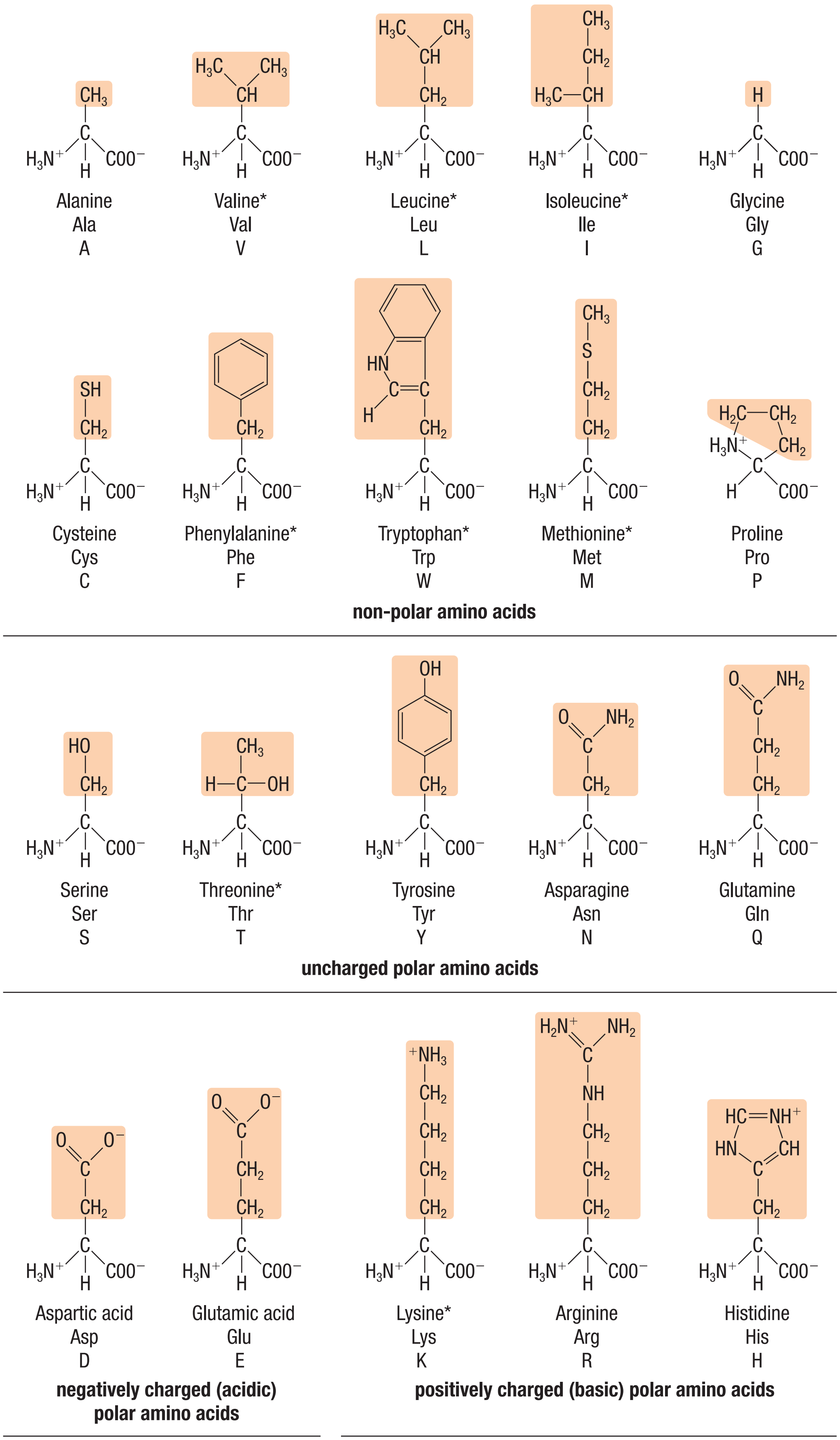

Figure 2 The structures of all 20 amino acids found in proteins. Every amino acid has the same basic structure, with the exception of proline. Below each amino acid is its name, followed by its three-letter abbreviation and its letter symbol. The asterisk denotes essential amino acids that must be obtained from nutrients.

Structural proteins provide much of the supportive framework of the cells (**Figure 3**). Defensive proteins called antibodies, which are found in the human body, help to fight off infections.

Figure 3 (a) Structural proteins are found in your hair. (b) A vaccine triggers the production of defence proteins. (c) The egg white and yolk inside a bird's egg contain proteins that are essential for the developing embryo. (d) Spider silk is a protein that is used to make a spiderweb.

Hormones and other messenger chemicals in the cell are signal proteins. Hemoglobin is a special protein in red blood cells that delivers oxygen to muscle and other tissues and organs. Transport proteins shuttle substances across biological membranes. Egg whites contain storage proteins to provide essential chemical building blocks for developing embryos. Other proteins serve as recognition and receptor molecules at the surfaces of cells, and some regulate the activity of other proteins and DNA. Motile proteins give cells and cellular structures the ability to move. Perhaps most importantly, special proteins called enzymes are largely responsible for making almost every biochemical reaction possible. They speed up the rate of chemical reactions. **Table 1** summarizes the functions of the various types of proteins.

Table 1 Different Types of Proteins and their Functions

Type of protein	Function	Example
structural	framework support	hair, tendons, and ligaments
defensive	infection fighters	antibodies
signal	messenger	hormones
carrier	transport of materials	hemoglobin
recognition and receptor	cellular markers	major histocompatibility complex
enzyme	catalyst	amylase
motile	movement	actin and myosin

Peptides

Peptide bonds link many amino acids into chains of subunits that make proteins. A peptide bond is a covalent bond that is formed by a dehydration synthesis reaction between the $-NH_2$ group of one amino acid and the $-COOH$ group of a second amino acid (**Figure 4**, next page). An amino acid chain always has an $-NH_2$ group at one end, called the N-terminal end, and a $-COOH$ group at the other end, called the C-terminal end. In cells, amino acids are added only to the $-COOH$ end of the growing peptide strand. The chain or polymer of amino acids that is formed by sequential peptide bonds is called a **peptide**. Unlike carbohydrate chains, there are no side branches of amino acids in a peptide, although many functioning proteins contain small non-amino acid components. A **polypeptide** is a peptide that is greater than 50 amino acids in length. A protein is one or more polypeptides that are folded into a precise three-dimensional shape. Only after folding occurs is the protein able to function.

peptide bond a covalent bond that links amino acids

peptide a chain of amino acid subunits that are connected by peptide bonds

polypeptide a peptide with more than 50 amino acids

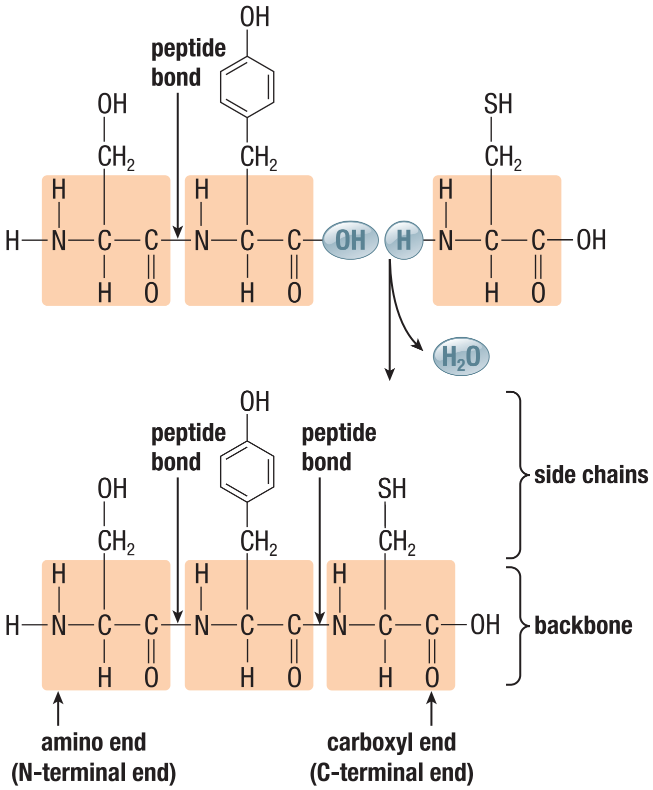

Figure 4 A peptide bond forms between two amino acids in a growing chain through a dehydration synthesis reaction. A water molecule is released as the bond forms between the carboxyl group of one amino acid and the amino group of another. The growing amino acid chain always has an amino group at one end and a carboxyl group at the other end.

Protein Structure

Proteins have up to four levels of structure, with each level imparting different characteristics and degrees of complexity to the overall protein.

PRIMARY STRUCTURE

The primary structure of a protein is the unique linear sequence of its amino acids in each polypeptide chain (**Figure 5(a)**, next page). Changing even a single amino acid in the primary structure will alter the overall structure of the protein to some degree. A single change can alter or even destroy the biological function of the protein.

There is an enormous diversity in the primary structures that can form. With 20 possible amino acids, there are 20^2, or 400, different combinations possible by joining only two amino acids. Furthermore, there are 20^3, or 8000, combinations possible by joining only three amino acids. The possible combinations of lengthy primary structures are virtually limitless.

SECONDARY STRUCTURE

Most polypeptides have portions that repeatedly coil or fold into patterns and contribute to the overall shape of a protein. This secondary structure is the result of hydrogen bonding between different parts of the same amino acid backbone. Specifically, hydrogen bonding occurs between electronegative nitrogen and oxygen atoms and partially positive hydrogen atoms.

Two common secondary structures are the beta-pleated (or β-pleated) sheet and the alpha-helix (or α-helix) (**Figure 5(b)**, next page). A β-pleated sheet forms by a side-by-side alignment of the amino acid chain. β-pleated sheets play an important role in the strength of silk. An α-helix is a delicate coil that is held together by hydrogen bonds between every fourth amino acid. It is found in filamentous proteins and transmembrane proteins, and it provides the necessary structure for their functions.

TERTIARY STRUCTURE

The secondary structure of a protein is the result of interactions between atoms in the backbone. The tertiary structure of a protein is the overall three-dimensional shape of a protein due to a range of interactions among the amino acid R groups (**Figure 5(c)**). Recall, from Figure 2 (page 40), the different types of R groups. It is in the tertiary structure that the interactions of the R groups determine the three-dimensional shape of the polypeptide chain. These interactions include hydrogen bonds, hydrophobic interactions, and disulfide bridges (**Figure 5(d)**). Hydrophobic interactions are the interaction of non-polar side groups that cluster together as a result of other amino acid R groups interacting with water. A disulfide bridge is the bond that is formed when the -SH groups of two cysteine amino acids line up and react to form an S-S covalent bond. This is a strong bond that holds two parts of the polypeptide strand together, stabilizing its shape. The tertiary structure is critical to the functions of proteins, especially enzymes. Extreme conditions (such as temperature and pH) can unfold a protein, causing **denaturation**, a loss of both the structure and the function of the protein.

denaturation the loss of both the structure and function of a protein

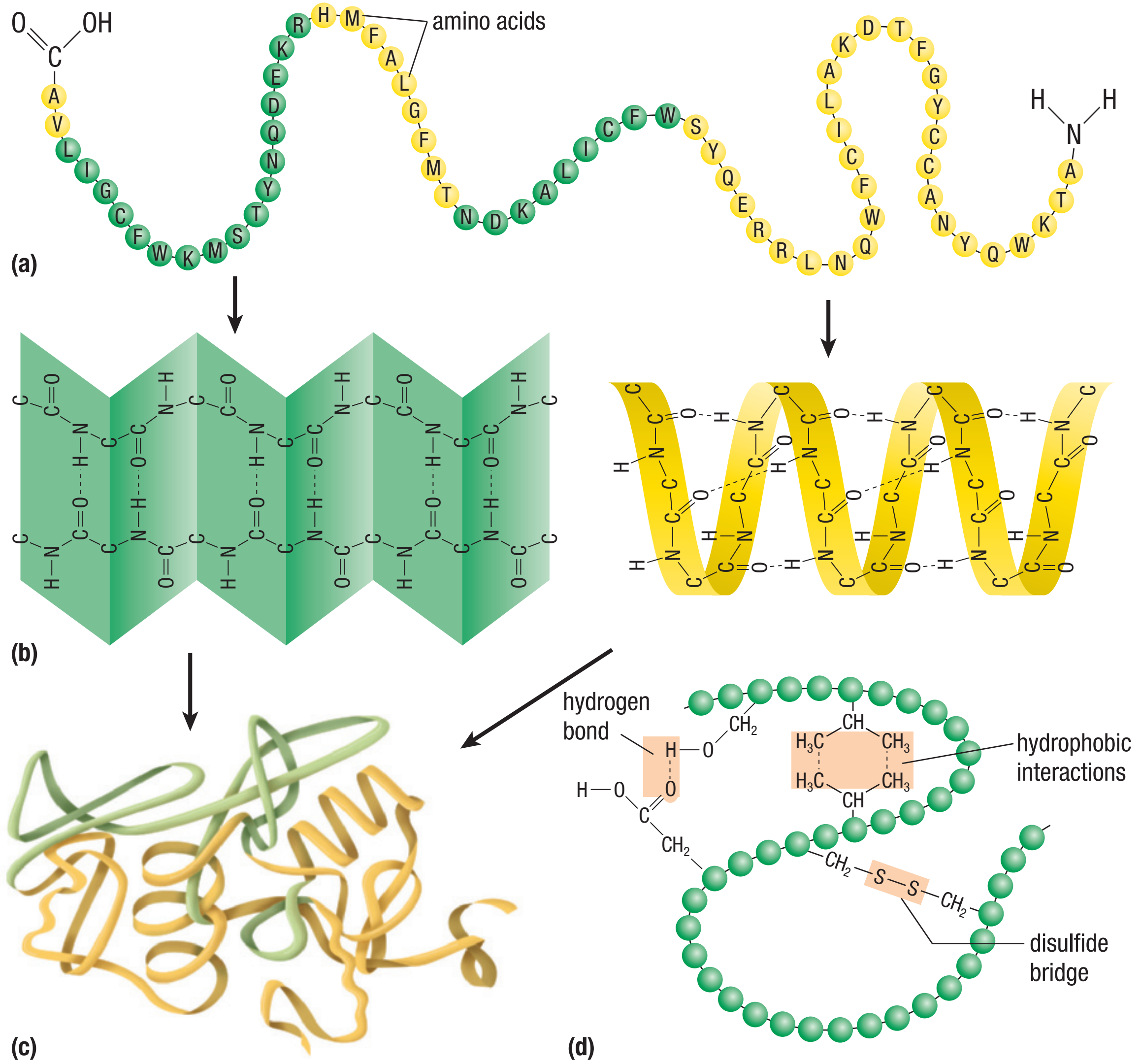

Figure 5 (a) The primary structure of a protein is the sequence of amino acids in a polypeptide strand. Each bead on the strand represents an individual amino acid. (b) Portions of the amino acid chain can fold and spiral. This secondary structure is frequently a folded β-pleated sheet (left) or a spiral α-helix (right). (c) (d) The polypeptide further folds into its tertiary structure, which is dependent on the amino acid side chains.

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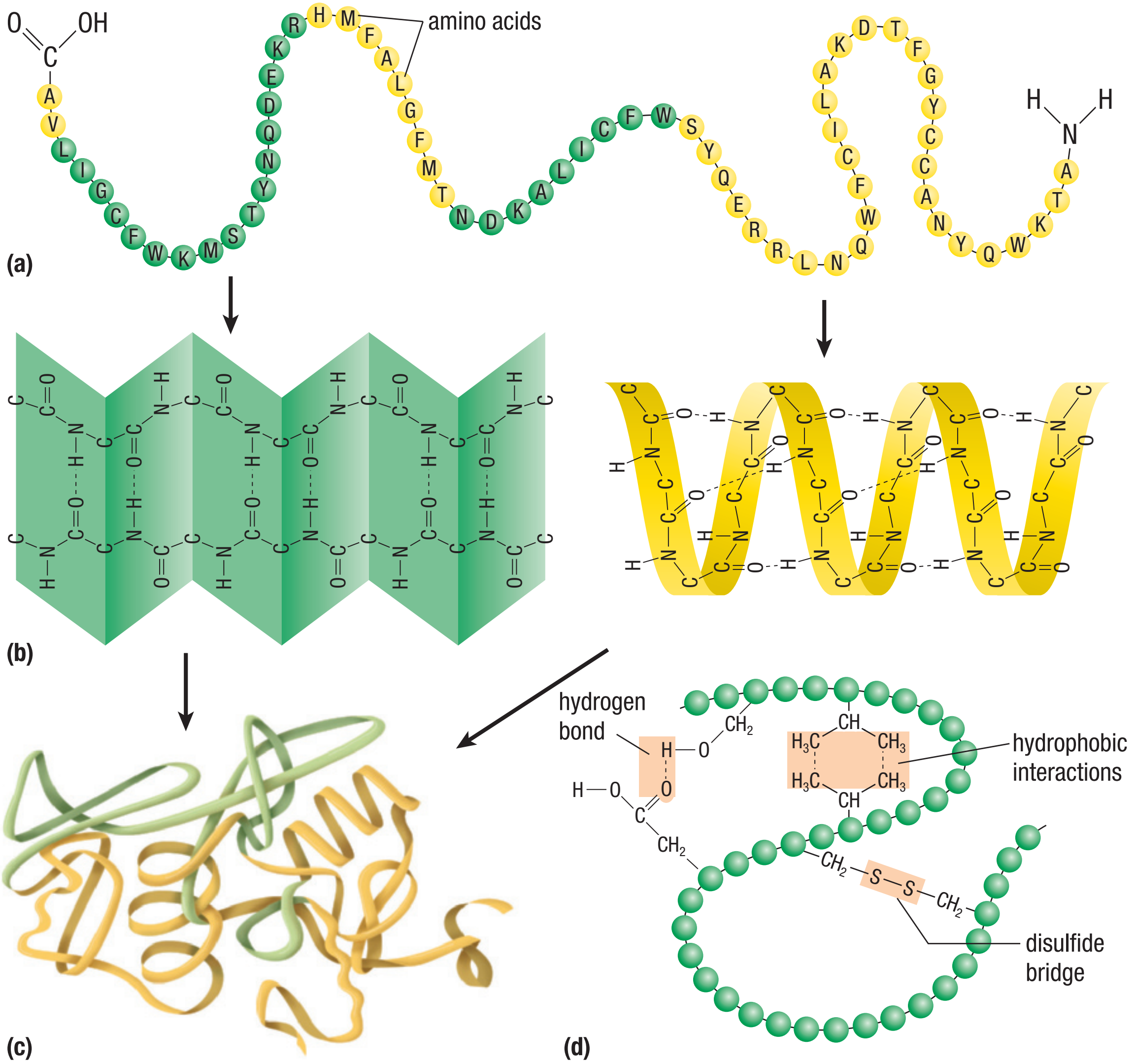

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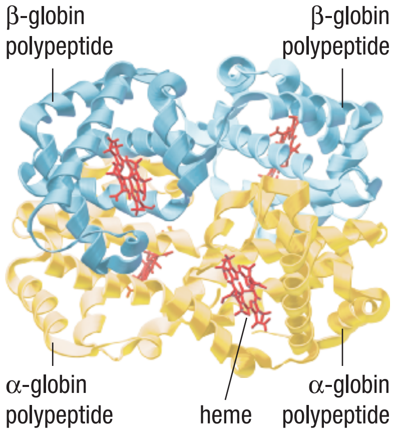


Figure 6 Hemoglobin is the combination of four polypeptides. The heme ring of each polypeptide is shown in red.

QUATERNARY STRUCTURE

Many proteins are composed of two or more polypeptides that come together to form the final functional proteins. This quaternary structure, which forms subunits, exists in many proteins. The same bonds and forces that fold single polypeptide chains into tertiary structures (including hydrogen bonds, polar and non-polar attractions, and disulfide linkages) also hold the multiple polypeptide chains together. The hemoglobin molecule is composed of four polypeptides, each consisting of more than 140 amino acids (**Figure 6**).

PROTEIN PROSTHETIC GROUPS

Besides properly folded polypeptide chains, many proteins require non-protein components, called prosthetic groups, to function. One example is found in hemoglobin, the major protein that is involved in O_2 transport in vertebrates. In hemoglobin, the four polypeptides do not bind the oxygen. Rather, the oxygen is bound to heme groups, which are themselves surrounded and held by the polypeptides. Each polypeptide chain contains one heme ring, in which there is a single iron (Fe^{2+}) ion (Figure 6). Therefore, there are four heme groups per hemoglobin, and four O_2 are carried. Many enzymes require prosthetic groups that contain metal ions in order to function. For example, some enzymes that are involved the process of cellular respiration require Mg^{2+} ions.

Protein Structure and Functional Relationship

The shape of a protein influences and enables its function. For example, long linear proteins align to form the strong fibres of silk, collagen, and keratin. This long linear formation provides the strength. Compact globular proteins, such as the hemoglobin protein, are good for transport. Hemoglobin proteins transport oxygen to muscles, and their shape enables them to be carried efficiently within red blood cells and through the body. Hemoglobin illustrates the complexity and enormous size of many proteins. A single hemoglobin protein is comprised of thousands of individual atoms, yet its function is to carry just four O_2 molecules. Enzymes and antibodies have special pockets that bind specific molecules, allowing these proteins to carry out their function.

UNIT TASK **BOOKMARK**

Consider how you can apply an understanding of the form and function of proteins as you work on your Unit Task (p. 108).

Mini **Investigation**

Building and Exploring Models of Proteins

Skills: Performing, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK A2.1

In this activity, you will build and observe three-dimensional models of several amino acids to explore how they assemble into polypeptides.

Equipment and Materials: chemical modelling kit

1. Construct models of a polar amino acid, a non-polar amino acid, and an ionic amino acid of your choice. Use Figure 2 as reference. Choose amino acids with relatively small R groups.
2. Draw each molecule in your lab notebook, and record the overall chemical formula for each amino acid.
3. Form a tripeptide by performing two dehydration synthesis reactions.

A. What gives each amino acid R group its key characteristics to make it polar, non-polar, or ionic? T/I

B. What functional groups are involved in the dehydration synthesis reaction? K/U

C. Explain why the acidic property of the amino acid changes as a result of the dehydration synthesis reaction. T/I

D. Compare the chemical formulas for the amino acids you formed. In what ways are they similar? In what ways are they different? K/U T/I

E. What element that is present in all amino acids is not present in most carbohydrates and lipids? Compare the C:H:O ratio in amino acids with the C:H:O ratios in carbohydrates and lipids. K/U

F. How might the solubility of peptides be influenced by the size of the peptides? How might it be influenced by the R group of the amino acids? T/I

G. Calculate the total number of peptides with 10 amino acids that can be formed from the 20 different types of amino acids. T/I

H. Would you consider the formation of a peptide bond to be an example of a neutralization reaction? Explain your reasoning. T/I

Nucleic Acids

Nucleic acids serve as the assembly instructions for all proteins in living organisms. Two types of nucleic acids exist: DNA and RNA. Deoxyribonucleic acid (DNA) stores the hereditary information that is responsible for inherited traits in all eukaryotes and prokaryotes and in many viruses. Ribonucleic acid (RNA) is the hereditary molecule of some viruses. There are several different forms of RNA involved in protein synthesis in all cells.

Nucleotides

All nucleic acids are polymers of units called nucleotides. A **nucleotide** consists of three parts linked together by covalent bonds: a nitrogenous base formed from rings of carbon and nitrogen atoms, a 5-carbon ring-shaped sugar, and one to three phosphate groups. In a nucleotide, each nitrogenous base links covalently to a 5-carbon sugar, either deoxyribose or ribose (**Figure 7**). The two sugars differ only in the chemical group that is bound to the 2′-carbon: deoxyribose has an —H, and ribose has an —OH group.

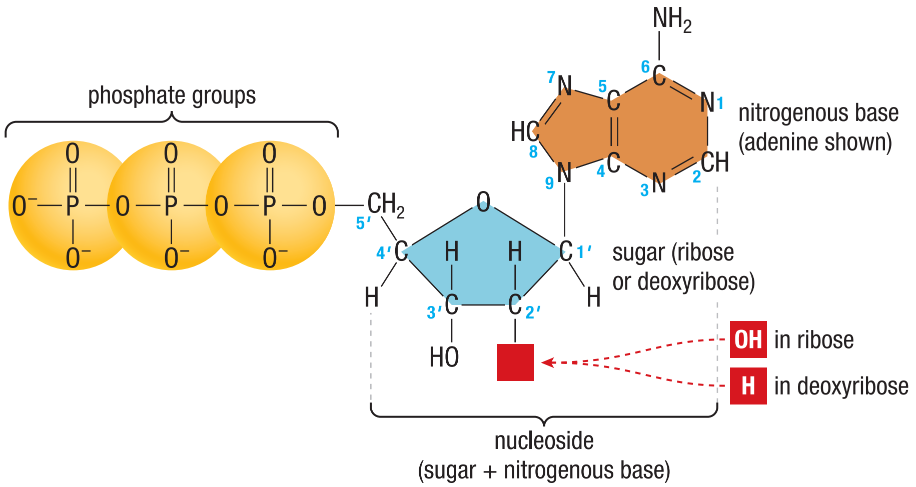


Figure 7 The chemical structure of a nucleotide. The carbons and nitrogens on the base ring structure are labelled 1 to 9, and the carbons on the sugar are labelled 1′ to 5′. A ribose sugar found in RNA has an —OH bound to the 2′ carbon. The deoxyribose found in DNA has an —H bound to the 2′ carbon.

There are two general types of nitrogenous base: pyrimidines and purines (**Figure 8**). Pyrimidine bases are single organic rings, whereas purine bases are two-ringed organic structures. Both types of bases have a high nitrogen content. The three pyrimidine bases are uracil (U), thymine (T), and cytosine (C). The two purine bases are adenine (A) and guanine (G).

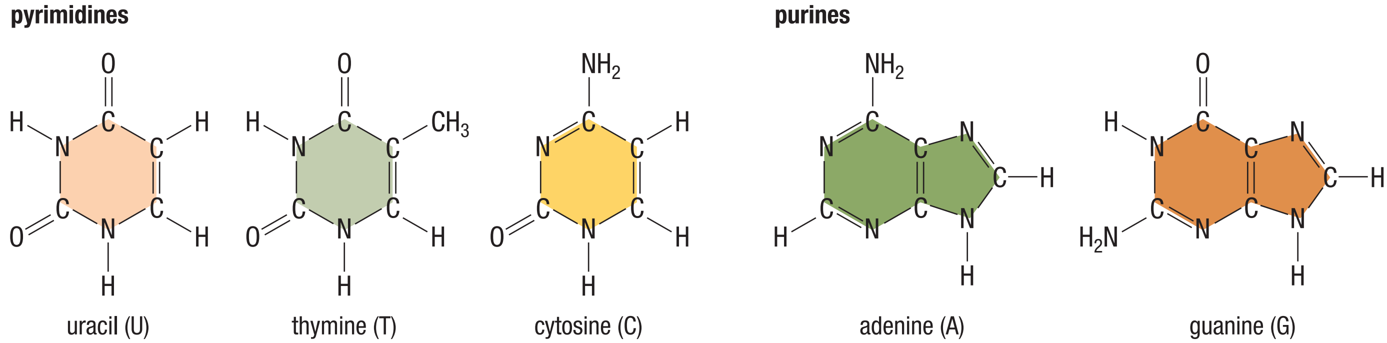


Figure 8 Nucleotide base chemical structures

DNA and RNA: Nucleotide Polymers

DNA and RNA consist of chains of nucleotides, called polynucleotide chains, with one nucleotide linked to the next by a single bridging phosphate group between the 5′-carbon of one sugar and the 3′-carbon of the next sugar in line. This type of linkage is called a **phosphodiester bond**. The arrangement of the alternating sugar and phosphate groups forms the backbone of a nucleic acid chain. The nitrogenous bases of the nucleotides

Investigation 1.5.1

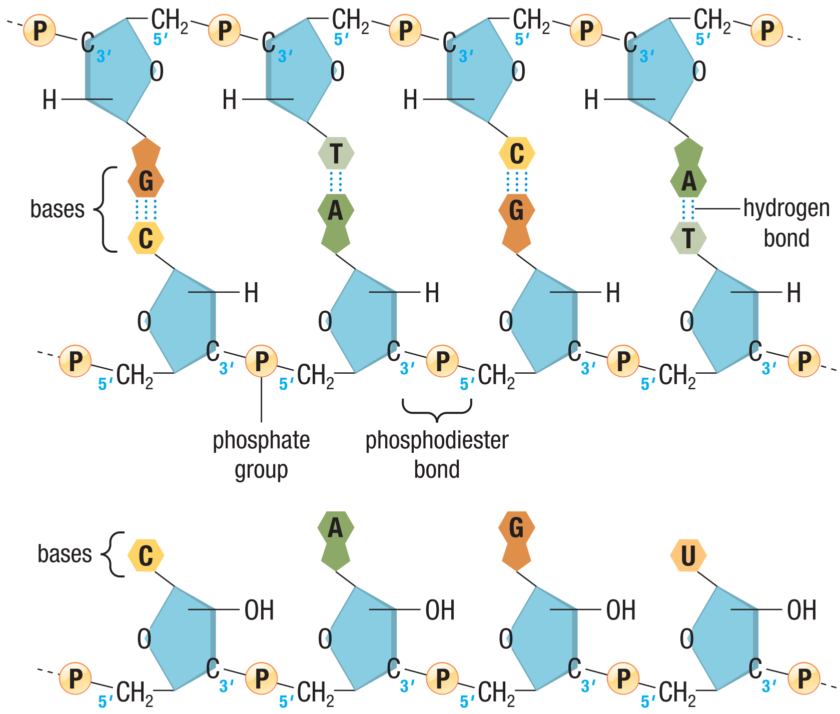
Testing for Macromolecules (p. 58)
Now that you have learned about macromolecules, you will conduct tests on sample compounds to determine whether they are carbohydrates, lipids, or proteins.

nucleotide the building block of nucleic acids; consists of a 5-carbon sugar, a nitrogenous base, and one to three phosphate groups

phosphodiester bond a link that is formed between nucleotides by a phosphate bridge project from this backbone. In a DNA chain, each nucleotide contains deoxyribose, a phosphate group, and one of the four bases A, T, G, or C. In an RNA chain, each nucleotide contains ribose, a phosphate, and one of the four bases A, U, G, or C.

antiparallel oriented in opposite directions

DNA is a double-stranded molecule in which the two strands of DNA run **antiparallel** to each other. This means that they are oriented in the opposite direction relative to the sugar-phosphate backbone. The end with the phosphate group is referred to as the 5′ end, and the opposite end of the same strand, with the deoxyribose sugar, is referred to as the 3′ end. Bases on opposite strands of DNA hydrogen bond to one another to form a double-stranded DNA molecule (**Figure 9**). G (guanine) forms three hydrogen bonds with C (cytosine), and A (adenine) forms two hydrogen bonds with T (thymine). As base pairs form between two strands of DNA, the molecule is twisted into a double helix configuration. Although DNA is almost always found as a very long double helix, RNA takes on a greater variety of structures. RNA structures include relatively short linear forms, as well as structures that fold back on themselves in clover or hairpin formations.



(a) DNA

(b) RNA

Figure 9 (a) DNA structure, with the hydrogen bonds between the bases shown with dotted lines; (b) RNA structure

Nucleotides perform many functions in cells, in addition to serving as the building blocks of nucleic acids. Two nucleotides in particular, adenosine triphosphate (ATP) and guanosine triphosphate (GTP), are the primary molecules that transport chemical energy from one reaction system to another (Chapter 3). These nucleotides also regulate and adjust cellular activity.

Carbohydrates, Lipids, Proteins, and Nucleic Acids

There are four major types of biological molecules: carbohydrates, lipids, proteins, and nucleic acids. Each type of molecule has many different roles in cellular processes. Throughout this course, you will learn more about these cellular processes and the roles of the four types of molecules as they work together in various combinations. For example, you will learn how carbohydrates and lipids are used to store, transfer, and release energy as you study cellular metabolism. You will learn how inherited chemical information is stored in nucleic acids, translated into proteins, and acted upon through a variety of molecules as you study genetics. You will also learn how chemical processes sustain a dynamic equilibrium within each cell and within each organism as a whole.

Investigation 1.5.2

Manipulating Macromolecules (p. 60)
Computer-generated molecules can be used as a tool to study the structure and function of large molecules. In this investigation, you will explore computer-generated macromolecules.

1.5 Review

Summary

- Amino acids are the monomer building blocks of proteins. There are 20 different amino acids. They all contain an amino group, a carboxyl group, and an R group. The R group gives each amino acid its unique characteristics.
- Proteins are complex polymers. They have primary, secondary, tertiary, and quaternary levels of structure, which contribute to their functions.
- Some proteins require non-protein components, called prosthetic groups, to function properly.
- All nucleotides consist of three parts: a nitrogenous base, a 5-carbon sugar, and one to three phosphates.
- DNA and RNA are polymers of nucleotides.
- The two general types of nitrogenous bases are pyrimidines (uracil, thymine, and cytosine) and purines (adenine and guanine).

Questions

1. What groups of atoms are found in all amino acids? K/U
2. Describe the difference between the primary and secondary protein structures. K/U
3. Explain why it is necessary for a protein to adopt specific tertiary and quaternary arrangements. K/U
4. Explain the role of hydrogen bonding and disulfide bonds between R groups. K/U
5. List some of the different types of proteins and their functions. Identify specific applications of these proteins in various living organisms. K/U
6. Relate the diversity in protein structure to the diversity in protein function. T/I
7. A researcher studying a newly discovered small protein finds that when dissolved in water, the solution has a pH above 7. T/I
   (a) What amino acids would you predict to be abundant in this protein? Why?
   (b) What amino acids would you predict to be uncommon in this protein? Why?
8. What is the role of the sugar and phosphate groups in the structure of nucleic acids? K/U
9. Explain the similarities and differences between DNA and RNA. K/U T/I
10. Draw the linkage of two nucleotides and two amino acids. T/I
11. How does the function of nucleic acids differ from that of other types of macromolecules? K/U
12. Your biology teacher tells you that nucleic acids, fatty acids, and amino acids can increase the H^+ concentration of a solution. Explain how this is possible. T/I
13. The human body can synthesize 12 of the 20 amino acids. Eight amino acids, called essential amino acids, must be obtained from the food we eat. Select one of these essential amino acids (see Figure 2, page 40). Research your selected amino acid and answer the following questions. T/I
    (a) Describe your amino acid's function in the human body.
    (b) What sources of food contain this amino acid?
    (c) What symptoms will a person experience if they are deficient in this amino acid?
14. Oxytocin and vasopressin are hormones with very different functions but relatively similar structures. Using the Internet and other sources, find the answers to the following questions. T/I
    (a) What are the general functions of each hormone?
    (b) They are both nine-amino-acid polypeptides but have two amino acids that are different. Which two amino acids in these hormones are different?

WEB LINK