2 CHAPTER | The Chemistry of Microbiology

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Chapter Summary

Atoms (pp. 27–29)

Matter is defined as anything that takes up space and has mass. The smallest chemical units of matter are **atoms**.

Atomic Structure

Atoms contain negatively charged particles called **electrons** spinning around a nucleus composed of uncharged particles called **neutrons** and positively charged particles called **protons**. (A hydrogen atom contains only one proton and no neutrons.) The number of electrons in an atom typically equals the number of protons, so atoms are electrically neutral overall.

An **element** is matter composed of a single type of atom. Elements differ from one another in their **atomic number**, which is the number of protons in their nuclei. The **atomic mass** (or *atomic weight*) of an atom is the sum of the masses of its protons, neutrons, and electrons. Because electrons have little mass, the atomic mass is estimated by summing the number of protons and neutrons. Thus, hydrogen has an atomic mass of 1. Of the 93 naturally occurring elements, organisms utilize only about 20.

Isotopes

Isotopes are atoms of an element that differ only in the numbers of neutrons they contain. For example, there are three naturally occurring isotopes of carbon, all of which have 6 protons: carbon-12 has 6 neutrons, carbon- 13 has 7 neutrons, and carbon-14 has 8 neutrons. Some isotopes are unstable and undergo *radioactive decay*, releasing subatomic particles. These are called *radioactive isotopes*.

Electron Configurations

Since only the electrons of an atom come close enough to interact with another atom, they determine an atom's chemical behavior. Electrons orbit their nucleus in three-dimensional *electron shells*, each of which can hold only a certain maximum number of electrons. For example, the first shell of any atom has a capacity of just two electrons, whereas the second shell has a capacity of eight. Electrons in the outermost shell are called *valence electrons* and are critical for interactions between atoms.

Chemical Bonds (pp.30–34)

The number of electrons in the **valence shell**—the outermost shell—determines the atom's reactivity: atoms with valence shells not containing the maximum number of electrons are more likely to give up or accept electrons from another atom until their outermost shell is full. The sharing or transferring of electrons to fill a valence shell results in the formation of **chemical bonds**. Two or more atoms held together by chemical bonds form a **molecule**. Any molecule containing atoms of more than one element is called a **compound**. For example, two hydrogen atoms that are bonded to an oxygen atom form a molecule of water (H_2O), which is a compound.

Nonpolar Covalent Bonds

A **covalent bond** is the sharing of a pair of electrons by two atoms. Two hydrogen atoms bind covalently to form a stable molecule of hydrogen, in which both atoms have full valence shells. Atoms such as oxygen that share two pairs of electrons have a *double covalent bond* with each other. The attraction of an atom for electrons is called its **electronegativity**. When atoms with similar electronegativities bind, the shared electrons tend to spend an equal amount of time around each nucleus of the pair. Since neither nucleus acts as a "pole" to exert an unequal pull, these are called **nonpolar covalent bonds**.

Molecules can be represented by *structural formulas* or *molecular formulas*. A structural formula represents the chemical bond or number of electrons shared between atoms. A molecular formula provides information on the number of atoms in a molecule but not the electron sharing.

Since carbon atoms have four electrons in their valence shells, they have an equal tendency to lose or gain four electrons, and form nonpolar covalent bonds with one another and with many other atoms. One result of this feature is that carbon atoms easily form very long chains that constitute the "backbone" of many biologically important molecules. Compounds that contain carbon and hydrogen atoms are called **organic compounds**.

Polar Covalent Bonds

When atoms with significantly different electronegativities combine, the electron pair will spend more time orbiting the "pole"; that is, the nucleus of the atom with greater electronegativity. Bonds with an unequal sharing of electrons are therefore called **polar covalent bonds**. A water molecule, for example, has two polar covalent bonds. Although they can form between many different elements, the most biologically important polar covalent bonds are those involving hydrogen because they allow hydrogen bonding.

Ionic Bonds

When two atoms with vastly different electronegativities approach each other, the atom with the higher electronegativity will strip one or more electrons from the valence shell of the other. This happens, for example, when chlorine, with seven electrons in its valence shell, encounters sodium, which has just one valence electron. When sodium loses an electron, it becomes positively charged; when chlorine gains an electron, it becomes negatively charged. Charged atoms are called *ions*; specifically, an ion such as sodium with a positive charge is called a **cation**, whereas an atom such as chlorine with a negative charge is called an **anion**. The opposite charges of cations and anions attract each other strongly to form an **ionic bond**. Molecules with ionic bonds form crystalline compounds known as **salts**, such as sodium chloride (NaCl). Notice that, in ionic bonds, electrons are transferred from one molecule to another; in contrast to covalent bonds, there is no sharing of electrons.

The polar bonds of water molecules interfere with the ionic bonds of salts, causing *dissociation* (also called *ionization*). When cations and anions dissociate in water, they are called **electrolytes** because they can conduct electricity through the solution.

Hydrogen Bonds

Like ionic bonds, **hydrogen bonds** do not involve the sharing of electrons. Instead, a transiently positively charged hydrogen atom is attracted to a full or transient negative charge on either a different region of the same molecule or another molecule. The cumulative effect of numerous hydrogen bonds is to stabilize the three-dimensional shapes of large molecules, such as DNA. Thus, although weak, they are essential to life. These weak bonds are also easily broken.

Chemical Reactions (pp. 34–35)

Chemical reactions result from making or breaking chemical bonds in a process in which **reactants**—the atoms, ions, or molecules that exist at the beginning of a reaction—are changed into **products**—the atoms, ions, or molecules that remain after the reaction is complete. *Biochemistry* involves the chemical reactions of living things.

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Synthesis Reactions

Synthesis reactions involve the formation of larger, more complex molecules. A common type is **dehydration synthesis**, in which two smaller molecules are joined together by a cova-lent bond, and a water molecule is removed from the reactants. Synthesis reactions require energy to break bonds in the reactants and to form new bonds to make products. They are said to be **endothermic reactions** because they trap energy within new molecular bonds. **Anabolism** is the sum of all synthesis reactions in an organism.

Decomposition Reactions

Decomposition reactions are the opposite of synthesis reactions, in that they break bonds within larger reactants to form smaller atoms, ions, and molecules. Because these reactions release energy, they are called **exothermic**. A common type of decomposition reaction is **hydrolysis**, the reverse of dehydration synthesis, in which a covalent bond in a large molecule is broken, and the ionic components of water (H^+ and OH^-) are added to the prod-ucts. Collectively, all the decomposition reactions in an organism are called **catabolism**.

Exchange Reactions

Exchange reactions involve the breaking and formation of chemical bonds and are therefore similar to synthesis and decomposition reactions. They differ in that atoms or groups are transferred (exchanged) between reactants. An important example is the phosphorylation of glucose. The sum of all chemical reactions in an organism is called **metabolism**.

Water, Acids, Bases, and Salts (pp. 36–39)

Inorganic chemicals usually lack carbon. Many—including water, acids, bases, and salts—are essential to life.

Water

Water constitutes 50–99% of the mass of living organisms and is vital to life. Water mole-cules have two polar covalent bonds allowing them to form hydrogen bonds. The resulting properties which make water vital include *surface tension*, which enables water to form a thin layer on the surface of cells through which dissolved molecules can be transported into and out of the cell. It is also an excellent *solvent* of ionic and polar molecules. Water remains liquid over a broad temperature range, has a high capacity to absorb heat, and participates in chemical reactions.

Acids and Bases

An **acid** is a substance that dissociates into one or more hydrogen ions (H^+) and one or more anions. A **base** is a molecule that binds with H^+ when dissolved in water. Some bases dissoci-ate into hydroxyl ions and cations. The concentration of hydrogen ions in a solution is expressed using a logarithmic **pH scale** in which acidity increases as pH values decrease. Organisms can tolerate only a narrow pH range. Thus, most organisms contain natural **buffers**, substances that prevent drastic changes in internal pH. Organisms called *acidophiles* require acid conditions, and many can change the pH of their environment. Some chemicals change color in response to changes in pH. Such pH indicators are commonly included in microbial media.

Salts

A salt is a compound that dissociates in water into cations and anions other than H^+ and OH^-. Acids and bases neutralize each other to produce salts. A cell uses the cations and anions of salts—electrolytes—to create electrical differences between its inside and external environment, to transfer electrons from one location to another, and as important components of many enzymes. Some organisms use salts to provide structural support for their cells.

Organic Macromolecules (pp. 39–51)

Organic molecules are generally large, complex molecules containing carbon and hydrogen atoms linked together in branched and unbranched chains, and rings that are bound to one or more other elements such as oxygen, nitrogen, phosphorus, or sulfur.

Functional Groups

In organic molecules, atoms often appear in certain common arrangements called **functional groups**. For example, the hydroxyl functional group is common to all alcohols. The letter **R** (*residue*) is used to designate atoms that vary among organic molecules of the same class.

Four types of very large *macromolecules* are used by all living things: lipids, carbohy-drates, proteins, and nucleic acids.

Lipids

Lipids are organic macromolecules that are composed almost entirely of carbon and hydro - gen atoms linked by nonpolar covalent bonds. Being nonpolar, they are **hydrophobic**; that is, they are insoluble in water.

The four major groups of lipids are fats, phospholipids, waxes, and steroids.

1. The molecules of **fats** are composed of a glycerol and three chainlike fatty acids. Fats are also called *triglycerides*. Fatty acids occur in a variety of sizes and forms. **Saturated fatty acids** contain only single bonds and have more hydrogen in their structural formulas than **unsaturated fatty acids**, which contain double bonds between some of their carbon atoms. If several double bonds exist, the fatty acid is called a **polyunsaturated fat**. Fats contain large amounts of chemical energy, and one of their functions is to store energy.
2. **Phospholipids** contain only two fatty acid chains and a phosphate functional group. Whereas the fatty acid "tail" of a phospholipid molecule is nonpolar and thus hydrophobic, the phospholipid "head" is polar and thus **hydrophilic**. This means that phospholipids placed in a watery environment will always self-assemble into forms that keep the fatty acid tails away from water like the lipid bilayers found in the membranes of nearly all cells.
3. **Waxes** contain one long-chain fatty acid linked covalently to a long-chain alcohol by an ester bond. They are completely water insoluble and are used as energy storage molecules by some organisms.
4. **Steroids** consist of four carbon rings fused to one another and attached to various side chains and functional groups. Many organisms have sterol molecules like *cholesterol* in their phospholipid membranes that keep them fluid at low temperatures.

The organic macromolecules of proteins, carbohydrates, and nucleic acids are composed of simple subunits called **monomers** that can be covalently linked to form chainlike **polymers**, which may be hundreds of thousands of monomers long.

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Carbohydrates

Carbohydrates are organic molecules that are composed solely of atoms of carbon, hydrogen, and oxygen in a ratio of CH_2O. They are used for immediate and long-term storage of energy, as structural components of DNA and RNA and some cell walls, and for conversion into amino acids. They also serve roles in intercellular interactions. There are three basic types.

1. **Monosaccharides** are simple sugars such as glucose and fructose. They usually take a cyclic (ring) form.
2. **Disaccharides** are formed when two monosaccharides are linked together via dehydration synthesis. Sucrose, lactose, and maltose are examples.
3. **Polysaccharides** are polymers composed of tens, hundreds, or thousands of monosaccharides that have been covalently linked in dehydration synthesis reactions, and may be branched or unbranched. Polysaccharides serve as both storage and structural molecules. Cellulose and glycogen are examples.

Proteins

The most complex organic macromolecules are **proteins**, which are composed mostly of carbon, hydrogen, oxygen, nitrogen, and sulfur. They function as structural components of cells, enzymatic catalysts, regulators of various activities, transporters of substances, and defense and offense molecules. A protein's function is determined by its shape. Proteins are polymers of **amino acids**, in which a central carbon is attached to an amino group, a hydrogen atom, a carboxyl group, and a side group that varies according to the amino acid. Amino acids exist in two *stereoisomers*, D and L, that are mirror images of each other. The L form almost always occurs in proteins. Amino acids are linked by **peptide bonds** into specific structural patterns determined genetically. Every protein has at least **three levels of structure** (primary, secondary, tertiary), and some have four (quaternary). **Denaturation** of a protein disrupts its structure and subsequently its function. Proteins may be modified by the addition of other molecules: *glycoproteins* contain carbohydrates, *lipoproteins* include a lipid component, *metaloproteins* contain metal ions, and *nucleoproteins* are bonded to a nucleic acid.

Nucleic Acids

The two nucleic acids **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)** comprise the genetic material of cells and viruses. Some RNAs are enzymes. DNA and RNA differ primarily in the structure of their monomers, which are called **nucleotides** . Each nucleotide consists of phosphate, a pentose sugar (deoxyribose or ribose), and one of five cyclic nitroge-nous bases: **adenine (A)** , **guanine (G)**, **cytosine (C)**, **thymine (T)**, and **uracil (U)**. DNA is a long polymer composed of A, G, C, and T nucleotides, whereas the RNA polymer contains A, G, C, and U nucleotides. The polymers are formed by bonds between the phosphates and sugars. DNA molecules in cells consist of two *antiparallel* polymers held together by hydro-gen bonding between the bases.

The structure of nucleic acids allows for genetic diversity, correct copying of genes for their passage on to the next generation, and the accurate synthesis of proteins.

Adenosine triphosphate (ATP) , which is made up of the nitrogenous base adenine, ribose sugar, and three phosphate groups, is the most important short-term energy storage molecule in cells. The bonds between the phosphate groups are *high energy bonds*. ATP is also incor-porated into the structure of many *coenzymes*.