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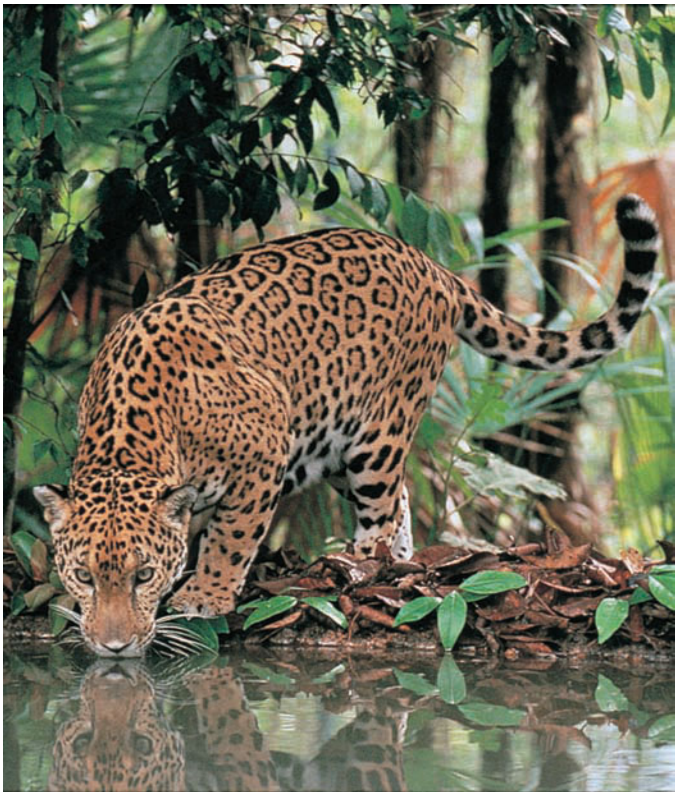
Atoms and Molecules: The Chemical Basis of Life



Frans Lanting/Minden Pictures

Water is a basic requirement for all life. A jaguar (*Panthera onca*), the largest cat in the Western Hemisphere, pauses to drink water from a rainforest stream.

KEY CONCEPTS

Carbon, hydrogen, oxygen, and nitrogen are the most abundant elements in living things.

The chemical properties of an atom are determined by its highest-energy electrons, known as valence electrons.

A molecule consists of atoms joined by covalent bonds. Other important chemical bonds include ionic bonds. Hydrogen bonds and van der Waals interactions are weak attractions.

The energy of an electron is transferred in a redox reaction.

Water molecules are polar, having regions of partial positive and partial negative charge that permit them to form hydrogen bonds with one another and with other charged substances.

Acids are hydrogen ion donors; bases are hydrogen ion acceptors. The pH scale is a convenient measure of the hydrogen ion concentration of a solution.

A knowledge of chemistry is essential for understanding organisms and how they function. This jaguar and the plants of the tropical rain forest, as well as abundant unseen insects and microorganisms, share fundamental similarities in their chemical composition and basic metabolic processes. These chemical similarities provide strong evidence for the evolution of all organisms from a common ancestor and explain why much of what biologists learn from studying bacteria or rats in laboratories can be applied to other organisms, including humans. Furthermore, the basic chemical and physical principles governing organisms are not unique to living things, for they apply to nonliving systems as well.

The success of the Human Genome Project and related studies has relied heavily on biochemistry and **molecular biology,** the chemistry and physics of the molecules that constitute living things. A biochemist may investigate the precise interactions among a cell's atoms and molecules that maintain the energy flow essential to life, and a molecular biologist may study how proteins interact with deoxyribonucleic acid (DNA) in ways that control the expression of certain genes. However, an understanding of chemistry is essential to *all* biologists. An evolutionary biologist may study evolutionary relationships by comparing the DNA of different types of organisms. An ecologist may study how energy is transferred among the organisms living in an estuary or monitor the biological effects of changes in the salinity of the water. A botanist may study unique compounds produced by plants and may even be a "chemical prospector," seeking new sources of medicinal agents.

In this chapter we lay a foundation for understanding how the structure of atoms determines the way they form chemical bonds to produce complex compounds. Most of our discussion focuses on small, simple substances known as **inorganic compounds.** Among the biologically important groups of inorganic compounds are water, many simple acids and bases, and simple salts. We pay particular attention to water, the most abundant substance in organisms and on Earth's surface, and we examine how its unique properties affect living things as well as their nonliving environment. In Chapter 3 we extend our discussion to **organic compounds,** carbon-containing compounds that are generally large and complex. In all but the simplest organic compounds, two or more carbon atoms are bonded to each other to form the backbone, or skeleton, of the molecule. ■

ELEMENTS AND ATOMS

Learning Objectives

1. Name the principal chemical elements in living things, and give an important function of each.
2. Compare the physical properties (mass and charge) and locations of electrons, protons, and neutrons. Distinguish between the atomic number and the mass number of an atom.
3. Define the terms *orbital* and *electron shell.* Relate electron shells to principal energy levels.

Elements are substances that cannot be broken down into simpler substances by ordinary chemical reactions. Each element has a **chemical symbol:** usually the first letter or first and second letters of the English or Latin name of the element. For example, O is the symbol for oxygen, C for carbon, H for hydrogen, N for nitrogen, and Na for sodium (from the Latin word *natrium*). Just four elements—oxygen, carbon, hydrogen, and nitrogen—are responsible for more than 96% of the mass of most organisms. Others, such as calcium, phosphorus, potassium, and magnesium, are also consistently present but in smaller quantities. Some elements, such as iodine and copper, are known as *trace elements,* because they are required only in minute amounts. ▮ Table 2-1 lists the elements that make up organisms and briefly explains the importance of each in typical plants and animals.

An **atom** is defined as the smallest portion of an element that retains its chemical properties. Atoms are much too small to be visible under a light microscope. However, by sophisticated techniques (such as scanning tunneling microscopy, with magnifications as great as 5 million times) researchers have been able to photograph the positions of some large atoms in molecules.

The components of atoms are tiny particles of **matter** (anything that has mass and takes up space) known as subatomic particles. Physicists have discovered a number of subatomic particles, but for our purposes we need consider only three: electrons, protons, and neutrons. An **electron** is a particle that carries a unit of negative electric charge; a **proton** carries a unit of positive charge; and a **neutron** is an uncharged particle. In an electrically neutral atom, the number of electrons is equal to the number of protons.

Clustered together, protons and neutrons compose the **atomic nucleus.** Electrons, however, have no fixed locations and move rapidly through the mostly empty space surrounding the atomic nucleus.

TABLE 2-1

Functions of Elements in Organisms

Element (chemical symbol)	Functions
O Oxygen	Required for cellular respiration; present in most organic compounds; component of water
C Carbon	Forms backbone of organic molecules; each carbon atom can form four bonds with other atoms
H Hydrogen	Present in most organic compounds; component of water; hydrogen ion (H^+) is involved in some energy transfers
N Nitrogen	Component of proteins and nucleic acids; component of chlorophyll in plants
Ca Calcium	Structural component of bones and teeth; calcium ion (Ca^{2+}) is important in muscle contraction, conduction of nerve impulses, and blood clotting; associated with plant cell wall
P Phosphorus	Component of nucleic acids and of phospholipids in membranes; important in energy transfer reactions; structural component of bone
K Potassium	Potassium ion (K^+) is a principal positive ion (cation) in interstitial (tissue) fluid of animals; important in nerve function; affects muscle contraction; controls opening of stomata in plants
S Sulfur	Component of most proteins
Na Sodium	Sodium ion (Na^+) is a principal positive ion (cation) in interstitial (tissue) fluid of animals; important in fluid balance; essential for conduction of nerve impulses; important in photosynthesis in plants
Mg Magnesium	Needed in blood and other tissues of animals; activates many enzymes; component of chlorophyll in plants
Cl Chlorine	Chloride ion (Cl^-) is principal negative ion (anion) in interstitial (tissue) fluid of animals; important in water balance; essential for photosynthesis
Fe Iron	Component of hemoglobin in animals; activates certain enzymes

*Other elements found in very small (trace) amounts in animals, plants, or both include iodine (I), manganese (Mn), copper (Cu), zinc (Zn), cobalt (Co), fluorine (F), molybdenum (Mo), selenium (Se), boron (B), silicon (Si), and a few others.

Key Point

The periodic table provides information about the elements: their compositions, structures, and chemical behavior.

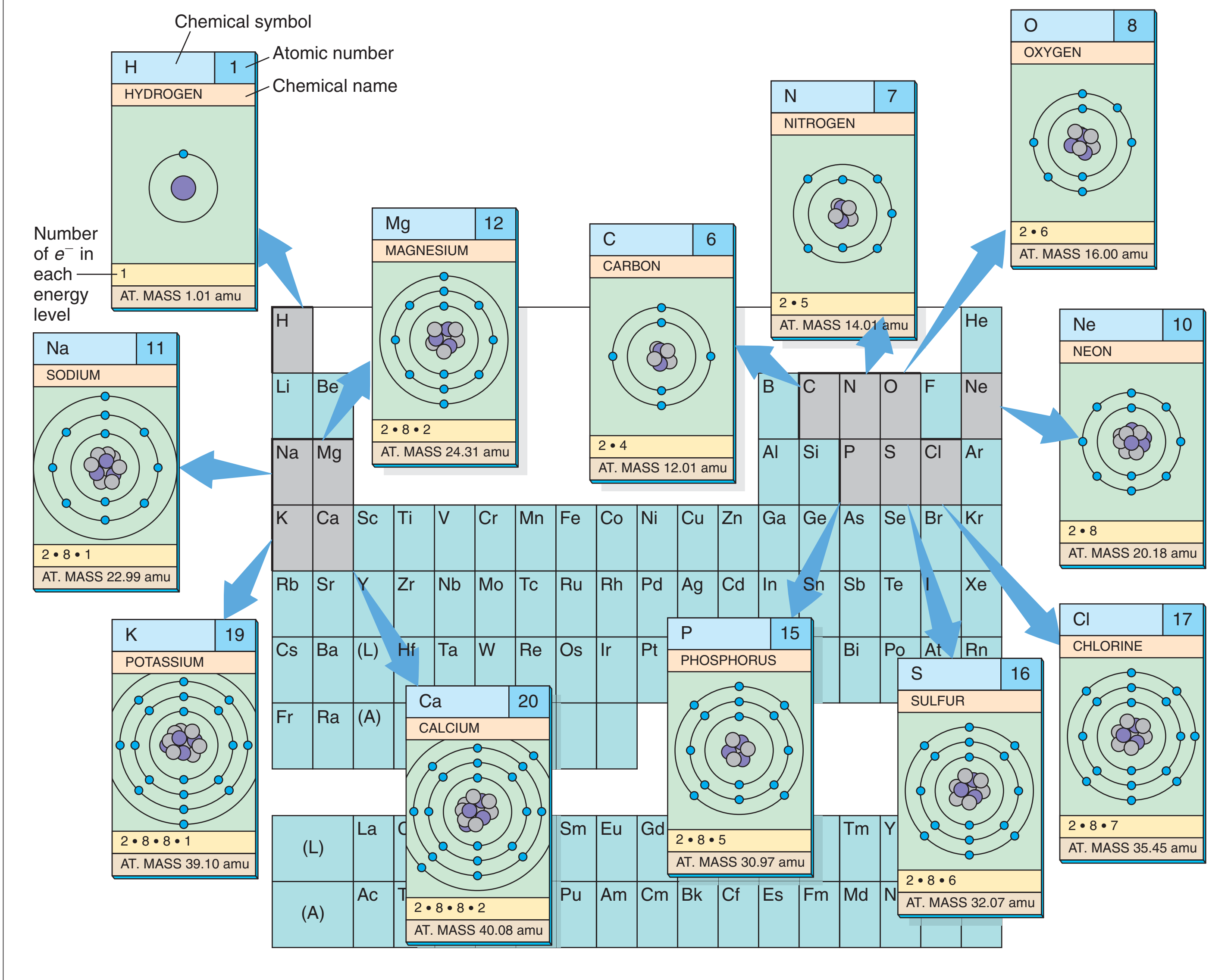


Figure 2-1 The periodic table

Note the Bohr models depicting the electron configuration of atoms of some biologically important elements. Although the Bohr model does not depict electron configurations accurately, it is commonly used because of its simplicity and convenience. A complete periodic table is given in Appendix A.

An atom is uniquely identified by its number of protons

Every element has a fixed number of protons in the atomic nucleus, known as the **atomic number.** It is written as a subscript to the left of the chemical symbol. Thus, $_1H$ indicates that the hydrogen nucleus contains 1 proton, and $_8O$ means that the oxygen nucleus contains 8 protons. The atomic number determines an atom's identity and defines the element.

The **periodic table** is a chart of the elements arranged in order by atomic number (Fig. 2-1 and Appendix A). The periodic table is useful because it lets us simultaneously correlate many of the relationships among the various elements.

Figure 2-1 includes representations of the **electron configurations** of several elements important in organisms. These *Bohr models,* which show the electrons arranged in a series of concentric circles around the nucleus, are convenient to use, but inaccurate. The space outside the nucleus is actually extremely large compared to the nucleus, and as you will see, electrons do not actually circle the nucleus in fixed concentric pathways.

Protons plus neutrons determine atomic mass

The mass of a subatomic particle is exceedingly small, much too small to be conveniently expressed in grams or even micrograms.[1] Such masses are expressed in terms of the **atomic mass unit (amu),** also called the **dalton** in honor of John Dalton, the English chemist who formulated an atomic theory in the early 1800s. One amu is equal to the approximate mass of a single proton or a single neutron. Protons and neutrons make up almost all the mass of an atom. The mass of a single electron is only about 1/1800 the mass of a proton or neutron.

The **atomic mass** of an atom is a number that indicates approximately how much matter it contains compared with another atom. This value is determined by adding the number of protons to the number of neutrons and expressing the result in atomic mass units or daltons.[2] The mass of the electrons is ignored because it is so small. The atomic mass number is indicated by a superscript to the left of the chemical symbol. The common form of the oxygen atom, with 8 protons and 8 neutrons in its nucleus, has an atomic number of 8 and a mass of 16 amu. It is indicated by the symbol ${}^{16}_{8}\text{O}$.

The characteristics of protons, electrons, and neutrons are summarized in the following table:

Particle	Charge	Approximate Mass	Location
Proton	Positive	1 amu	Nucleus
Neutron	Neutral	1 amu	Nucleus
Electron	Negative	Approx. 1/1800 amu	Outside nucleus

Isotopes of an element differ in number of neutrons

Most elements consist of a mixture of atoms with different numbers of neutrons and thus different masses. Such atoms are called **isotopes.** Isotopes of the same element have the same number of protons and electrons; only the number of neutrons varies. The three isotopes of hydrogen, ${}^{1}_{1}\text{H}$ (ordinary hydrogen), ${}^{2}_{1}\text{H}$ (deuterium), and ${}^{3}_{1}\text{H}$ (tritium), contain 0, 1, and 2 neutrons, respectively. Figure 2-2 shows Bohr models of two isotopes of carbon, ${}^{12}_{6}\text{C}$ and ${}^{14}_{6}\text{C}$. The mass of an element is expressed as an average of the masses of its isotopes (weighted by their relative abundance in nature). For example, the atomic mass of hydrogen is not 1.0 amu, but 1.0079 amu, reflecting the natural occurrence of small amounts of deuterium and tritium in addition to the more abundant ordinary hydrogen.

Because they have the same number of electrons, all isotopes of a given element have essentially the same chemical characteristics. However, some isotopes are unstable and tend to break down, or decay, to a more stable isotope (usually becoming a different element); such **radioisotopes** emit radiation when they decay. For example, the radioactive decay of ${}^{14}_{6}\text{C}$ occurs as a neutron decomposes to form a proton and a fast-moving electron, which is emitted from the atom as a form of radiation known as a beta (β) particle. The resulting stable atom is the common form of nitrogen, ${}^{14}_{7}\text{N}$. Using sophisticated instruments, scientists can detect and measure β particles and other types of radiation. Radioactive decay can also be detected by a method known as **autoradiography,** in which radiation causes the appearance of dark silver grains in photographic film (Fig. 2-3).

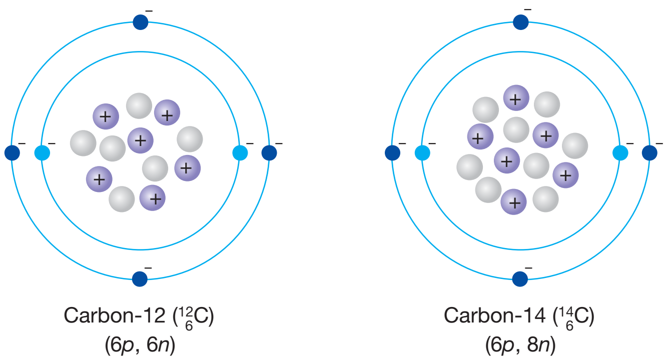


Figure 2-2 Isotopes

Carbon-12 (${}^{12}_{6}\text{C}$) is the most common isotope of carbon. Its nucleus contains 6 protons and 6 neutrons, so its atomic mass is 12. Carbon-14 (${}^{14}_{6}\text{C}$) is a rare radioactive carbon isotope. It contains 8 neutrons, so its atomic mass is 14.

Peter J. Bryant/Biological Photo Service

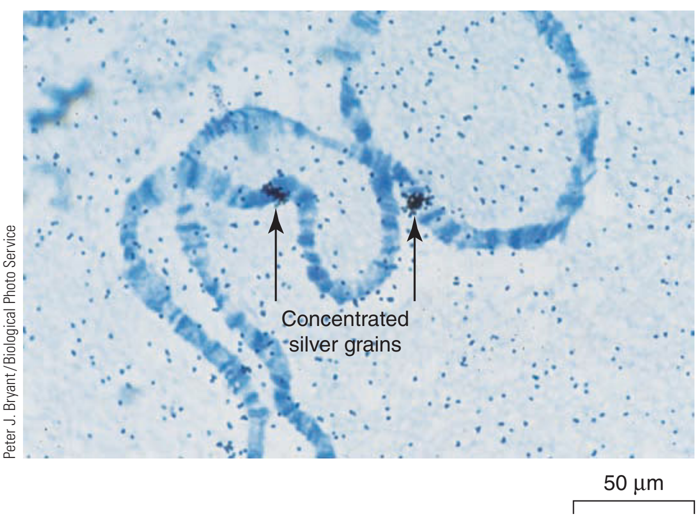


Figure 2-3 Autoradiography

The chromosomes of the fruit fly, *Drosophila melanogaster,* shown in this light micrograph, have been covered with photographic film in which silver grains (*dark spots*) are produced when tritium (${}^{3}\text{H}$) that has been incorporated into DNA undergoes radioactive decay. The concentrations of silver grains (*arrows*) mark the locations of specific DNA molecules.

[1] Tables of commonly used units of scientific measurement are printed inside the back cover of this text.

[2] Unlike weight, mass is independent of the force of gravity. For convenience, however, we consider mass and weight equivalent. Atomic weight has the same numerical value as atomic mass, but it has no units.