CHAPTER 2: BASIC CHEMISTRY OF LIFE

At the end of this chapter, student will be able to:

a) Define the terms *element*, *atom*, *proton*, *neutron*, and *electron*.
b) Describe the formation and purpose of ionic bonds, covalent bonds, disulfide bonds, and hydrogen bonds.
c) Describe what happens in synthesis and decomposition reactions.
d) Explain the importance of water to the functioning of the human body.
e) Name and describe the water compartments.
f) Explain the roles of oxygen and carbon dioxide in cell respiration.
g) State what trace elements are, and name some, with their functions.
h) Explain the pH scale. State the normal pH ranges of body fluids.
i) Explain how a buffer system limits great changes in pH.
j) Describe the functions of monosaccharides, disaccharides, oligosaccharides, and polysaccharides.
k) Describe the functions of true fats, phospholipids, and steroids.
l) Describe the functions of proteins, and explain how enzymes function as catalysts.
m) Describe the functions of DNA and RNA.

2.1 INTRODUCTION

Chemistry is the science of the structure and interactions of matter.

The air we breathe is a mixture of chemicals in the form of gases. Water, gasoline, and diet soda are chemicals in liquid form. Our foods are chemicals, and our bodies are complex arrangements of thousands of chemicals. Recall from Chapter 1 that the simplest level of organization of the body is the chemical level.

2.2 ELEMENTS AND ATOMS

All matter, both living and not living, is made of elements, the simplest chemicals. An **element** is a substance made of only one type of atom (therefore, an atom is the smallest part of an element).

There are 92 naturally occurring elements in the world around us (Twenty additional elements have been created in the laboratory).

Examples are hydrogen (H), iron (Fe), oxygen (O), calcium (Ca), nitrogen (N), and carbon (C). In nature, an element does not usually exist by itself but rather combines with the atoms of other elements to form compounds.

Examples of some compounds important to our study of the human body are water (H_2O), in which two atoms of hydrogen combine with one atom of oxygen; carbon dioxide (CO_2), in which an atom of carbon combines with two atoms of oxygen; and glucose ($C_6H_{12}O_6$), in which six carbon atoms and six oxygen atoms combine with 12 hydrogen atoms.

The elements carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur are found in all living things. Elements can be identified by their names or their chemical symbols, which are abbreviations of the modern or Latin names of the elements

Atoms are the smallest parts of an element that have the characteristics of that element. An atom consists of three major subunits or particles: protons, neutrons, and electrons. A **proton** has a positive electrical charge and is found in the nucleus (or center) of the atom. A **neutron** is electrically neutral (has no charge) and is also found in the nucleus. An **electron** has a negative electrical charge and is found outside the nucleus orbiting in what may be called an electron cloud or shell around the nucleus.

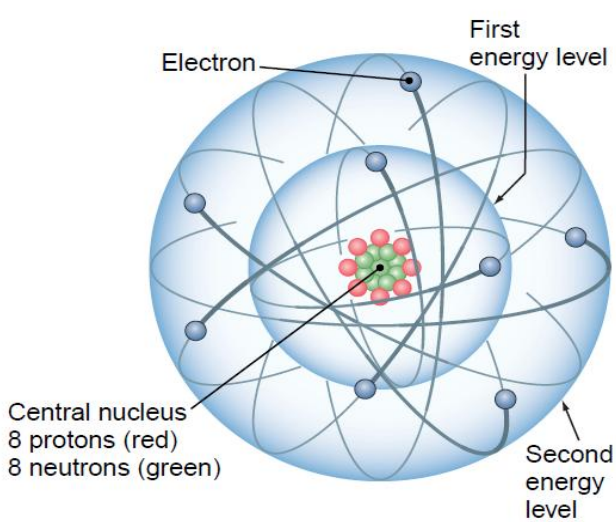

Figure: Representation of the oxygen atom. Eight protons and eight neutrons are tightly bound in the central nucleus. The eight electrons are in orbit around the nucleus, two at the first energy level and six at the second.

2.3 CHEMICAL BONDS

A chemical bond is not a structure, but rather a force or attraction between positive and negative electrical charges that keeps two or more atoms closely associated with each other to form a molecule. By way of comparison, think of gravity. We know that gravity is not a "thing," but rather the force that keeps our feet on the floor and allows us to pour coffee with consistent success. Molecules formed by chemical bonding often have physical characteristics different from those of the atoms of the original elements.

For example, the elements hydrogen and oxygen are gases, but atoms of each may chemically bond to form molecules of water, which is a liquid. The type of chemical bonding depends upon the tendencies of the electrons of atoms involved.

Four kinds of bonds are very important to the chemistry of the body: ionic bonds, covalent bonds, disulfide bonds, and hydrogen bonds.

1) An **ionic bond** involves the loss of one or more electrons by one atom and the gain of the electron(s) by another atom or atoms. Compounds formed by ionic bonds that release ions when they are in solution are called **electrolytes.**

Example: When an atom of sodium loses an electron to an atom of chlorine, their ions have unlike charges (positive and negative) and are thus attracted to one another. The result is the formation of a molecule of sodium chloride: NaCl, or common table salt. The bond that holds these ions together is called an ionic bond.

2) **Covalent bonds** involve the sharing of electrons between atoms.

Example: an atom of oxygen needs two electrons to become stable. It may share two of its electrons with another atom of oxygen, also sharing two electrons. Together they form a molecule of oxygen gas (O_2), which is the form in which oxygen exists in the atmosphere.

If electrons are equally shared in forming a molecule, the electrical charges are evenly distributed around the atoms and the bond is described as a *nonpolar covalent bond*. In a water molecule, the shared electrons are actually closer to the oxygen at any one time making that region of the molecule more negative.

Such bonds are called *polar covalent bonds,* because one part of the molecule is more negative and one part is more positive at any one time.

3) Two other types of bonds that are important to the chemistry of the body are disulfide bonds and hydrogen bonds. Disulfide bonds are found in some proteins. Hydrogen bonds are part of many different molecules.

- A **disulfide bond** (also called a disulfide bridge) is a covalent bond formed between two atoms of sulfur, usually within the same large protein molecule. The hormone insulin, for example, is a protein that must have a very specific three-dimensional shape in order to function properly to regulate the blood glucose level. Each molecule of insulin has two disulfide bonds that help maintain its proper shape and function. Other proteins with shapes that depend upon disulfide bonds are antibodies of the immune system and keratin of the skin and hair.
- A **hydrogen bond** does not involve the sharing or exchange of electrons, but rather results because of a property of hydrogen atoms. When a hydrogen atom shares its one electron in a covalent bond with another atom, its proton has a slight positive charge and may then be attracted to a nearby oxygen or nitrogen atom, which has a slight negative charge.

  Although they are weak bonds, hydrogen bonds are important in several ways. Large organic molecules such as proteins and DNA have very specific functions that depend upon their three-dimensional shapes. The shapes of these molecules, so crucial to their proper functioning, are often maintained by hydrogen bonds. Hydrogen bonds also make water cohesive; that is, each water molecule is attracted to nearby water molecules. Within the body, the cohesiveness of water helps keep blood a continuous stream as it flows within the blood vessels, and keeps tissue fluid continuous around cells.

2.4 CHEMICAL REACTIONS

A chemical reaction is a change brought about by the formation or breaking of chemical bonds. Two general types of reactions are synthesis reactions and decomposition reactions.

In a **synthesis reaction**, bonds are formed to join two or more atoms or molecules to make a new compound. The production of the protein hemoglobin in potential red blood cells is an example of a synthesis reaction. Proteins are synthesized by the bonding of many amino acids, their smaller subunits. Synthesis reactions require energy for the formation of bonds.

In a **decomposition reaction**, bonds are broken, and a large molecule is changed to two or more smaller ones. One example is the digestion of large molecules of starch into many smaller glucose molecules.

2.5 INORGANIC COMPOUNDS OF IMPORTANCE

Inorganic compounds are usually simple molecules that often consist of only one or two different elements. Despite their simplicity, however, some inorganic compounds are essential to normal structure and functioning of the body.

a. WATER

Water makes up 60% to 75% of the human body, and is essential to life for several reasons:

1. *Water is a **solvent***; that is, many substances (called solutes) can dissolve in water. Nutrients such as glucose are dissolved in blood plasma (which is largely water) to be transported to cells throughout the body. The sense of taste depends upon the solvent ability of saliva; dissolved food stimulates the receptors in taste buds. The excretion of waste products is possible because they are dissolved in the water of urine.
2. *Water is a lubricant*, which prevents friction where surfaces meet and move. In the digestive tract, swallowing depends upon the presence of saliva, and mucus is a slippery fluid that permits the smooth passage of food through the intestines. Synovial fluid within joint cavities prevents friction as bones move.
3. *Water changes temperature slowly*. Water has a high heat capacity, which means that it will absorb a great deal of heat before its temperature rises significantly, or it must lose a great deal of heat before its temperature drops significantly. This is one of the factors that helps the body maintain a constant temperature. Water also has a high heat of vaporization, which is important for the process of sweating. Excess body heat evaporates sweat on the skin surfaces, rather than overheating the body's cells, and because of water's high heat of vaporization, a great deal of heat can be given off with the loss of a relatively small amount of water.

- **Water compartments:**

All water within the body is continually moving, but water is given different names when it is in specific body locations, which are called compartments.

Intracellular fluid (ICF): the water within cells; about 65% of the total body water

Extracellular fluid (ECF): all the rest of the water in the body; about 35% of the total. More specific compartments of extracellular fluid include:

Plasma: water found in blood vessels

Lymph: water found in lymphatic vessels

Tissue fluid or interstitial fluid: water found in the small spaces between cells

Specialized fluids: synovial fluid, cerebrospinal fluid, aqueous humor in the eye, and others

b. OXYGEN

Oxygen in the form of a gas (O_2) is approximately 21% of the atmosphere, which we inhale. What does oxygen do? Oxygen is important to us because it is essential for a process called cell respiration, in which cells break down simple nutrients such as glucose in order to release energy. The reason we breathe is to obtain oxygen for cell respiration and to exhale the carbon dioxide produced in cell respiration.

c. CARBON DIOXIDE

Carbon dioxide (CO_2) is produced by cells as a waste product of cell respiration. If the amount of carbon dioxide in the body fluids increases, it causes these fluids to become too acidic. Therefore, carbon dioxide must be exhaled as rapidly as it is formed to keep the amount in the body within normal limits. Normally this is just what happens, but severe pulmonary diseases such as pneumonia or emphysema decrease gas exchange in the lungs and permit carbon dioxide to accumulate in the blood. When this happens, a person is said to be in a state of **acidosis**, which may seriously disrupt body functioning.

2.6 CELL RESPIRATION

Cell respiration is the name for energy production within cells and involves both respiratory gases, oxygen and carbon dioxide. Many chemical reactions are involved, but in its simplest form, cell respiration may be summarized by the following equation:

$$C_6H_{12}O_6+6O_2 \rightarrow 6CO_2+6H_2O+ATP+heat$$

This reaction shows us that glucose and oxygen combine to yield carbon dioxide, water, ATP, and heat.

2.7 TRACE ELEMENTS AND THEIR FUNCTIONS

Trace elements are those that are needed by the body in very small amounts. When they are present in food or nutritional supplements, we often call them minerals, and examples are iron, cobalt, and zinc. Although they may not be as abundant in the body as are carbon, hydrogen, or oxygen, they are nonetheless essential.

Element	**Function**
Calcium	• Provides strength in bones and teeth • Necessary for blood clotting • Necessary for muscle contraction
Phosphorus	• Provides strength in bones and teeth • Part of DNA, RNA, and ATP • Part of cell membranes
Iron	• Part of hemoglobin in red blood cells; transports oxygen • Part of myoglobin in muscles; stores oxygen • Necessary for cell respiration
Copper	• Necessary for cell respiration • Necessary for hemoglobin synthesis
Sodium and potassium	• Necessary for muscle contraction • Necessary for nerve impulse transmission
Sulfur	• Part of some proteins such as insulin and keratin
Cobalt	• Part of vitamin B12
Iodine	• Part of thyroid hormones—thyroxine

2.8 ACIDS, BASES, AND pH

An **acid** may be defined as a substance that increases the concentration of hydrogen ions (H^-) in a water solution. A **base** is a substance that decreases the concentration of H_ ions, which, in the case of water, has the same effect as increasing the concentration of hydroxyl ions (OH^-).

The acidity or alkalinity (basicity) of a solution is measured on a scale of values called **pH** (parts hydrogen). The values on the **pH scale** range from 0 to 14, with 0 indicating the most acidic level and 14 the most alkaline. A solution with a pH of 7 is neutral because it contains the same number of H_ ions and OH_ ions. Pure water has a pH of 7. A solution with a higher concentration of H_ ions than OH_ ions is an acidic solution with a pH below 7. An alkaline solution, therefore, has a higher concentration of OH_ ions than H_ ions and has a pH above 7.

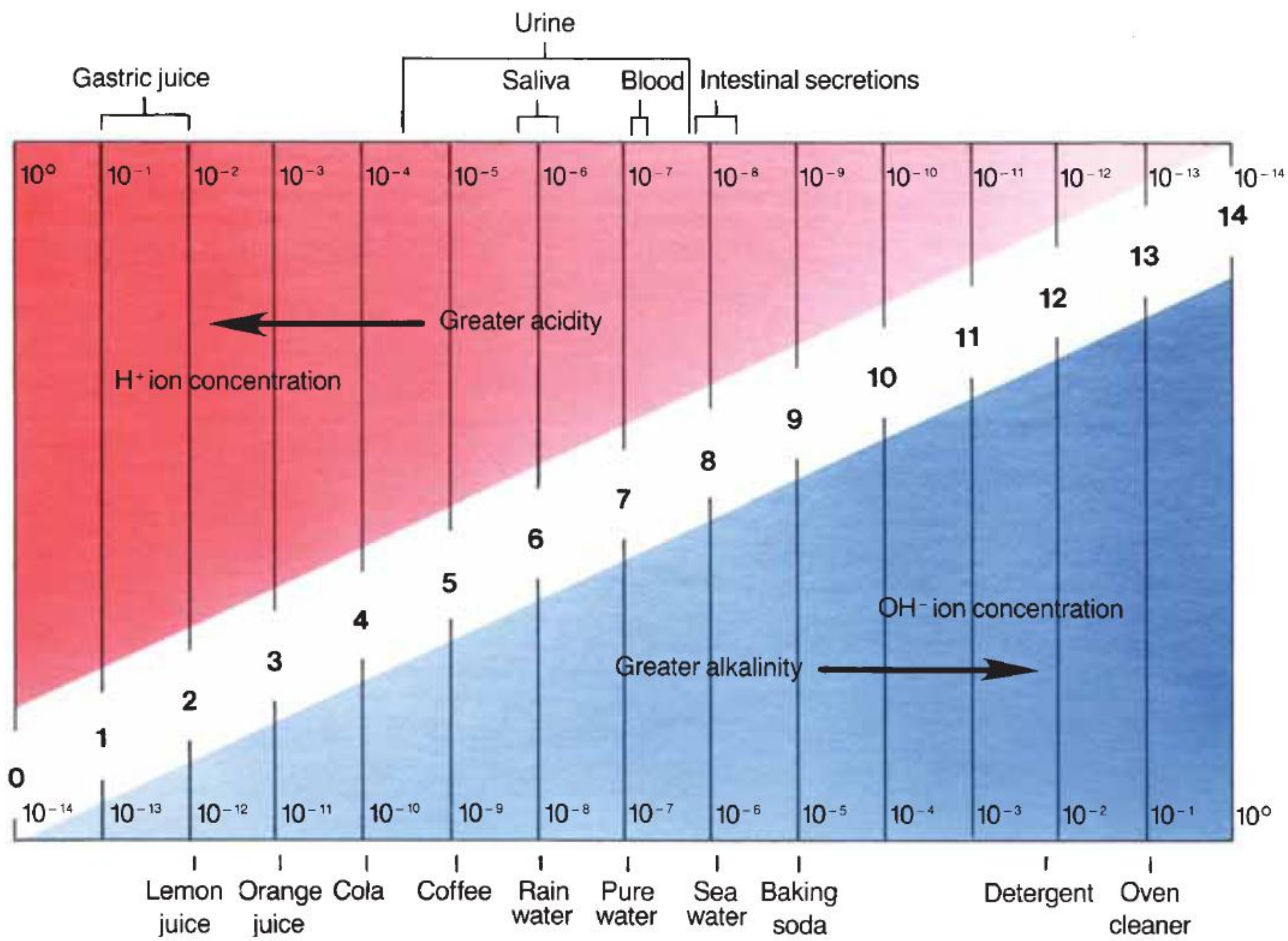

Figure: The pH scale. The pH values of several body fluids are indicated above the scale. The pH values of some familiar solutions are indicated below the scale.

Notice that gastric juice has a pH of 1 and coffee has a pH of 5.

This means that gastric juice has 10,000 times as many H_ ions as does coffee. Although coffee is acidic, it is a weak acid and does not have the corrosive effect of gastric juice, a strong acid.

The cells and internal fluids of the human body have a pH close to neutral. The pH of intracellular fluid is around 6.8, and the normal pH range of blood is 7.35 to 7.45. Fluids such as gastric juice and urine are technically external fluids, because they are in body tracts that open to the environment. The pH of these fluids may be more strongly acidic or alkaline without harm to the body. Normal metabolism tends to make body fluids more acidic, and this tendency to acidosis must be continually corrected. Normal pH of internal fluids is maintained by the kidneys, respiratory system, and buffer systems.

- **Buffer Systems**

A **buffer system** is a chemical or pair of chemicals that minimizes changes in pH by reacting with strong acids or strong bases to transform them into substances that will not drastically change pH. Expressed in another way, a buffer may bond to H_ ions when a body fluid is becoming too acidic, or release H_ ions when a fluid is becoming too alkaline.

As a specific example, we will use the bicarbonate buffer system, which consists of carbonic acid (H_2CO_3), a weak acid, and sodium bicarbonate ($NaHCO_3$), a weak base.

This pair of chemicals is present in all body fluids but is especially important to buffer blood and tissue fluid.

Carbonic acid ionizes as follows (but remember, because it is a weak acid it does not contribute many H_ ions to a solution):

$$H_2CO_3 \rightarrow H^- + HCO_3^-$$

Sodium bicarbonate ionizes as follows:

$$NaHCO_3 \rightarrow Na^- + HCO_3^-$$

If a strong acid, such as HCl, is added to extracellular fluid, this reaction will occur:

$$HCl + NaHCO_3 \rightarrow NaCl + H_2CO_3$$

If a strong base, such as sodium hydroxide, is added to the extracellular fluid, this reaction will occur:

$$NaOH + H_2CO_3 \rightarrow H_2O + NaHCO_3$$

2.9 ORGANIC COMPOUNDS OF IMPORTANCE

Organic compounds all contain covalently bonded carbon and hydrogen atoms and perhaps other elements as well. In the human body there are four major groups of organic compounds: carbohydrates, lipids, proteins, and nucleic acids.

a. CARBOHYDRATES

A primary function of **carbohydrates** is to serve as sources of energy in cell respiration. All carbohydrates contain carbon, hydrogen, and oxygen and are classified as monosaccharides, disaccharides, oligosaccharides, and polysaccharides. *Saccharide* means sugar, and the prefix indicates how many are present.

Monosaccharides, or single-sugar compounds, are the simplest sugars. Glucose is a **hexose**, or sixcarbon, sugar with the formula $C_6H_{12}O_6$. Fructose and galactose also have the same formula, but the physical arrangement of the carbon, hydrogen, and oxygen atoms in each differs from that of glucose.

Disaccharides are double sugars, made of two monosaccharides linked by a covalent bond. Sucrose, or cane sugar, for example, is made of one glucose and one fructose. Others are lactose (glucose and galactose) and maltose (two glucose), which are also present in food. Disaccharides are digested into monosaccharides and then used for energy production.

The prefix *oligo* means "few"; **oligosaccharides** consist of from 3 to 20 monosaccharides. In human cells, oligosaccharides are found on the outer surface of cell membranes. Here they serve as **antigens**, which are chemical markers (or "signposts") that identify cells. The A, B, and AB blood types, for example, are the result of oligosaccharide antigens on the outer surface of red blood cell membranes. All of our cells have "self" antigens, which identify the cells that belong in an individual. The presence of "self" antigens on our own cells enables the immune system to recognize antigens that are "non-self."

Polysaccharides are made of thousands of glucose molecules, bonded in different ways, resulting in different shapes.

Starches are branched chains of glucose and are produced by plant cells to store energy. We have digestive enzymes that split the bonds of starch molecules, releasing glucose. The glucose is then absorbed and used by cells to produce ATP.

Glycogen, a highly branched chain of glucose molecules, is our own storage form for glucose. After a meal high in carbohydrates, the blood glucose level rises. Excess glucose is then changed to glycogen and stored in the liver and skeletal muscles. When the blood glucose level decreases between meals, the glycogen is converted back to glucose, which is released into the blood (these reactions are regulated by insulin and other hormones). The blood glucose level is kept within normal limits, and cells can take in this glucose to produce energy.

b. LIPIDS

Lipids contain the elements carbon, hydrogen, and oxygen; some also contain phosphorus. In this group of organic compounds are different types of substances with very different functions. We will consider three types: true fats, phospholipids, and steroids.

- **True fats** (also called neutral fats) are made of one molecule of glycerol and one, two, or three fatty acid molecules. If three fatty acid molecules are bonded to a single glycerol, a **triglyceride** is formed. Two fatty acids and a glycerol form a **diglyceride**, and one fatty acid and a glycerol form a **monoglyceride**.

The fatty acids in a true fat may be **saturated** or **unsaturated**. Each of these carbons is then bonded to the maximum number of hydrogens; this is a saturated fatty acid, meaning saturated with hydrogen. The other fatty acids have one or more (poly) double covalent bonds between their carbons and less than the maximum number of hydrogens; these are unsaturated fatty acids. Some organs, however, such as the eyes and kidneys, are enclosed in a layer of fat that acts as a cushion to absorb shock.

- **Phospholipids** are diglycerides with a phosphate group (PO_4) in the third bonding site of glycerol. Although similar in structure to the true fats, phospholipids are not stored energy but rather structural components of cells.

Lecithin is a phospholipid that is part of our **cell membranes** (each phospholipid molecule looks like a sphere with two tails; the sphere is the glycerol and phosphate, the tails are the two fatty acids). Another phospholipid is **myelin**, which forms the myelin sheath around nerve cells and provides electrical insulation for nerve impulse transmission.

- The structure of **steroids** is very different from that of the other lipids. **Cholesterol** is an important steroid; it is made of four rings of carbon and hydrogen.

The liver synthesizes cholesterol, in addition to the cholesterol we eat in food as part of our diet. Cholesterol is another component of cell membranes and is the precursor (raw material) for the synthesis of other steroids. In the ovaries or testes, cholesterol is used to synthesize the steroid hormones estrogen or testosterone, respectively. A form of cholesterol in the skin is changed to vitamin D on exposure to sunlight.

Liver cells use cholesterol for the synthesis of bile salts, which emulsify fats in digestion. Despite its link to coronary artery disease and heart attacks, cholesterol is an essential substance for human beings.

c. PROTEINS

Proteins are made of smaller subunits or building blocks called **amino acids**, which all contain the elements carbon, hydrogen, oxygen, and nitrogen.

Some amino acids contain sulfur, which permits the formation of disulfide bonds. There are about 20 amino acids that make up human proteins. Each amino acid has a central carbon atom covalently bonded to an atom of hydrogen, an amino group (NH_2), and a carboxyl group (COOH).

At the fourth bond of the central carbon is the variable portion of the amino acid, represented by R.

$R-CH(NH_2)-COOH$

The R group may be a single hydrogen atom, or a CH3 group, or a more complex configuration of carbon and hydrogen. This gives each of the 20 amino acids a slightly different physical shape. A bond between two amino acids is called a **peptide bond**, and a short chain of amino acids linked by peptide bonds is a **polypeptide**.

A protein may consist of from 50 to thousands of amino acids. The sequence of the amino acids is specific and unique for each protein, and is called its primary structure. This unique sequence, and the hydrogen bonds and disulfide bonds formed within the amino acid chain, determines how the protein will be folded to complete its synthesis. The folding may be simple, a helix (coil) or pleated sheet, called the secondary structure, or a more complex folding may occur to form a globular protein, called the tertiary structure. Myoglobin, found in muscles, is a globular protein. When complete, each protein has a characteristic three-dimensional shape, which in turn determines its function.

- **Enzymes**

Enzymes are **catalysts**, which means that they speed up chemical reactions without the need for an external source of energy such as heat. The many reactions that take place within the body are catalyzed by specific enzymes; all of these reactions must take place at body temperature.

The way in which enzymes function as catalysts is called the **active site theory**, and is based on the shape of the enzyme and the shapes of the reacting molecules, called **substrates**. Notice that the enzyme has a specific shape, as do the substrate molecules. The active site of the enzyme is the part that matches the shapes of the substrates. The substrates must "fit" into the active site of the enzyme, and temporary bonds may form between the enzyme and the substrate.

This is called the enzyme–substrate complex. In this case, two substrate molecules are thus brought close together so that chemical bonds are formed between them, creating a new compound. The product of the reaction, the new compound, is then released, leaving the enzyme itself unchanged and able to catalyze another reaction of the same type.

d. NUCLEIC ACIDS (DNA and RNA)

The **nucleic acids**, **DNA** (deoxyribonucleic acid) and **RNA** (ribonucleic acid), are large molecules made of smaller subunits called nucleotides. A **nucleotide** consists of a pentose sugar, a phosphate group, and one of several nitrogenous bases. In DNA nucleotides, the sugar is deoxyribose, and the bases are adenine, guanine, cytosine, or thymine. In RNA nucleotides, the sugar is ribose, and the bases are adenine, guanine, cytosine, or uracil.

Notice that DNA looks somewhat like a twisted ladder; this ladder is two strands of nucleotides called a double helix (two coils). Alternating phosphate and sugar molecules form the uprights of the ladder, and pairs of nitrogenous bases form the rungs.

The size of the bases and the number of hydrogen bonds each can form the complementary base pairing of the nucleic acids. In DNA, adenine is always paired with thymine (with two hydrogen bonds), and guanine is always paired with cytosine (with three hydrogen bonds).
DNA makes up the chromosomes of cells and is, therefore, the **genetic code** for hereditary characteristics.

- **Applications to the nursing care**

1. **NITRIC OXIDE**

Nitric oxide is a gas with the molecular formula NO. You have probably heard of it as a component of air pollution and cigarette smoke, but it is synthesized by several human tissues, and this deceptively simple molecule has important functions.

Nitric oxide is produced by the endothelium (lining) of blood vessels and promotes vasodilation of arterioles, permitting greater blood flow and oxygen delivery to tissues. It is involved in nerve impulse transmission in the brain, and may contribute to memory storage. Some immune system cells produce nitric oxide as a cytotoxic (cell-poisoning) agent to help destroy foreign cells such as bacteria.

Nitric oxide is also being used therapeutically in clinical trials. It has been found useful in the treatment of pulmonary hypertension to relax abnormally constricted arteries in the lungs to permit normal gas exchange. Other studies show that nitric oxide helps some premature babies breathe more easily and efficiently. Much more research is needed, including a determination of possible harmful side effects of greater than normal amounts of nitric oxide.

2. **LIPIDS IN THE BLOOD**

Triglycerides and cholesterol are transported in the blood in combination with proteins. Such molecules made by the small intestine are called chylomicrons.

Those made by the liver are called lipoproteins and are categorized by their density, which reflects the proportion of protein to cholesterol. Low-density lipoproteins (LDLs, which are low in protein and high in cholesterol) transport cholesterol to the tissues, where it is used to synthesize cell membranes or secretions. LDLs are also called “bad cholesterol,” because in this form the cholesterol is more likely to be deposited in the walls of blood vessels, leading to atherosclerosis.

High-density lipoproteins (HDLs, which are higher in protein and lower in cholesterol than

LDLs) transport cholesterol from the tissues to the liver. HDLs are also called “good cholesterol,” because in this form cholesterol is more easily removed from the blood by the liver and excreted in bile.

A diet low in total fat, with most of it unsaturated fat, tends to raise HDL levels and lower LDL levels. The benefit is the delaying of atherosclerosis and coronary artery disease. A simple blood test called a lipid profile (or lipid panel) can determine levels of total cholesterol, triglycerides, HDLs, and LDLs.