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BY GEORGE H. FRIED AND
GEORGE J. HADEMENOS

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THE CHEMISTRY OF LIFE

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Atoms, Molecules, and Chemical Bonding

All matter is built up of simple units called **atoms**. **Elements** are substances that consist of the same kinds of atoms. **Compounds** consist of units called **molecules**, which are intimate associations of different atoms joined in precise arrangements.

Every atom is made up of a positively charged nucleus and a series of orbiting, negatively charged electrons surrounding the nucleus. A simple atom, such as hydrogen, has only one electron circulating around the nucleus, while a more complex atom may have as many as 106 electrons in the various concentric **shells** around the nucleus. Each shell may contain one or more **orbitals** within which electrons may be located. Every atom of an element has the same number of orbiting electrons, which is equal to the number of positively charged **protons** in the nucleus. The balanced number of charges is the **atomic number** of the element. The **atomic weight**, or mass, of the element is the sum of the protons and neutrons in its nucleus. Atoms interact with one another to form molecules, which are held together by chemical bonds resulting from the tendency of atoms to try to fill their outermost shells.

An **ionic bond** is formed when one atom donates electrons to another atom, resulting in oppositely charged ions. **Covalent bonding** occurs when each atom donates an electron to a shared pair. Two or three pairs may be shared forming a double or triple bond.

Example 1.1 Carbon dioxide (CO_2) is a compound in which each of two oxygen (O) atoms forms a double bond with a single carbon (C) atom, which in its unbonded state has four electrons in its outer shell. In this reaction, two electrons from a C atom join with two electrons from an O atom to form one double bond; the remaining two electrons in the outer shell of the C atom join two electrons from a second O atom to form a second double bond. As a result, the C atom and each O atom has eight electrons in their outer shell, as shown in Fig. 1-1.

Figure 1-1 The formation of CO_2.

In many covalent bonds, the electron pair is held more closely by one of the atoms than by the other imparting a degree of polarity to the molecule. Since oxygen nuclei have a strong attraction for electrons, water (H_2O) behaves like a charged molecule, or dipole, with a negative oxygen end and a positive hydrogen end. Many properties of water are based on this polarity.

In the **hydrogen bond** a proton (H^+) serves as a link between two molecules or different portions of the same large molecule. H bonds are weaker than covalent bonds, but they play an important role in the 3-D structure of large molecules such as proteins and nucleic acids.

Osmosis

If we were to divide a container into two compartments using a **semi-permeable membrane** and were to place different concentrations of a solution on each side of the membrane, the solute molecules would be unable to pass through the membrane but the solvent molecules would move to the region where they are less crowded. Water would move from less concentrated solute concentrations to more concentrated solute concentrations. This phenomenon is known as **osmosis**.

Special Case of Water

Water is the single most significant inorganic molecule in all life forms. Because of its polar quality, it promotes the dissociation of many molecules into ions, which play a role in regulating such biological properties as muscle contraction, permeability, and nerve impulse transmission.

Water molecules cohere tightly to one another through hydrogen bonding. This gives water a high surface tension and the property of expanding upon freezing. Water also has a high specific heat and, thus, prevents sharp changes in temperature that would be destructive to the structure of many macromolecules within the cell.

pH

Acidity and alkalinity are measured by a standard that is based on slight ionization of water. Acidity is determined by the concentration of H^+, while alkalinity is a function of the concentration of OH^-; therefore, the ionization of water H_2O ($H^+ + OH^-$) theoretically yields a neutral system. In pure water, dissociation occurs so slightly that at equilibrium, 1 mol (18 g) of water yields 10^{-7} mol of H^+ and 10^{-7} mol of OH^-. We may treat the un-ionized mass of water as having a concentration of 1M, since its ionization is so small. Thus

$$\frac{[H^+][OH^-]}{[H_2O]} = \frac{[10^{-7}][10^{-7}]}{1} = K_{eq} = 10^{-14}$$

The meaning of this relationship in practical terms is that $[H^+]$ multiplied by $[OH^-]$ will always be 10^{-14}, the equilibrium constant for water (K_{eq}). Thus, as $[H^+]$ increases, $[OH^-]$ must decrease. The expression **pH** is defined as the negative logarithm (1/logarithm) of the $[H^+]$. Since pH is an exponential function, each unit of pH represents a 10-fold change in $[H^+]$. Neutral solutions have a pH of 7, while the maximum acidity in aqueous solutions is given by a pH of 1 and the maximum alkalinity is given by a pH of 14.

Don't get confused!!!

The *lower* the pH, the *greater* the hydrogen ion concentration . . . So, a pH of 3 represents 10^{-3} mol of H^+ ions, but a pH of 2 indicates the presence of 10^{-2} mol.

The pH encountered within most organisms and their constituent parts is generally close to neutral. Excess H^+ or OH^- produced during metabolic reactions are neutralized by **buffer systems** such as the carbonic acid-bicarbonate ion system of the blood.

Organic Chemistry

Organic compounds are the complex compounds of carbon. The backbone of most organic compounds consists of C chains of varying lengths and shapes to which H, O, and N atoms are usually attached. Each C atom has 4 electrons in its outermost shell and the ability to form double and triple bonds with its neighbors. The organic compounds most associated with basic life processes are carbohydrates, proteins, lipids, and nucleic acids.

Example 1.2 Among the organic compounds found in nature are the **hydrocarbons**, the molecular associations of C and H, which are nonsoluble in water. **Aldehydes** have a double-bonded O attached to a terminal C atom; this carbon-oxygen combination is referred to as a **carboxyl group**. **Ketones** contain a double-bonded O attached to an internal C atom. An **organic alcohol** contains one or more hydroxyl (–OH) groups, and an **organic acid** contains a **carboxyl group** (an –OH and a double-bonded O attached to a terminal C atom).

Carbohydrates

Carbohydrates are hydrates of C with a general **empirical formula** of $C_x(H_2O)_x$. The basic subunit of carbohydrates is a **monosaccharide**, or simple sugar. The most common monosaccharides contain six C atoms and are known as **hexoses.**

Example 1.3 A typical hexose monosaccharide such as **glucose** consists of a carbon chain to which are attached hydroxyl groups. (Figure 1-2 shows the structural formula for glucose.) These –OH groups confer both sweetness and water solubility upon the molecule.

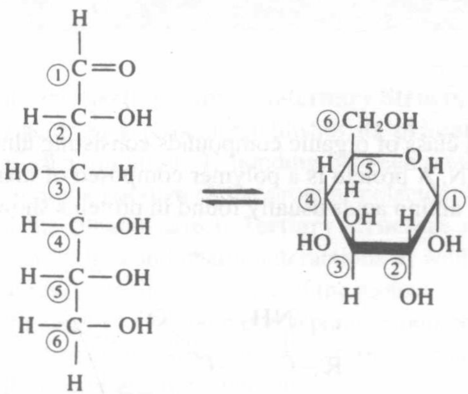


Figure 1-2 Glucose.

Monosaccharides may fuse through a process known as **condensation,** or **dehydration synthesis**. In this process two monosaccharides are joined to yield a **disaccharide**, and a molecule of water is liberated (an OH from one monosaccharide and an H from the second are removed to create the COC bond between the two **monomers**, or basic units). Common table sugar is a disaccharide formed by the condensation of glucose and fructose. Condensation may occur many times to yield **polysaccharides**. Breaking the bonds is accomplished by a reversal of the condensation process: water is added back to the molecule. This process is called **hydrolysis.**

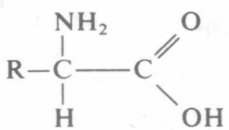
Think about it:

"carbo-hydrates" = carbon atoms + water

Glycogen is a highly branched polysaccharide chain of glucose units that serves as an energy storage molecule in animals, principally in liver and muscle. In plants, **starch** is the primary storage form of glucose. The primary structural component in plants is **cellulose**, a water insoluble polysaccharide. A structural polymer similar to cellulose, but found in fungi and in the exoskeletons of insects and other arthropods, is **chitin**.

Proteins

Proteins are a class of organic compounds consisting almost entirely of C, H, O, and N. A protein is a polymer composed of many **amino acid** subunits. The amino acids usually found in proteins show the following structure:



The COOH (carboxyl) group is characteristic of all organic acids and is attached to the same C as the NH_2 group. This C is designated the **carbon** atom. The **R** is a general designation for a variety of side groups that differentiate the 20 different amino acids found in nature. Such properties of a protein as its water solubility or charge are due to the kinds of R groups found in its amino acids.

Amino acids join by expelling a molecule of water. An OH is removed from the carboxyl group of one amino acid, and an –H is removed from the amino group of a second. The resultant bond between the C and N atoms of the carboxyl and amino groups is called a **peptide bond**, and the compound formed is a **dipeptide**. If many amino acids are joined in this condensation process, the result is a **polypeptide**; such chains of amino acids may range from 100 to 1000 amino acids.

To Summarize ✓

Dehydration = removal of water to synthesize
Hydrolysis = addition of water to break down

It is the same process whether you are building polymers of amino acids or of sugars!

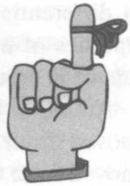
Primary, Secondary, Tertiary, and Quaternary Structure. The linear order of amino acids in a protein establishes its **primary structure**. Changes in conformation due to H-bonding between amino acids constitute the **secondary structure** of the protein molecule. Examples are the **α-helix** and the **pleated sheet**. **Tertiary structure** may be influenced by disulfide bridges and charge interactions as well as by hydrogen bonding and results in the 3-D shape of the molecule. Finally, some proteins are composed of two or more separable polypeptide chains. The aggregation of multiple polypeptides to form a single functioning protein is called the **quaternary structure**.

Heat or an appreciable change in pH can lead to alterations in the secondary, tertiary, and quaternary structure of a protein. This is known as **denaturation**. Denatured proteins generally lose their enzymatic activity and may demonstrate dramatic changes in physical properties.

Remember

Structure determines function.

This is a common biological theme.



Many proteins are intimately attached to nonprotein organic or inorganic groups to form **conjugated proteins**. Among such nonprotein (prosthetic) groups commonly encountered are carbohydrates (glycoproteins), lipids (lipoproteins), and such specialized compounds as the heme portion of hemoglobin.

Proteins as Enzymes. As **enzymes**, proteins serve as catalysts that regulate the rates of the many reactions occurring in the cell. Enzymes, typically characterized by the suffix **ase**, facilitate many biochemical reactions involved in cellular metabolism by lowering the activation energy of these reactions. The catalyzed reaction proceeds at velocities between 10^6- to 10^8-fold greater than the uncatalyzed reaction at a given temperature. Enzymes are generally complex globular proteins with a special region in the molecule known as the **active site**. The substance that the enzyme acts upon, the **substrate**, fits into the active site. As a result, the substrate is stretched or distorted and thus more readily undergoes appropriate chemical change. Essentially, the enzyme lowers the resistance of the substrate to alteration and promotes a reaction in which the substrate is changed to its products that allows biological reactions to proceed at relatively low temperatures.

Lipids

Lipids are a class of organic compounds that tend to be insoluble in water or other polar solvents but soluble in organic solvents such as toluene or ether. They consist mainly of C, H, and O. Lipids have much more energy associated with their bonding structure than do the carbohydrates or proteins.

Besides serving as media of energy storage, certain kinds of lipids cushion and protect the internal organs of the body, while others, in the form of a layer of fat just below the skin in many mammals, provide insulation against possible low environmental temperatures.

Among the major classes of lipids functioning within living organisms are

1. the neutral fats (triglycerides),
2. the phospholipids,
3. the steroids, and
4. waxes (found as protective layers on the surfaces of many plants and animals).

Solved Problems

Problem 1.1 What is the basis for interaction of atoms with one another?

All the chemical reactions that occur in nature appear to be due to the necessity of atoms to fill their outer electron shells. The noble gases already possess a full complement of electrons in their outer shell and are chemically unreactive.

Problem 1.2 Diffusion is the tendency of molecules to disperse throughout a medium or container in which they are found. How does diffusion differ from osmosis; how is it similar?

Diffusion involves movement of *solute* particles in the absence of a semipermeable membrane. Osmosis is a special case of diffusion involving movement of *solvent* molecules (water) through a semipermeable membrane. The two processes are similar in that movement of the molecules in each is driven by their collisions and rebounds with their own kind and proceeds toward areas in which collisions are less likely, namely, areas with fewer molecules of their kind.

Chapter 2
CELL STRUCTURE AND FUNCTION

IN THIS CHAPTER:

✔ *The Cell Doctrine*
✔ *Cellular Organelles*
✔ *Tissue Organization*
✔ *Movement into and out of the Cell*
✔ *Cellular Respiration*
✔ *Solved Problems*

The Cell Doctrine

All living things are made up of **cells**. The cell is the basic unit of life. Many whole organisms consist of a single cell, while others are a highly complex arrangement of up to trillions of cells. The cell doctrine maintains:

1. All living things are made up of cells.
2. Cells are the units of structure and function.
3. All cells arise from preexisting cells.

Cellular Organelles

Cells consist of an outer membrane, an interior nucleus, and a large mass of cytoplasm surrounding the nucleus. The functions of the cell are accomplished by specialized structures called **organelles** (see Fig. 2-1).

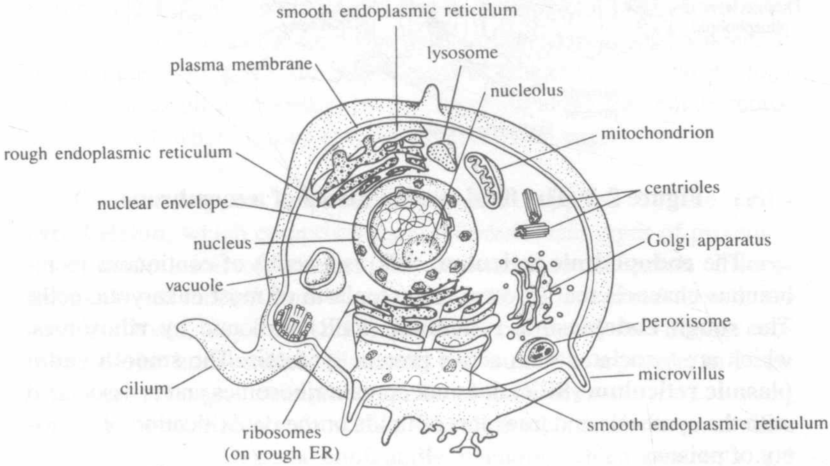


Figure 2-1 Structure of a typical animal cell.

The **cell membrane** or **plasma membrane** is the outer layer of both prokaryotic and eukaryotic cells. It controls the passage of materials into and out of the cell. The **fluid mosaic model** (see Fig. 2-2) proposes a double layer of phospholipids, with their polar ends facing the inner and outer surfaces and the hydrophobic, nonpolar ends apposed at the center of the bilayer. Proteins may reside on the exterior or interior face of the lipid bilayer (**extrinsic proteins**) or may be located in the phospholipid matrix (**intrinsic proteins**); some may be embedded in the bilayer but project through to the exterior, the interior, or both surfaces of the membrane. The plasma membrane is surrounded by a supportive **cell wall** in some organisms. In plants, fungi, and bacteria, this outer coat is composed, respectively, of cellulose, chitin, or a variety of complex carbohydrate and amino acid combinations.

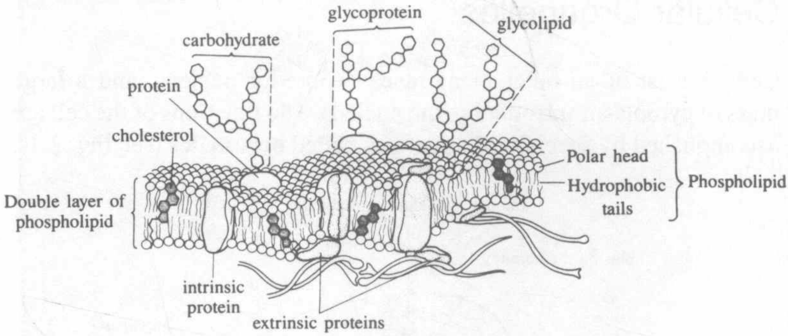


Figure 2-2 The fluid mosaic model of a membrane.

The **endoplasmic reticulum** (ER) is a series of continuous membranous channels that traverse the cytoplasm of most eukaryotic cells. The **rough endoplasmic reticulum** (RER) is bound by **ribosomes**, which are associated with active protein synthesis. The **smooth endoplasmic reticulum** (SER) does not contain ribosomes and is associated with the synthesis and transport of lipids or the detoxification of a variety of poisons.

The **Golgi apparatus** is similar in membrane structure to the ER. Its major function is storage, modification, and packing of materials produced for secretory export. Its secretory material is released within secretory vesicles that migrate to the surface of the cell. It may also provide material for the cell membrane.

Mitochondria have a double wall: a smooth membrane that forms the outer boundary and an inner membrane that is extensively folded. The mitochondria contain their own DNA and ribosomes and a variety of enzymes, which are involved in the systematic degradation of organic molecules to yield energy for the cell.

Lysosomes are full of powerful enzymes used for intracellular digestion. **Peroxisomes** are similar except that the enzymes contained in these organelles are involved in the oxidative deamination of amino acids.

Flagella and **cilia** are hair-like projections used for motility. Both derive their motility from **micotubules**, elongated, cylindrical structures assembled from two protein subunits called α- and β-tubulin. The flagella and cilia of eukaryotes contain an outer circle of nine pairs of microtubules that surround a central core of two microtubules. A **basal body**, to which each flagellum or cilium is attached, lies just under the surface of the cell. **Centrioles**, which are also made of microtubules, play a role in the formation of the spindle apparatus, which is an essential feature of both mitosis and meiosis.

Example 2.1 A human sperm cell has an active beating flagellum at its posterior end. The energy for this activity is derived from a mitochondria-rich midpiece, to which the flagellum is attached. The nuclear payload of the sperm cell is propelled by the flagellum along the female reproductive tract, where it may eventually fertilize an egg.

Cellular support and movement are supplied by the cell's **cytoskeleton**, which comprises three different main types of protein—microtubules, microfilaments, and intermediate filaments. **Microfilaments** are formed from the protein actin. In combination with the protein myosin, they form sliding filaments associated with muscle contraction. The **intermediate filaments** are found, for example, in dense meshworks that give strength to epithelial tissue sheets.

Vacuoles are reservoirs within the cell that contain water and salts. Many protozoans have a **contractile vacuole**, which contracts and forces fluid out of the cell. This prevents an accumulation of fluids in organisms that live in fresh water. Vacuoles containing digestive enzymes may also be formed around ingested food particles in a variety of cells. In the cells of many plants, a large **central vacuole** swells against the cell wall, giving the cell a high degree of rigidity, or **turgor**.

Plant cells contain a variety of tiny membrane-enclosed sacs called **plastids** that contain pigments or provide storage space for starch. **Chloroplasts** are included in this group (see Chap. 8).

The **nucleus** is a round or oval body lying near the center of the cell. It is surrounded by a double membrane, the nuclear membrane or envelope. **Pores** provide a route for materials to leave the nucleus. Within the nucleus, one or more nucleoli may be seen. The **nucleoli** are involved in the assembly and synthesis of ribosomes. **Chromosomes** contain the cell's genetic material. The number of chromosomes may differ between species but is constant within a species.