

## Key Terms

**aerobic catabolism** (p. 50)

**amino acids** (p. 54)

**anabolism** (p. 48)

**anaerobic catabolism** (p. 50)

**base pairing** (p. 57)

**base sequencing** (p. 57)

**carbohydrates** (p. 48)

**catabolism** (p. 48)

**deoxyribonucleic acid (DNA)** (p. 56)

**gluconeogenesis** (p. 51)

**glucose** (p. 48)

**glycogen** (p. 50)

**glycolysis** (p. 50)

**lipids** (p. 52)

**metabolism** (p. 48)

**monosaccharides** (p. 48)

**peptide bond** (p. 55)

**protein** (p. 54)

**ribonucleic acid (RNA)** (p. 57)

## Objectives

1. Define *metabolism*, *anabolism*, and *catabolism*.
2. Explain the use of carbohydrates in the body, and differentiate between the anaerobic and aerobic metabolism of carbohydrates.
3. Explain the use of fats in the body.
4. Explain the use of proteins in the body.
5. Describe the roles of DNA and RNA in protein synthesis, the structure of a nucleotide, and the steps in protein synthesis.

To carry on its function, the cell, like a factory, must bring in and use raw material. The raw material comes from the food we eat and includes carbohydrates, protein, and fat. Once inside the cell, the raw materials undergo thousands of chemical reactions. The cellular processing of the raw materials is called *metabolism*.

## METABOLISM

**Metabolism** can be divided into two parts: anabolism and catabolism (Figure 4-1).

**Anabolism** (ah-NAB-oh-liz-em) includes reactions that build larger, more complex substances from simpler substances, such as the building of a large protein from individual amino acids. The process is similar to the building of a brick wall from individual bricks. Anabolic reactions generally require an input of energy in the form of adenosine triphosphate (ATP).

**Catabolism** (kah-TAB-oh-liz-em) includes reactions that break down larger, more complex substances into simpler substances, such as the breakdown of a large protein into individual amino acids. This process is similar to the knocking down of a brick wall. Catabolism releases energy that is converted into ATP and used to “run” the body.

## CARBOHYDRATES

We have all eaten sugars and starchy food. Bread, potatoes, rice, pasta, and jelly beans are some of our favorite foods. These are all carbohydrates. **Carbohydrates** are organic compounds composed of carbon (C), hydrogen (H), and oxygen (O). Carbohydrates are classified according to size (Figure 4-2). **Monosaccharides** (mon-oh-SAK-ah-rides) are single (mono) sugar (saccharide) compounds. **Disaccharides** (dye-SAK-ah-rides) are double (di) sugars, and **polysaccharides** (pahl-ee-SAK-ah-rides) are many (poly) sugar compounds. The shorter monosaccharides and disaccharides are called *sugars*, and the longer chain polysaccharides are called *starches*. The carbohydrates are listed in Table 4-1.

## MONOSACCHARIDES

Monosaccharides are sugars containing three to six carbons. The six-carbon simple sugars include glucose, fructose, and galactose. **Glucose** is the most important of the three and is used by the cells as an immediate source of energy.

There are also five-carbon monosaccharides; they include ribose and deoxyribose. These sugars are used in the synthesis of ribonucleic acid (RNA) and deoxyribonucleic acid (DNA).

**Go Figure**

- 1. According to Figures 3-1 and 3-2**
  - a. All cells look like the “typical cell.”
  - b. The ER and Golgi apparatus are membranous cytoplasmic organelles.
  - c. All ribosomes are attached to the ER and are concerned with protein synthesis.
  - d. The nucleus is separated from the cytoplasm by an impermeable nuclear membrane.
- 2. According to Figures 3-2, 3-3, and 3-4**
  - a. Ribosomes are present on all endoplasmic reticulum.
  - b. The Golgi apparatus is located within the nucleus; it “packages” protein for expulsion from the cell.
  - c. The cell membrane is composed exclusively of phospholipids.
  - d. Mitochondria are organelles that generate ATP.
- 3. According to Figures 3-6 and 3-7**
  - a. Gases cannot diffuse.
  - b. Diffusion and facilitated diffusion are represented by Figure 3-6, *B*.
  - c. Beaker 2 in Figure 3-7, *A*, represents equilibrium.
  - d. Oxygen diffuses from the sacs (alveoli) in the lungs into the blood.
- 4. According to Figures 3-6 and 3-9**
  - a. Osmosis and filtration are represented by Figure 3-6, *B*.
  - b. Equilibrium cannot be achieved if the volumes in the beaker are unequal.
  - c. To achieve the results in Figure 3-9, the membrane must be impermeable to the solute.
  - d. Solute concentration has no effect on osmosis.
- 5. The transport in Figure 3-12**
  - a. Occurs in a manner that is consistent with Figure 3-6, *A*.
  - b. Is the same as the transport mechanism described in Figure 3-8.
  - c. Only involves the movement of a substance into the cell.
  - d. Can move a solute against its gradient.
- 6. According to Figures 3-13 and 3-14**
  - a. The cell rests when it enters interphase.
  - b. The M phase consists of the  $G_1$  phase, S phase, and  $G_2$  phase.
  - c. The cell divides during the M phase.
  - d. The cell is most active during the  $G_0$  phase.

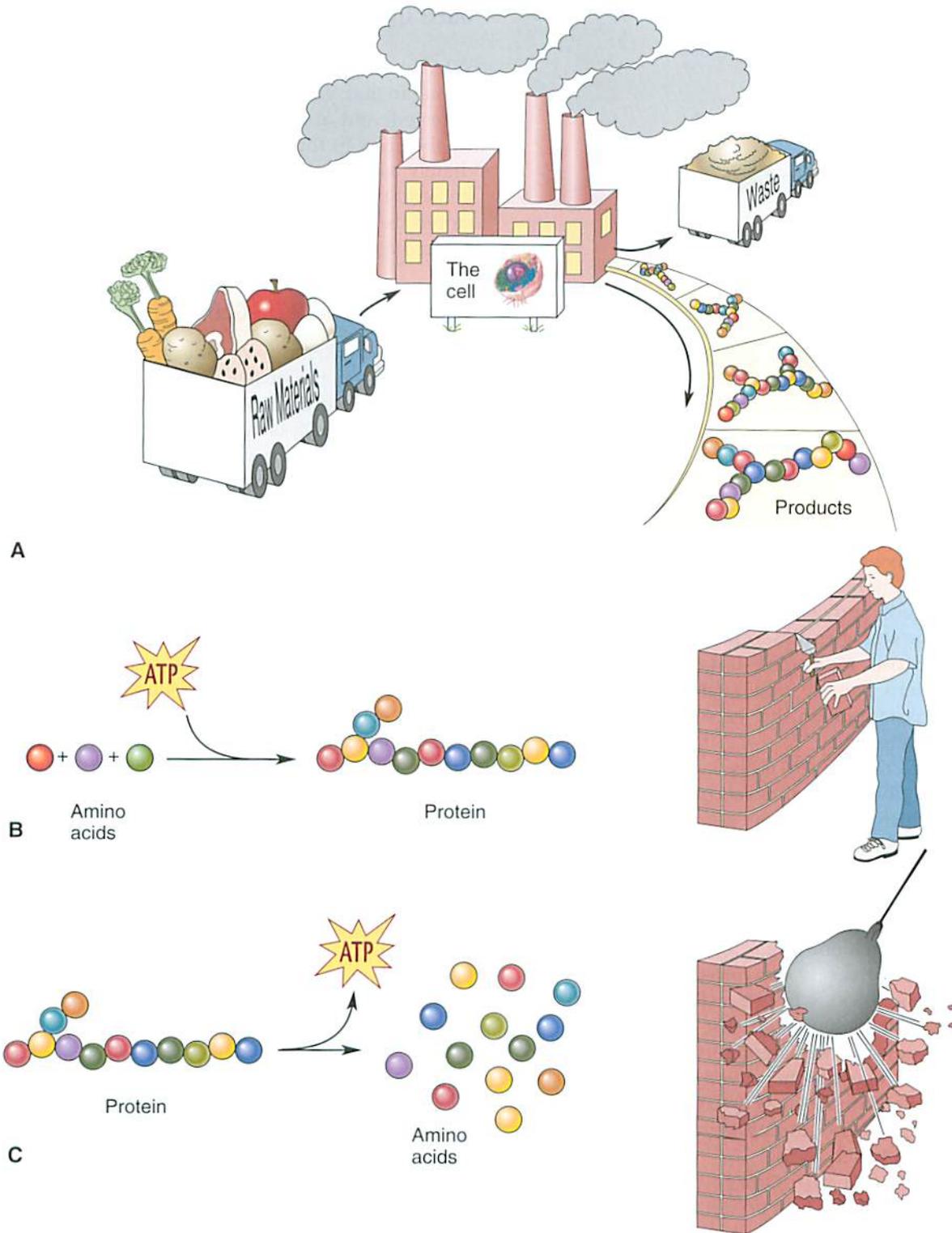


FIGURE 4-1 Metabolism. **A**, Raw materials to run the factory. **B**, Anabolism. **C**, Catabolism.

## DISACCHARIDES

Disaccharides are double sugars and are made when two monosaccharides are linked together. The disaccharides include sucrose (table sugar), maltose, and lactose; they are present in the food we eat. They must be digested, or broken down, into monosaccharides

before they can be absorbed across the walls of the digestive tract and used by the cells.

## POLYSACCHARIDES

Polysaccharides are made of many glucose molecules linked together. Some are linked together in straight

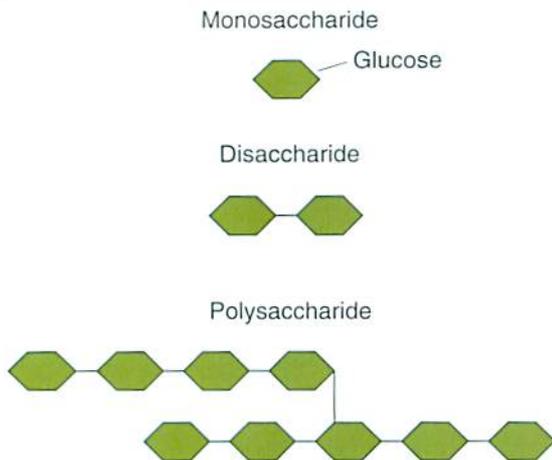


FIGURE 4-2 Carbohydrates.

chains, and others in branched chains. The three polysaccharides of interest to us are plant starch, animal starch (glycogen), and cellulose.

Starch is the storage polysaccharide in plants. It is a series of glucose molecules linked together in a branched pattern. Starchy foods such as potatoes, peas, grains, and pasta contain this type of starch and are part of our healthy diet.

**Glycogen** (GLYE-koh-jen) is also called animal starch and is a highly branched polysaccharide. Glycogen is the form in which humans store glucose; these glucose molecules are joined together in long branched chains called *glycogen*. Glycogen is stored primarily in the liver and skeletal muscle. Glycogen performs two important roles. First, glycogen stores help regulate blood sugar. When blood sugar levels become low, the glycogen in the liver is converted to glucose and released into the blood, where it restores normal blood sugar levels. When blood glucose increases after a meal, the excess glucose is converted in the liver to glycogen for storage. Second, glycogen acts as storage energy in skeletal muscle. When muscle contractile activity increases, as in running, glycogen is converted to glucose and burned as fuel.

Cellulose is a straight-chain polysaccharide found in plants. Although humans do not have the enzymes to digest cellulose as a source of nutrients, this polysaccharide plays an important role in our digestive process. The cellulose provides the fiber in our diet and improves digestive function.

### ? Re-Think

1. What is the relationship between glucose and glycogen?
2. Where is most glycogen stored?
3. How does glycogen help in the regulation of blood glucose levels?

## USES OF GLUCOSE

What about that mound of jelly beans, those oval globs of sugar that you just ate? The jelly beans are eaten, digested, and absorbed. Then what? Glucose is used by the body in three ways: (1) it can be burned immediately as fuel for energy; (2) it can be stored as glycogen and burned as fuel at a later time; and (3) it can be stored as fat and burned as fuel at a later time. The “stored as fat” phrase is the most distressing!

## THE BREAKDOWN OF GLUCOSE

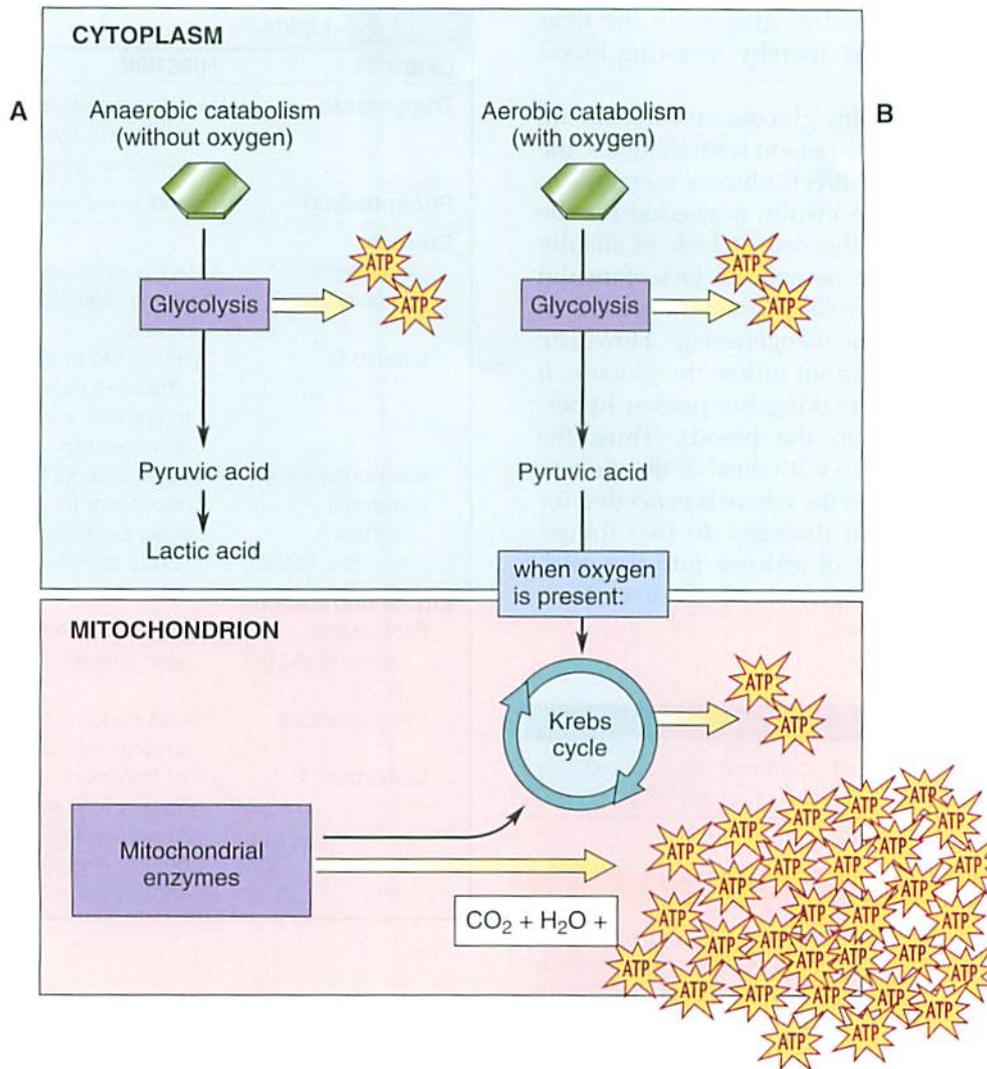
Glucose is broken down under the following two conditions: (1) in the absence of oxygen (the process is called **anaerobic catabolism**); and (2) in the presence of oxygen (this process is called **aerobic catabolism**). In the absence of oxygen, glucose is broken down through a series of chemical reactions, first into pyruvic acid and then into lactic acid. This anaerobic process occurs in the cytoplasm and is called **glycolysis** (glye-KOHL-i-sis) (Figure 4-3, A). Because most of the energy is still locked up in the lactic acid molecule, glycolysis produces only a small amount of ATP.

If oxygen is available, glucose is completely broken down to form carbon dioxide, water, and ATP (see Figure 4-3, B). The glucose is first broken down to pyruvic acid in the cytoplasm. The pyruvic acid molecules then move into the mitochondria—the power plants of the cell. In the presence of oxygen and special enzymes in the mitochondria, the pyruvic acid

Table 4-1 Carbohydrates

NAME	FUNCTION
<b>Monosaccharides (Simple Sugars)</b>	
Glucose	Most important energy source
Fructose	Converted to glucose
Galactose	Converted to glucose
Deoxyribose	Sugar in DNA
Ribose	Sugar in RNA
<b>Disaccharides (Double Sugars)</b>	
Sucrose	Splits into monosaccharides (glucose + fructose)
Maltose	Splits into monosaccharides (glucose + glucose)
Lactose	Splits into monosaccharides (glucose + galactose)
<b>Polysaccharides (Many Sugars)</b>	
Starches	Found in plant foods; digested to monosaccharides
Glycogen	Animal starch; excess glucose stored in liver and skeletal muscle
Cellulose	Nondigestible by humans; forms dietary fiber or roughage

DNA, Deoxyribonucleic acid; RNA, ribonucleic acid.



**FIGURE 4-3** Breakdown of glucose. **A**, Anaerobic catabolism, to lactic acid and little ATP. **B**, Aerobic catabolism, to carbon dioxide, water, and lots of ATP.

fragments are completely broken down to carbon dioxide and water. This process is accompanied by the release of a large amount of energy (ATP). Two sets of enzymes exist in the mitochondria: the enzymes of the Krebs cycle and the enzymes of the electron transport chain. Both sets of enzymes work together to produce ATP aerobically.

Three important points about aerobic catabolism should be considered. First, the chemical reactions occurring in the mitochondria require oxygen. If the cells are deprived of oxygen, they soon become low in energy and cannot carry out their functions. This need for oxygen is the reason we need to breathe continuously—to ensure a continuous supply of oxygen to the cells. Second, when glucose is broken down completely to carbon dioxide and water, all the stored energy is released. Some of the energy is transferred to ATP, and the rest is released as heat. Thus, the aerobic breakdown of glucose produces much more ATP than the anaerobic breakdown of glucose. Third,

if oxygen is not available to the cell, the pyruvic acid cannot enter the mitochondria. Instead, the pyruvic acid is converted to lactic acid in the cytoplasm. The buildup of lactic acid is the reason that a lack of oxygen in a critically ill patient causes lactic acidosis.

### THE MAKING OF GLUCOSE

As we have seen, glucose can be broken down in the cells as a source of energy. The body requires a constant supply of glucose for fuel. Dietary carbohydrates provide glucose, as does the conversion of glycogen into glucose. In addition, the body is capable of making glucose from noncarbohydrate substances. Protein, for example, can be broken down and the breakdown products used to make glucose. The making of glucose from nonglucose sources, especially protein, is called *gluconeogenesis*. **Gluconeogenesis** (gloo-koh-nee-oh-JEN-eh-sis) is an important mechanism in the regulation of blood sugar. For example, if blood sugar

declines, protein is converted to glucose in the liver and released into the blood, thereby restoring blood sugar to normal.

Clinical conditions affecting glucose metabolism are common. For instance, in the person with diabetes, the lack of the insulin hormone affects glucose metabolism in two ways. First, because insulin is needed for the transport of glucose into the cell, a lack of insulin deprives the cells of glucose. Second, the lack of insulin causes body protein to be broken down and then converted into glucose (gluconeogenesis). However, because the diabetic cells cannot utilize the glucose, it accumulates in the blood, making the person hyperglycemic (excess glucose in the blood). Thus, the person with diabetes ends up with most of the glucose in the blood and not in the cells, where it is needed for energy. Drugs used to treat diabetes do two things: they increase the transport of glucose into the cells, and they suppress gluconeogenesis by the liver. Both effects lower blood glucose.

### ? Re-Think

Define gluconeogenesis. What purpose is served by gluconeogenesis?

### 2+2 Sum It Up!

The body, like a factory, requires raw material for growth, repair, and operation. The raw materials for the body come in the form of food: carbohydrates, proteins, and fats. Metabolism refers to the millions of chemical reactions that make the body run. Anabolic reactions are involved in the synthesis of complex substances from simpler substances. Catabolic reactions break down complex substances into simpler substances, generally in an effort to liberate energy stored within the food substances. Carbohydrates and fats are the body's primary fuel. Glucose can be broken down and used as fuel in two ways: anaerobically (glycolysis), yielding little ATP, and aerobically, within the mitochondria (Krebs cycle and electron transport chain enzymes), yielding large amounts of ATP. In addition to the consumption of dietary carbohydrates, glucose can also be made from the breakdown products of protein by a process called *gluconeogenesis*.

## LIPIDS (FATS)

**Lipids** are organic compounds that are commonly called *fats* and *oils*. Fats are solid at room temperature whereas oils are liquid. Most of the lipids are eaten as fatty meats, egg yolks, dairy products, and oils. The lipids found most commonly in the body include triglycerides, phospholipids, and steroids. Other relatives of lipids, called *lipoid substances*, are listed in Table 4-2.

The building blocks of lipids are fatty acids and glycerol. The lipid illustrated in Figure 4-4, *A*, is a triglyceride (try-GLL-ser-ride). It has three (tri)

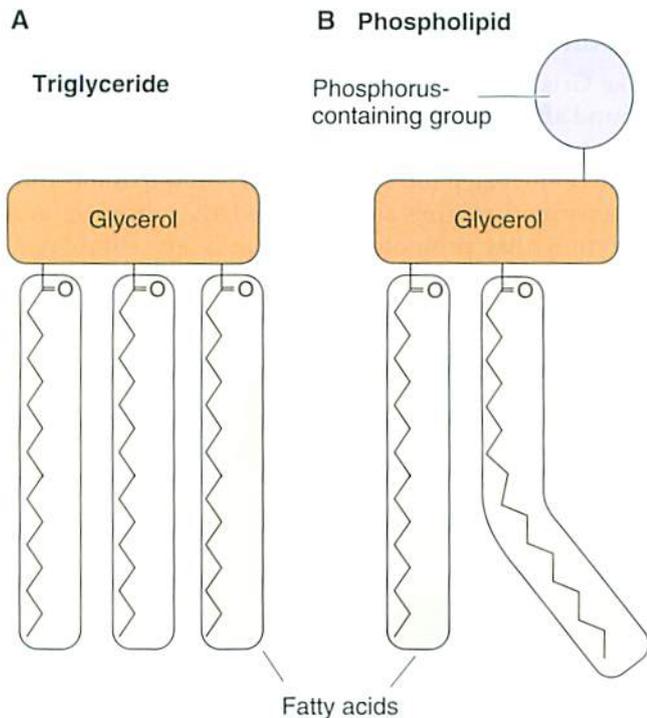
Table 4-2 Lipids

LIPID TYPE	FUNCTION
<b>Triglyceride</b>	In adipose tissue: protect and insulate body organs; major source of stored energy
<b>Phospholipid</b>	Found in cell membranes
<b>Steroid</b>	
Cholesterol	Used in synthesis of steroids
Bile salt	Assist in digestion and absorption of fats
Vitamin D	Synthesized in skin on exposure to ultraviolet radiation; contributes to calcium and phosphate homeostasis
Hormones from adrenal cortex, ovaries, testes	Adrenal cortical hormones are necessary for life and affect every body system; ovaries and testes secrete sex hormones
<b>Lipoid substances</b>	
Fat-soluble vitamins (A, D, E, K)	Variety of functions (identified in later chapters)
Prostaglandins	Found in cell membranes; affect smooth muscle contraction
Lipoproteins	Help transport fatty acids; high-density lipoprotein (HDL) is "good cholesterol" and low-density lipoprotein (LDL) is "bad cholesterol"

long chains of fatty acids attached to one small glycerol molecule. A phospholipid is formed when a phosphorus-containing group attaches to one of the glycerol sites (see Figure 4-4, *B*). Phospholipids are important components of the cell membrane. (Do not confuse glycerol with glycogen.)

The steroid is a third type of lipid. The most important steroid in the body is cholesterol (see Figure 4-4, *C*).

Although cholesterol is consumed in the diet, the body can also synthesize cholesterol in the liver. In fact, most of our cholesterol is made by the liver from saturated fat. This observation raises an interesting point regarding the dietary control of cholesterol. The dietary intake of a healthy diet results in only a slight increase in blood cholesterol, whereas the dietary intake of saturated fats (meat, eggs, cheeses) accounts for a significant increase of blood cholesterol as it is used by the liver to synthesize cholesterol. Thus, the focus of dietary control of blood cholesterol is the restriction of saturated fats. Despite all the bad press about it, cholesterol performs several important functions. For example, cholesterol is found in all cell membranes and is necessary for the synthesis of vitamin D in the skin. It is also used in the ovaries and testes in the synthesis of the sex hormones.



**C Steroid (cholesterol)**

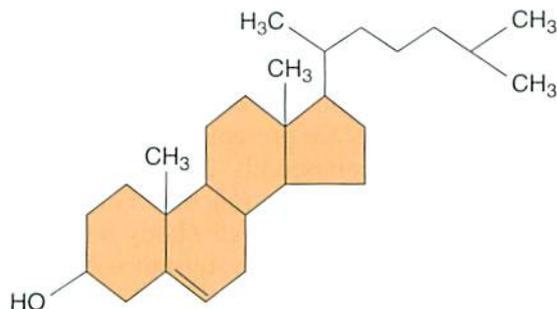


FIGURE 4-4 Lipids.

**Ramp It Up!**

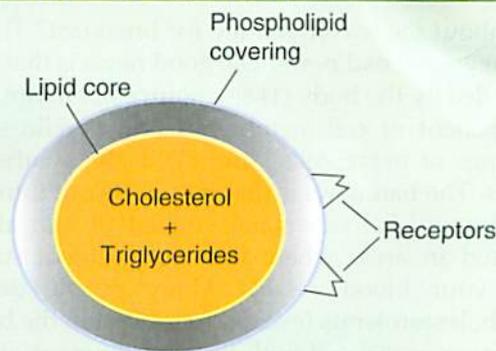
**Cholesterol, Triglycerides, and Lipoproteins**

Cholesterol and triglycerides are lipids that we love to hate, often for very good reason. Both have been implicated in coronary artery heart disease. Cholesterol and triglycerides are lipids and therefore are not soluble in water. Both, however, must be transported by the blood, a water (or aqueous) solution. How is the solubility problem solved? Enter the lipoproteins! They make the cholesterol and triglycerides soluble in water. Read on.

**LIPOPROTEINS**

A lipoprotein has a basic lipid-soluble core composed of cholesterol and triglycerides, surrounded by a single layer of phospholipid. It is the phospholipid coat that makes the lipid water-soluble. In addition to increasing the solubility of the lipid core, the phospholipid layer contains receptors. These receptors play a role in the delivery and excretion of cholesterol and triglycerides.

**Ramp It Up!—cont'd**



There are six major classes of lipoproteins, but we will describe only three: very low-density lipoprotein (VLDL), low-density lipoprotein (LDL), and high-density lipoprotein (HDL). This classification is based on the density, which is determined by the percentage composition of lipid and protein. Protein is more dense than lipid. Thus, lipoproteins that have a greater proportion of protein than lipid have a relatively high density. Conversely, lipoproteins with a lower percentage of protein have a lower density.

**VERY LOW-DENSITY LIPOPROTEIN (VLDL)**

VLDLs contain mostly triglycerides and little cholesterol as the core lipid; the triglycerides in VLDL account for almost all the triglycerides in the blood. The role of VLDLs is to transport triglycerides to adipose tissue and muscle. It is unclear about the role of VLDLs in heart disease, but marked elevations cause pancreatitis. The degradation of VLDLs produces LDLs.

**LOW-DENSITY LIPOPROTEIN (LDL)**

LDLs contain cholesterol as the core lipid and account for most (60%–70%) of the cholesterol in the blood. The role of LDLs is to deliver cholesterol to nonhepatic (nonliver) tissue. Cells of the target tissues have membrane receptors that recognize and bind to LDLs; on binding, the cholesterol is ingested by the cells by endocytosis. Of all lipoproteins, LDLs make the greatest contribution to atherosclerotic heart disease and are therefore called “bad” cholesterol. The goal of drug therapy for coronary heart disease is to decrease LDL levels.

There are a number of drugs that reduce LDLs. The most effective drugs are the “statins,” such as lovastatin and pravastatin. The statins reduce LDLs by decreasing the hepatic synthesis of cholesterol and increasing the number of receptors on the liver cells (hepatocytes). The increased number of hepatic receptor sites increases the elimination of cholesterol into the bile. Because cholesterol synthesis is greater at night, the statins are generally administered at bedtime. Also, statins target the liver and hepatotoxicity may therefore develop as an adverse drug reaction. Other cholesterol- or triglyceride-lowering drugs do so by decreasing the formation of VLDLs, the producers of LDLs.

**HIGH-DENSITY LIPOPROTEIN (HDL)**

HDLs contain cholesterol as the primary core lipid and account for 20% to 30% of all cholesterol in the blood. HDLs carry cholesterol from the peripheral tissues to the liver for excretion into the bile. Thus, HDLs promote the removal of cholesterol from the blood. Unlike LDLs, which increase the risk of coronary heart disease, elevation of HDLs reduces the risk. Because HDLs are cardioprotective, they are called “good” cholesterol. Adherence to dietary guidelines, weight reduction, and exercise elevate HDLs.

## USES OF LIPIDS

What about the bacon you ate for breakfast? There is good news and bad news. The good news is that lipids are needed by the body (1) as a source of energy, (2) as a component of *cell membranes* and myelin sheath (coverings of nerve cells), and (3) in the synthesis of steroids. The bad news is that fat can be put into long-term storage. Fat can make you fat! It can also be deposited in areas where it is not wanted, such as inside your blood vessels. Many people develop hypercholesterolemia (excess cholesterol in the blood), a condition associated with the development of coronary artery disease. Cholesterol-related fatty plaques develop in the walls of the blood vessels (coronary arteries) that supply the heart. Over time, the plaques block the flow of blood to the heart, resulting in the death of heart muscle (commonly called a heart attack).

### ? Re-Think

1. What is a triglyceride?
2. Why is it unwise to feed an infant only "fat-free" milk?

## METABOLISM OF LIPIDS

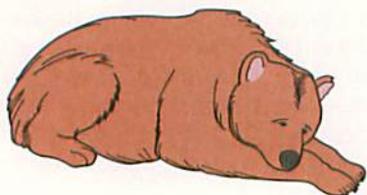
Like glucose, fatty acids and glycerol can be broken down in order to release the stored energy. Because the fatty acids are long structures, however, they must be chopped into tiny units before entering the mitochondria and being catabolized within the Krebs cycle. The aerobic burning of the fatty acid units in the mitochondria releases a huge amount of energy that is captured as ATP. Because the fatty acids are much longer than the glucose molecules, the amount of energy released in the burning of fatty acids is much greater than the amount released in the burning of glucose.

### Do You Know...

#### That Griz Does Not Urinate during His Hibernating Months?

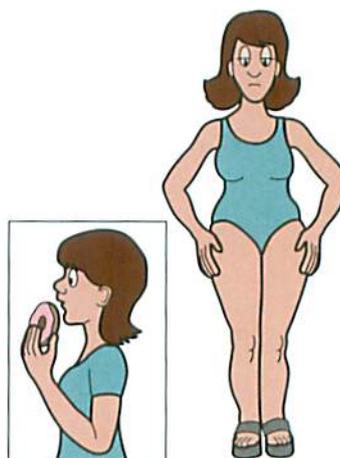
Nature encourages the grizzly bear ("Griz") to overeat and gain weight. By doing so, Griz is able to hibernate during the winter months because he can live off the fat stored during the summer feeding frenzy. While hibernating, the bear's fat is gradually broken down, and the energy that is released is sufficient to keep him alive.

What, then, about the waste produced by his metabolizing body? The bear has apparently developed the metabolic ability to convert his waste (urea) into a substance that can be used by the body. He literally recycles his urine. An understanding of this recycling process would certainly benefit the many persons who require dialysis because of kidney failure.



## MAKING FAT

Like Griz, we too can go on a feeding frenzy and gain pound after pound! However, we do not hibernate and therefore do not easily shed those excess pounds. The extra donut eaten today is worn on your hip tomorrow. When excess calories are consumed, the hormones and enzymes that promote fat synthesis are stimulated. The fat is deposited in adipose tissue throughout the body.



## PROTEINS

**Protein** is the most abundant organic matter in the body. Because proteins are present in so many physiologically important compounds, it is safe to say that they participate in every body function. For example, almost every chemical reaction in the body is regulated by an enzyme, which is a protein substance. Most hormones are proteins; they exert important widespread effects throughout the body. Hemoglobin, which delivers oxygen to every cell in the body, is a protein. Finally, muscles contract because of their contractile proteins. As you can see, proteins are essential to life.

## AMINO ACIDS

The building blocks of protein are **amino acids**. About 20 amino acids are used to build body protein. Most amino acids come from protein foods, especially lean meat, milk, and eggs. More than half of the amino acids can be synthesized by the body. If the diet lacks the amino acid alanine, for example, alanine can be synthesized in the liver.

Some amino acids, however, cannot be synthesized by the body and must be obtained from dietary sources. Because dietary intake of these amino acids is essential, these amino acids are called *essential amino acids*. The amino acids that can be synthesized by the liver are called *nonessential amino acids*, meaning that these amino acids are not absolutely necessary in the diet. See Box 4-1 for a list of common amino acids.

**Box 4-1** Common Amino Acids

Alanine	Leucine*
Arginine	Lysine*
Asparagine	Methionine*
Aspartic acid	Phenylalanine*
Cysteine	Proline
Glutamic acid	Serine
Glutamine	Threonine*
Glycine	Tryptophan*
Histidine*	Tyrosine
Isoleucine*	Valine*

\*Essential amino acids.

**NOTE:** The word *nonessential* does not mean that these amino acids are not essential to the body. The term refers to the ability of the body to synthesize these amino acids when they are not included in the diet.

Like carbohydrates and lipids, amino acids are composed of carbon, hydrogen, and oxygen. In addition to these three elements, amino acids also contain nitrogen. The nitrogen appears as an amine group ( $\text{NH}_2$ ). At the other end of the amino acid is the acid group ( $-\text{COOH}$ ); hence, the name *amino acid*. Note the amine group and the acid group in Figure 4-5, A; the amino acid alanine is used as an example.

Amino acids are joined together by peptide bonds. A **peptide bond** is formed when the amine group ( $\text{NH}_2$ ) of one amino acid joins with the acid group ( $-\text{COOH}$ ) of a second amino acid. A peptide is formed when several amino acids are joined together by peptide bonds (see Figure 4-5, B). A polypeptide is formed when many amino acids are joined together. Proteins are very large polypeptides. Most proteins are composed of more than one polypeptide chain. The polypeptide chains are curly and coil around each other, creating a large and uniquely shaped protein. The amino acid sequence, and the size and shape of the protein are important to its function. If the amino acids are not assembled in the correct order, the shape of the protein changes and its function is impaired. For example, in sickle cell anemia, only one of the amino acids is “out of order” in the hemoglobin protein, the major component of a red blood cell. The improperly constructed hemoglobin causes the red blood cells to sickle and break apart.

Proteins can bond with other organic compounds. For example, the combination of a sugar and a protein forms a glycoprotein, whereas the combination of a lipid and protein creates a lipoprotein.

**? Re-Think**

1. What is the difference between an essential and nonessential amino acid?
2. Why do peptide bonds form between amino acids and not between glycogen molecules?

**USES OF PROTEINS**

Proteins are used in three ways. The most important use is in the synthesis of hormones, enzymes, antibodies, plasma, muscle proteins, hemoglobin, and most cell membranes. In one way or another, proteins play a key role in every physiological function. The various types of proteins and their functions are listed in Table 4-3. With such a large demand for protein, most of the amino acids are carefully conserved by the body and used in the synthesis of protein.

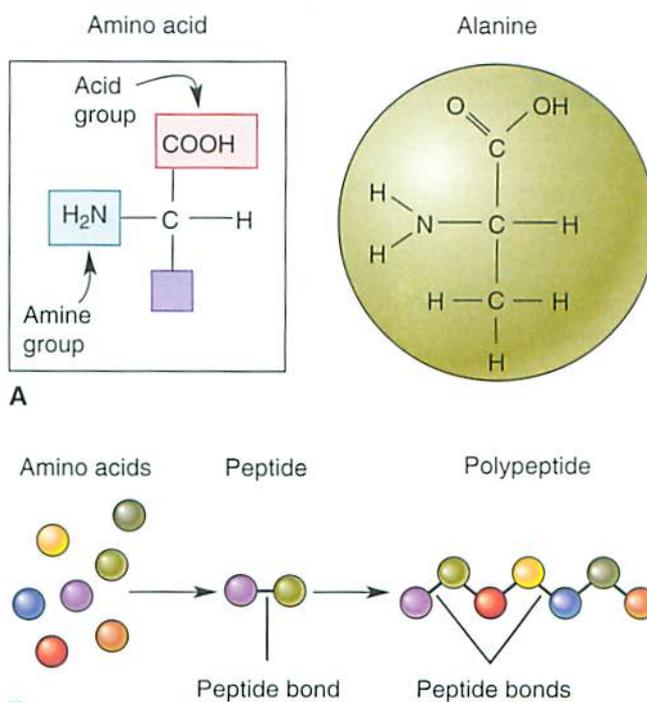
Proteins have two less common uses. First, protein can be broken down and used as fuel, as a source of energy for ATP production. This process, however, is not desirable. The preferred energy sources are glucose and fat. Second, protein can be broken down and converted to glucose (gluconeogenesis). This mechanism is used by the body to ensure that the blood glucose level does not become too low to sustain life. In severe starvation, the body catabolizes its own protein, including the heart muscle, in order to survive.

**? Re-Think**

What is the most important use of amino acids?

**BREAKDOWN OF PROTEIN AND THE PROBLEM WITH AMMONIA**

Because amino acids contain nitrogen, as well as carbon, hydrogen, and oxygen, the breakdown of



**FIGURE 4-5** Amino acids and proteins. **A**, The structure of an amino acid (alanine). **B**, The assembly of amino acids to form a polypeptide. Note the peptide bonds.

protein poses a special problem. Carbon, hydrogen, and oxygen can be broken down into carbon dioxide and water and eliminated from the body. The nitrogen part of the amino acid, however, must be handled in a special way, primarily by the liver. Nitrogen is either recycled and used to synthesize different amino acids or converted to urea and excreted.

### Formation of Urea

Some of the nitrogen released by the breakdown of amino acids is converted to urea by the liver (Figure 4-6). Note the nitrogen in the structural formula of urea. Blood then carries the urea, a nitrogenous waste, from the liver, where it is made, to the kidneys, where it is eliminated in the urine. This is important clinical information and forms the basis for several diagnostic tests.

**Worrying About Ammonia.** Why does the liver “worry” about ammonia? Under normal conditions, the liver extracts ammonia ( $\text{NH}_3$ ) from the blood and converts it to urea. Why? Ammonia is toxic to brain cells and causes disorientation and a diminished level of consciousness. In liver failure, the extraction of ammonia from the blood is diminished, so blood levels of ammonia rise. The toxic effect of ammonia on the brain is called *hepatic encephalopathy* (heh-PAT-ik en-sef-al-OP-eh-thee). A diagnostic test called the *blood urea nitrogen* (BUN) test measures the amount of urea in the blood. A change in BUN can be caused from either poor liver function (cannot make urea) or poor kidney function (cannot excrete it).

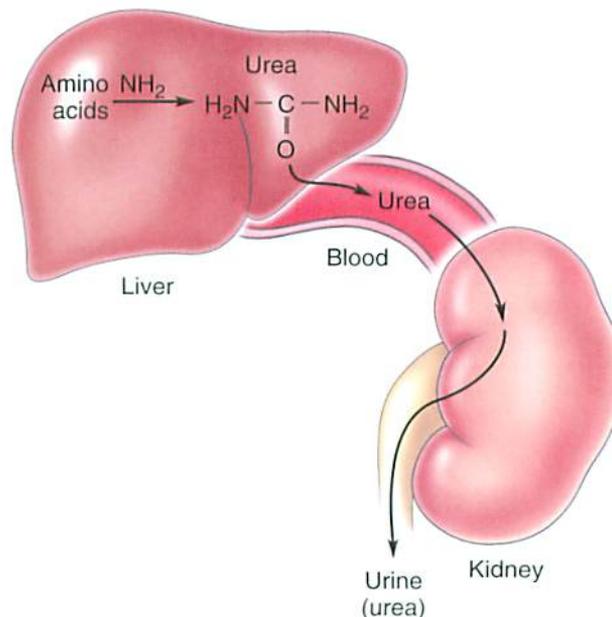


FIGURE 4-6 Urea: formation in the liver and excretion by the kidney.

### Re-Think

1. Why is urea production so important?
2. What happens if a damaged liver is unable to make urea?
3. Why may an elevated BUN indicate poor kidney function?

### 2+2 Sum It Up!

There are three types of lipids: triglycerides, phospholipids, and steroids. Cholesterol is the most important steroid. Lipids are used in the synthesis of cell membranes and steroids and in the storage of energy; they are catabolized as fuels. Amino acids are used primarily in the synthesis of body proteins: hormones, enzymes, antibodies, plasma proteins, and structural components of cells. Amino acids join together by peptide bonds, whereby the amine group ( $-\text{NH}_2$ ) of one amino acid joins with the acid group ( $-\text{COOH}$ ) of a second amino acid. In addition to carbon, hydrogen, and oxygen, the catabolism of proteins produces nitrogen that is toxic to the brain. The hepatic (liver) production and renal (kidney) excretion of the nitrogenous waste, urea, is the biochemical solution to ammonia ( $\text{NH}_3$ ) toxicity.

### PROTEIN SYNTHESIS AND DNA

Proteins play a crucial role in every body function. Protein synthesis involves the arrangement of amino acids in a specific sequence. Because the sequencing of amino acids is so precise, there is an elaborate protein-synthesizing mechanism in each cell. How does the cell know the exact pattern of amino acid assembly? The pattern of amino acid assembly is coded and stored in the **deoxyribonucleic acid (DNA)** in the nucleus. In fact, the essential role of DNA is to serve as a code for the structure of protein.

Table 4-3 Proteins

TYPE	FUNCTION
Structural proteins	
Components of cell membranes	Perform many functions: determine pore size; allow hormones to “recognize” cell
Collagen	Structural component of muscle and tendons
Keratin	Part of skin and hair
Peptide hormones	Many hormones are proteins; have widespread effects on many organ systems (e.g., insulin, growth hormone)
Hemoglobin	Transports oxygen
Antibodies	Protect body from disease-causing microorganisms
Plasma proteins	Used in blood clotting, fluid balance, and defense against disease
Muscle proteins	Enable muscles to contract
Enzymes	Regulate the rates of chemical reactions

## DNA STRUCTURE

DNA is a nucleic acid. Nucleic acids are composed of smaller units called *nucleotides* (Figure 4-7, A). A nucleotide has three parts: a sugar, a phosphate group, and a base. Nucleotides are joined together to form long strands. Two strands of nucleotides are arranged in a twisted ladder formation (the double helix) to form DNA (see Figure 4-7, B). The two sides of the DNA ladder are composed of sugar and phosphate molecules. The rungs, or steps, of the ladder are composed of bases, one base from each side. The names of the bases in DNA are adenine (A), cytosine (C), guanine (G), and thymine (T). Note the different shapes of the bases in the rungs of the ladder. Note also that the bases have a particular arrangement. Adenine can pair only with thymine, and cytosine can pair only with guanine. Adenine and thymine are base pairs, as are cytosine and guanine. This system is called **base pairing**.

### THE GENETIC CODE

The protein-synthesizing code is stored within the DNA. More specifically, the information is stored, or encoded, within the sequence of bases along one strand (one side of the ladder) of DNA (Figure 4-8). Because the DNA is arranged in hereditary units called *genes*, the code is called the *genetic code*. (Genes and heredity are discussed further in Chapter 27.)

### Reading the Code

A single strand of DNA (see Figure 4-8) reads vertically (according to the bases in the rungs), such as GAC-GCCCAA. GAC (a sequence of three bases) codes for a particular amino acid, GCC codes for another amino acid, and CAA codes for a third amino acid. The list of bases in triplicate is called **base sequencing**. In this way, DNA codes for the proper sequence of amino acids and therefore the synthesis of protein.

**NOTE:** Do not confuse base pairing with base sequencing. *Base pairing* describes the way in which two strands of DNA are linked together by the bases. *Base sequencing* describes the sequence, or order, of the bases along a single strand of DNA. The code is stored within the sequence of bases.

### Copying the Code: mRNA

The code for protein synthesis is stored in the nucleus in the DNA. DNA does not leave the nucleus because it is too large to fit through the pores of the nuclear membrane. Protein synthesis, however, occurs along the ribosomes in the cytoplasm. The big question? How does the code get out of the nucleus and into the cytoplasm? The copying and delivery of the code is done by a second nucleic acid called **ribonucleic acid (RNA)**.

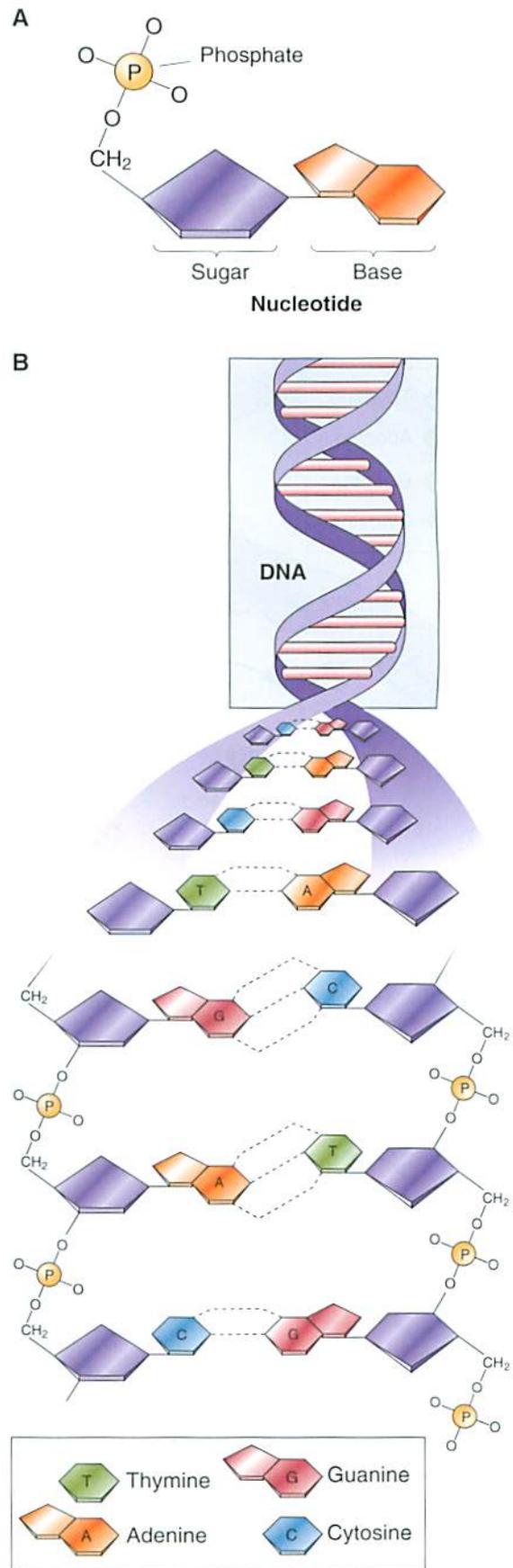


FIGURE 4-7 A, Nucleotide. B, The ladder structure of DNA. Note the base pairing of the DNA strands.

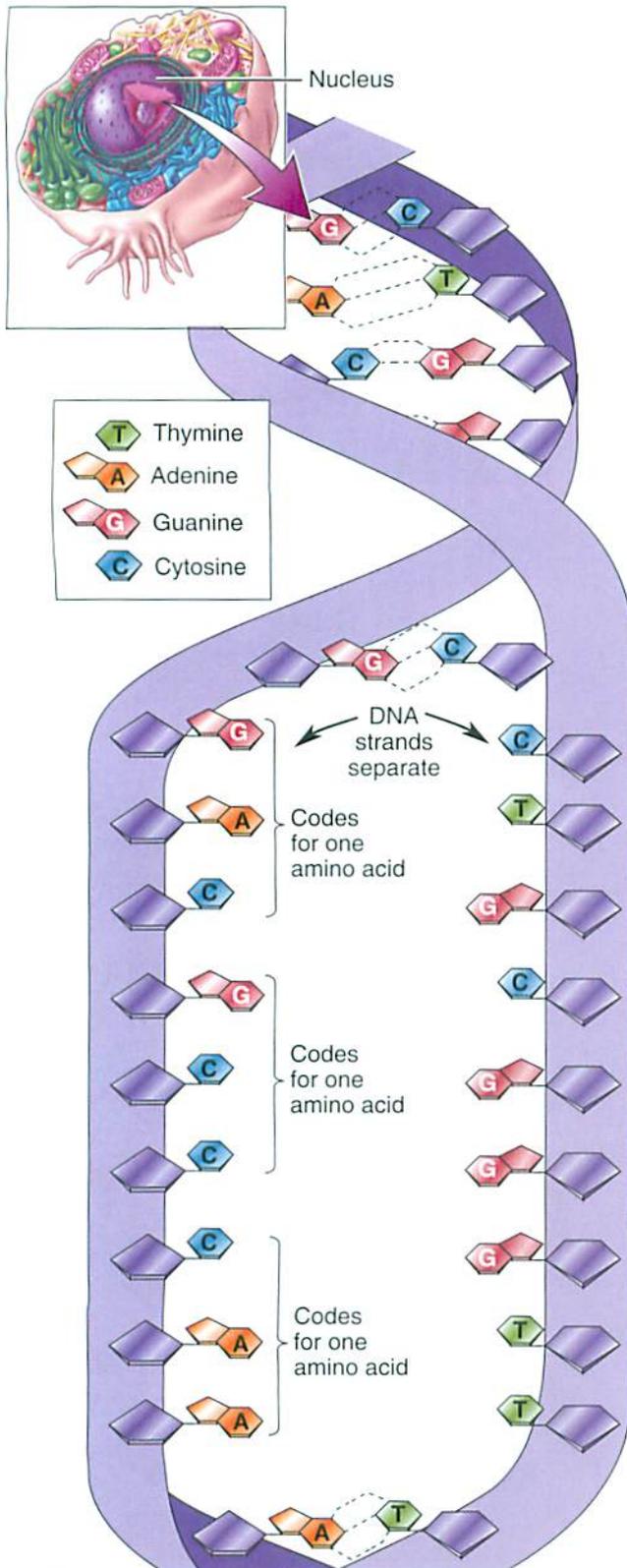


FIGURE 4-8 DNA: genetic code and base sequencing.

Table 4-4 Comparison of DNA and RNA Structures

	DNA	RNA
Sugar	Deoxyribose	Ribose
Base	Adenine Guanine Cytosine Thymine	Adenine Guanine Cytosine Uracil
Strands	Double (two)	Single (one)

RNA is a nucleic acid composed of nucleotides and resembles the structure of DNA. RNA differs from DNA in three ways:

1. The sugars are different. The sugar in DNA is deoxyribose, whereas the sugar in RNA is ribose.
2. DNA has two strands, whereas RNA has only one strand.
3. There is a difference in one of the bases. Both DNA and RNA contain cytosine (C), guanine (G), and adenine (A). The fourth base differs. DNA contains thymine (T), whereas RNA contains uracil (U). The uracil in RNA forms a base pair with adenine. The differences between DNA and RNA are summarized in Table 4-4.

There are three types of RNA, but we are concerned only with messenger RNA (mRNA) and transfer RNA (tRNA). Messenger RNA copies the code from DNA in the nucleus and then carries the code, or message, to the ribosomes in the cytoplasm. Because this type of RNA acts as a messenger, it is called *mRNA*.

Transfer RNA (tRNA) is found attached to individual amino acids within the cytoplasm and, through its own base sequencing, can “read” the code on the mRNA sitting on the ribosome. Each individual amino acid is carried by tRNA to its proper site on the mRNA. The amino acids are assembled in the proper sequence as the polypeptide (protein) is formed.

### mRNA as Copycat

Refer to Figure 4-8 as we see how mRNA copies the code. DNA separates and exposes the base sequences, GACGCCAA. A strand of mRNA reads the base sequence by forming base pairs. The strand of mRNA has this code: CUGC GGUU. (The mRNA is not shown.) The copying of the code by mRNA is called *transcription*.

NOTE: Transcription is a base-pairing event. Following transcription, the mRNA takes the code to the ribosomes in the cytoplasm, where the amino acids will be assembled.

### ? Re-Think

1. List three differences between DNA and RNA.
2. What is the difference between base pairing and base sequencing?



### Do You Know...

#### What Are Purines and Pyrimidines, and Why Are Cancer Drugs Aimed at Them?

The bases in the nucleotides that make up DNA and RNA are classified as either purines or pyrimidines. Adenine and guanine are purines, and cytosine, thymine, and uracil are pyrimidines. This terminology is important to know because some anticancer drugs are called *purine analogs* and others *pyrimidine analogs*. This means that the drugs resemble purines and pyrimidines. When incorporated in the DNA or RNA molecules, the drugs introduce errors into the genetic code, impair protein synthesis, and kill the cancer cell. Unfortunately, the drugs are also incorporated into many normal cells, thereby causing their death and producing many of the toxic effects of cancer therapy. No wonder these anticancer drugs are classified as cytotoxic agents; they are toxic to both cancer and normal cells.

### STEPS IN PROTEIN SYNTHESIS

How do DNA and RNA control protein synthesis? See Figure 4-9 and identify the following five steps in protein synthesis:

1. When a particular protein is to be synthesized, the strands of DNA in the nucleus separate. The exposed sequence of bases on the separated DNA strand is copied onto a strand of mRNA (transcription).
2. The mRNA leaves the nucleus and travels to the ribosomes in the cytoplasm.
3. The code on the mRNA (now sitting on a ribosome) determines which amino acids can attach to it. For example, the code may specify that only the amino acid alanine can bind to site 1 and only the amino acid cysteine can bind to site 2.

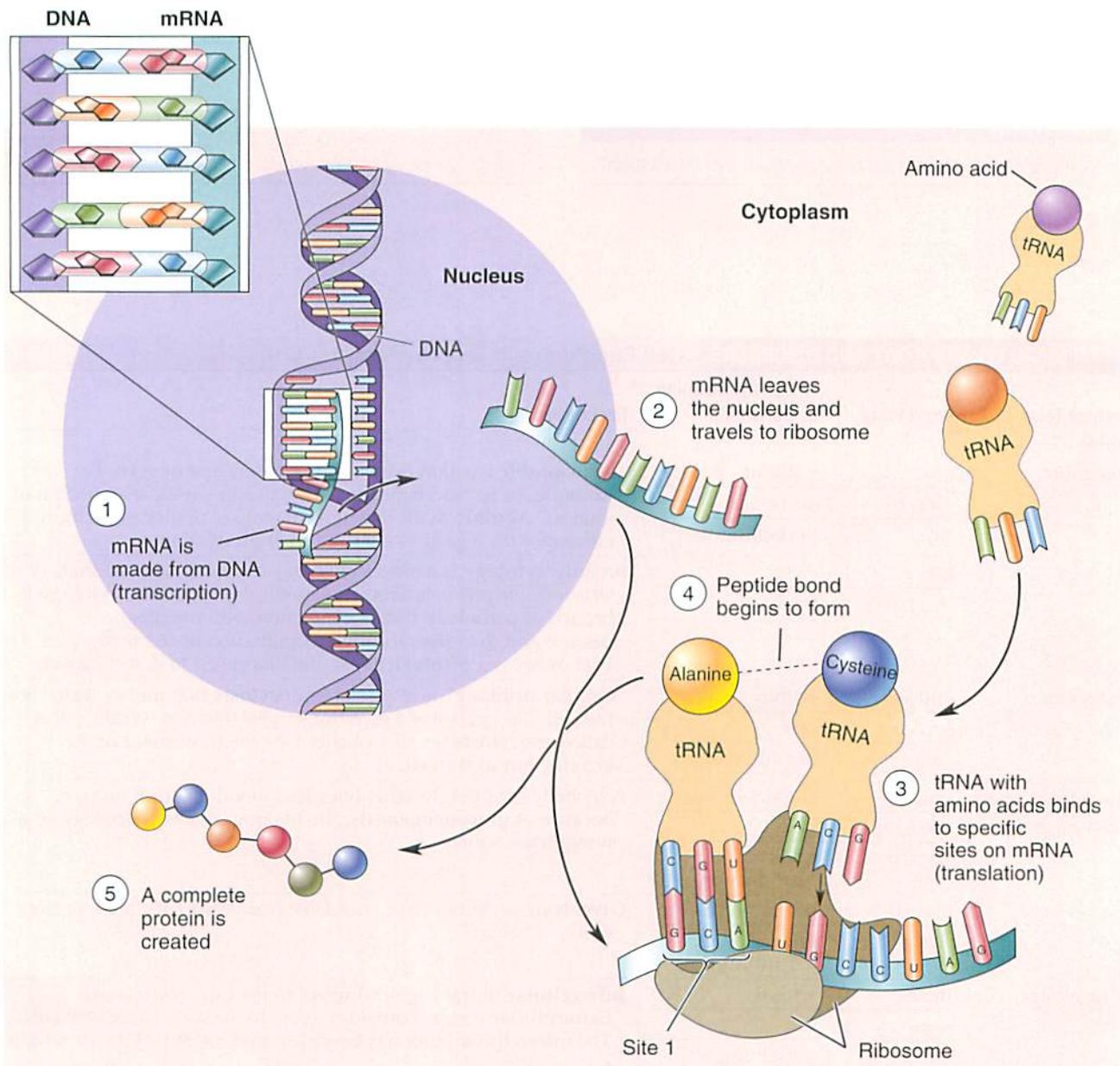


FIGURE 4-9 Steps (1 to 5) in protein synthesis.

How does alanine (located in the cytoplasm) know that it should move to the ribosome for protein assembly? Alanine is attached to tRNA. The tRNA contains bases, a sequence called its *anticodon*, that can recognize and pair with the bases on mRNA. For example, if mRNA contains the base sequence GCA, then only a tRNA with the base sequence (anticodon) of CGU can attach to that site. The reading of the mRNA code by tRNA is called *translation*. Like transcription (nucleus), translation (cytoplasm–ribosomes) is a base-pairing event.

- The amino acids are lined up in proper sequence along the ribosome. A peptide bond forms between each amino acid, creating a growing peptide chain.
- When all the amino acids have been assembled in the exact sequence dictated by the code, the protein chain is terminated. A complete protein has been created. The protein is now ready for use in the cell or for export to another site outside the cell.

### Re-Think

What is the difference between transcription and translation?

### 2+2 Sum It Up!

Body structure and function are largely determined by the specific proteins synthesized by the cells. Because of the crucial roles played by proteins, an elaborate cellular mechanism guides the assembly of the amino acids into proteins. Your protein blueprint, or genetic code, is stored in the DNA in the nucleus. When there is need for protein synthesis, the code must be transferred to the ribosome by mRNA, where amino acid assembly takes place. Protein synthesis occurs in five steps (see Figure 4-9).

### As You Age

- Age brings a decrease in the number and function of organelles such as mitochondria. Because mitochondria play a key role in metabolism, a decrease in mitochondrial function affects metabolism.
- In general, metabolism slows with aging. This effect is a result of a decrease in hormonal secretion, particularly the thyroid hormones. A decreased metabolism has several effects: less tolerance to cold, a tendency to gain weight, and metabolic effects, such as a decreased efficiency in using glucose.
- The rate of protein synthesis decreases. Tissue growth and repair slow down, as does the synthesis of other proteins, such as digestive enzymes.

## MEDICAL TERMINOLOGY AND DISORDERS Cell Function and Disorders of the Cell

Medical Term	Word Parts	Word Part Meaning or Derivation	Description
<b>Words</b>			
anaerobic	an- -aer/o- -ic	without air or gas pertaining to	An <b>anaerobic</b> reaction occurs in the absence of oxygen. For example, lactic acid is produced by the anaerobic metabolism of glucose. <b>Aerobic</b> (with oxygen) catabolism of glucose is more efficient with regard to energy (ATP) production.
cytology	cyt/o- -logy	cell study of	Broadly, <b>cytology</b> is a branch of biology concerned with the study of cell structure and function. From the medical perspective, cytology is a branch of pathology that is concerned with the diagnosis of disease and disorders through examination of tissue samples. The Pap smear is a <b>cytological</b> examination used to detect cancer.
endocytosis	endo- -cyt/o- -osis	within cell condition of	“Cellular drinking” is a type of <b>endocytosis</b> that moves water into the cell. The ejection of a digestive enzyme from a pancreatic cell is called <b>exocytosis</b> (ex/o = outside), or the movement of the enzyme out of the cell.
gluconeogenesis	gluc/o- -neo- -gen/o-	sugar, glucose new origin, production	A diabetic is hyperglycemic (elevated blood glucose), in part, because of <b>gluconeogenesis</b> , the making of new glucose from a nonglucose source.
glycolysis	glyc/o- -lysis	sugar, glucose break down, dissolution	<b>Glycolysis</b> is the anaerobic breakdown (catabolism) of glucose to lactic acid.
intracellular	intra- -cell- -ar	within cell pertaining to	<b>Intracellular</b> (intra = within) refers to the space inside a cell. <b>Extracellular</b> (extra = outside) refers to the space outside the cell. The <b>intercellular</b> (inter = between) space is the space between the cells.


**MEDICAL TERMINOLOGY AND DISORDERS**
**Cell Function and Disorders of the Cell—cont'd**

Medical Term	Word Parts	Word Part Meaning or Derivation	Description
isotonic	iso-	same with regard to stretch of the membrane	An <b>isotonic</b> (same stretch) <b>solution</b> is a solution that does not cause a change in cell volume or pressure.
	-ton/o-	tension	
	-ic	pertaining to	
metabolism	meta-	beyond	<b>Metabolism</b> includes all of the enzymatic reactions needed to run the body. It includes <b>anabolism</b> (ana = up, and a Greek word meaning “to throw”) and <b>catabolism</b> (cat = down, and a Greek word meaning “to throw”).
	-bol-	From a Greek word, <i>ballein</i> , meaning “to throw”	
	-ism	condition of	
monosaccharide	mono-	one	Glucose is a <b>monosaccharide</b> , or a simple sugar. Sucrose is table sugar, or a <b>disaccharide</b> (di = two). Glycogen is a <b>polysaccharide</b> (poly = many).
	-saccharide	From a Greek word meaning “sugar”	
synthesis	syn-	together, with	<b>Synthesis</b> means the putting together of simpler substances to make a larger, more complex substance.
	-thesis	From a Greek word meaning “to put”	
transport	trans-	across	<b>Transport</b> means to carry from one place to another. Most water and dissolved solute is transported by diffusion.
	-port	From a Latin word meaning “to carry”	
<b>Disorders</b>			
<b>Adaptive Cellular Changes</b>			
atrophy	a-	without	A cellular adaptive process that results in a decrease in the size of a tissue or organ caused by a decrease in the number of cells or a reduction in cell size. Numerous causes: resulting from a disease such as muscular dystrophy; diminished blood supply, muscle inactivity, nutritional deficiency, and the natural aging process.
	-troph-	development; nourishment	
	-y	condition of	
hypertrophy	hyper-	excessive	An increase in the size (not number) of cells. <b>Hypertrophy</b> is a response to increased workload. Lifting weights hypertrophies arm and shoulder muscles.
	-troph-	development	
	-y	condition of, process	
hyperplasia	hyper-	excessive	An increase in the number of cells caused by an increase in cell division. There is compensatory and hormonal hyperplasia. An increase in the number of liver cells subsequent to the removal of part of the liver is an example of <b>compensatory hyperplasia</b> . The uterine response to estrogen is an example of <b>hormonal hyperplasia</b> .
	-plasia	formation	
metaplasia	meta-	beyond, after, change	A reversible cellular transformation (from one cell type to another). Cigarette smoking can cause the transformation of columnar epithelium into squamous epithelium; cessation of smoking can reverse the cellular change.
	-plasia	formation	
<b>Maladaptive Cellular Changes</b>			
dysplasia	dys-	faulty	A maladaptive cellular disorder in which the cells show evidence of abnormal differentiation, resulting in changes in cell size, shape, and appearance. Dysplasias, such as cervical dysplasia, are considered malignant precursors.
	-plasia	formation	
anaplasia	ana-	up; apart	A serious maladaptive (mal = bad) cellular change. Cells are poorly differentiated (immature and embryonic). Anaplastic cell growth is characteristic of malignant (cancerous) cells.
	-plasia	formation	

## Get Ready for Exams!

### Summary Outline

To carry on its functions, the cell must metabolize carbohydrates, proteins, and fats.

#### I. Metabolism

- Anabolism: chemical reactions that build more complex substances from simpler substances
- Catabolism: chemical reactions that break down complex substances into simpler substances

#### II. Carbohydrates: Structure and Function

- Carbohydrates: composed of carbon, hydrogen, and oxygen; classified as monosaccharides, disaccharides, and polysaccharides
- Glucose: the primary source of energy
- Glucose: can be stored as glycogen or converted to and stored as fat
- Glucose: can be catabolized anaerobically and aerobically. Anaerobically, glucose is incompletely broken down (glycolysis) into lactic acid and small amounts of ATP. Aerobically, glucose is broken down completely (Krebs cycle) into carbon dioxide (CO<sub>2</sub>) and water (H<sub>2</sub>O) and large amounts of energy (ATP).
- Glucose: can be synthesized from nonglucose substances such as protein; called gluconeogenesis

#### III. Lipids

- Most common lipids are triglycerides, phospholipids, and steroids.
- Cholesterol: the most important steroid; made soluble by lipoprotein; called "good" and "bad"
- Lipids: used primarily in the synthesis of membranes and fuel
- Long fatty acid chains: broken down into two-carbon units and metabolized by the enzymes of Krebs cycle and electron transport chain enzymes to CO<sub>2</sub> and H<sub>2</sub>O, releasing large amounts of energy (ATP)

#### IV. Proteins

- Proteins: composed of amino acids linked together by peptide bonds in a specific sequence
- Proteins: used primarily in the synthesis of hormones, enzymes, antibodies, plasma proteins, muscle proteins, hemoglobin, and cell membranes; also used as fuel and for gluconeogenesis
- Urea synthesis: special handling of protein nitrogen by enzymes in the liver

#### V. Protein Synthesis and DNA

- DNA (deoxyribonucleic acid)
  - DNA: stores the code for protein synthesis
  - DNA: double-stranded series of nucleotides, arranged in a twisted ladder formation
  - Nucleotide: composed of a sugar, a phosphate group, and a base. For DNA, the sugar is deoxyribose; the bases are adenine, thymine, cytosine, and guanine.
  - Genetic code: stored in a sequence of three bases
  - Base pairs with DNA and RNA

#### B. RNA

- Ribonucleic acid (RNA): similar structure to DNA, with the following differences. In RNA, the sugar is ribose, RNA is single-stranded, and the RNA bases are adenine, uracil, cytosine, and guanine.
  - Two types of RNA: messenger RNA (mRNA) and transfer RNA (tRNA)
  - Transcription: DNA and mRNA (occurs within nucleus)
  - Translation: mRNA and tRNA (occurs within cytoplasm/ribosomes)
- C. Protein synthesis: five steps, summarized in Figure 4-9

### Review Your Knowledge

#### Matching: Carbohydrates, Proteins, and Fats

Directions: Match the following words with their descriptions below. Some words may be used more than once.

- glycogen
- amino acids
- lipids
- urea
- monosaccharides
- glucose
- disaccharides
- fatty acids and glycerol

- \_\_\_ Nitrogen-containing waste product
- \_\_\_ Building blocks of proteins
- \_\_\_ Classification of steroids and triglycerides
- \_\_\_ Sucrose, maltose, and lactose
- \_\_\_ Monosaccharide that is chief fuel for the body
- \_\_\_ Building blocks held together by peptide bonds
- \_\_\_ Building blocks of lipids
- \_\_\_ Storage form of glucose
- \_\_\_ Glucose, fructose, and galactose
- \_\_\_ Animal starch stored in the liver and skeletal muscles

#### Matching: Biochemistry Terms

Directions: Match the following words with their descriptions below. Some words may be used more than once.

- glycolysis
  - Krebs cycle and electron transport chain enzymes
  - gluconeogenesis
  - enzyme
  - ketone bodies
- \_\_\_ Series of aerobic reactions that occur within the mitochondria
  - \_\_\_ Series of anaerobic reactions that occur within the cytoplasm
  - \_\_\_ Process of converting protein to glucose
  - \_\_\_ Catalyst
  - \_\_\_ Series of reactions that convert glucose to lactic acid
  - \_\_\_ Metabolic consequence of rapid and incomplete breakdown of fatty acids