Key Terms

isotope  atoms of the same element that have different numbers of neutrons
radioisotope  an unstable isotope that decays over time by emitting radiation

molecule  a substance composed of two or more non-metal atoms that are covalently bonded together
organic molecule  a carbon-containing molecule in which carbon atoms are nearly always bonded to each other and to hydrogen
biochemistry  the study of the activity and properties of biologically important molecules

Chemistry in Living Systems

All matter is composed of elements—substances that cannot be broken down into simpler substances by ordinary chemical methods. Only about 92 naturally occurring elements serve as the building blocks of matter, including the matter that comprises you and the millions of species of organisms in the world around you. And yet only six elements—carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur—are the chemical foundation for this great diversity of life. Carbon and hydrogen form the underlying structures of biological molecules, with the other four elements providing particular properties to these molecules.

The smallest particle of an element that retains the properties of that element is an atom. Each atom has its own specific atomic mass, which is the sum of its protons and neutrons. While all atoms of an element have the same number of protons, the number of neutrons can vary. Isotopes are atoms of the same element that differ in the number of their neutrons. For example, carbon has three common isotopes: carbon-12 has six neutrons (the most abundant form), carbon-13 has seven neutrons, and carbon-14 has eight neutrons. Some isotopes are unstable, which means that their nucleus decays (breaks down) by emitting radiation in the form of subatomic particles or electromagnetic waves. Unstable isotopes are radioactive and are referred to as radioisotopes. Carbon-14 is an example. Radioisotopes are valuable diagnostic tools in medicine. Using a method called radioisotope tracing doctors can inject radioactive material into a patient and trace its movement in the body. For example, cancerous tissues in the body are characterized by a much higher level of activity than healthy tissues. Consequently, cancerous cells take in more glucose—a common cellular energy source—than healthy cells. Injecting a patient with radioactive glucose and then performing a positron emission tomography (PET) scan such as the one shown in Figure 1.1, is one method to diagnose a cancerous tumour.

Figure 1.1 This positron emission tomography (PET) scan is of a 62-year-old man's brain. The yellow and orange area represents a tumour, which breaks down the injected radioactive glucose at a faster rate than normal cells.

Studying the Interactions of Molecules

For most biological studies, chemical elements are not considered in the form of individual atoms but, rather, as components of molecules. Recall that a molecule is composed of two or more atoms and is the smallest unit of a substance that retains the chemical and physical properties of the substance. Many of the molecules of life are organic molecules. Organic molecules are carbon-based, and the carbon atoms are usually bonded to each other and to hydrogen. Many organic molecules also include atoms of nitrogen, oxygen, phosphorus, and/or sulfur.

There are major classes of biologically important organic molecules that are the cornerstones of most research in biochemistry. Biochemistry is often viewed as a field of study that forms a bridge between chemistry (the study of the properties and interactions of atoms and molecules) and biology (the study of the properties and interactions of cells and organisms). Biochemists are concerned mainly with understanding the properties and interactions of biologically important molecules. Understanding the physical and chemical principles that determine the properties of these molecules is essential to understanding their functions in the cell and in other living systems.
Interactions within Molecules

The forces that hold atoms together within a molecule are intramolecular forces ("intra" meaning within). These forces are what are generally thought of as the chemical bonds within a molecule. Bonds within molecules are covalent bonds. A covalent bond forms when the electron shells of two non-metal atoms overlap so that valence electrons of each atom are shared between both atoms. Each atom has access to the electrons in the bond, as well as to its other valence electrons. In this way, both atoms obtain a full valence shell. To illustrate this, a molecule of water, H₂O, is shown in Figure 1.2A.

Some atoms attract electrons much more strongly than other atoms. This property is referred to as an atom's electronegativity. Oxygen, O, nitrogen, N, and chlorine, Cl, are atoms with high electronegativity. Hydrogen, H, carbon, C, and phosphorus, P, are examples of atoms with lower electronegativity. When two atoms with significantly different electronegativities share electrons in a covalent bond, the electrons are more attracted to the atom with the higher electronegativity, so they are more likely to be found near it. Because electrons have a negative charge, this causes that atom to assume a slightly negative charge, called a partial negative charge (δ−). The atom with lower electronegativity assumes a partial positive charge (δ+). This unequal sharing of electrons in a covalent bond creates a polar covalent bond. Figure 1.2B shows how a water molecule contains two polar covalent O–H bonds. The electrons in each bond are more strongly attracted to the oxygen atom than to the hydrogen atom and are more likely to be found near the oxygen atom. This results in the oxygen atom being partially negative and the hydrogen atoms being partially positive. Molecules such as water, which have regions of partial negative and partial positive charge, are referred to as polar molecules.

When covalent bonds are formed between atoms that have similar electronegativities, the electrons are shared fairly equally between the atoms. Therefore, these bonds are considered non-polar. If this type of bond predominates in a molecule, the molecule is considered a non-polar molecule. For example, bonds between carbon and hydrogen atoms are considered non-polar, because carbon and hydrogen have similar electronegativities. As you will see in this unit, the polarity of biological molecules greatly affects their behaviour and functions in a cell.

Figure 1.2 As shown in the electron model (A), two hydrogen atoms each share a pair of electrons with oxygen to form covalent bonds in a molecule of water, H₂O. Because oxygen is more electronegative than hydrogen, there is a partial negative charge on the oxygen and a partial positive charge on each hydrogen, as shown in the space-filling model (B).

Predict how two water molecules might interact, based on this diagram.
Interactions between Molecules

In addition to forces within molecules, there are also forces between molecules. These intermolecular forces ("inter" meaning between) may form between different molecules or between different parts of the same molecule if that molecule is very large. Intermolecular interactions are much weaker than intramolecular interactions. They determine how molecules interact with each other and with different molecules, and therefore they play a vital role in biological systems. Most often, intermolecular interactions are attractive forces, making molecules associate together. However, because they are relatively weak, intermolecular forces can be broken fairly easily if sufficient energy is supplied. As a result, intermolecular forces are responsible for many of the physical properties of substances. Two types of intermolecular interactions are particularly important for biological systems: hydrogen bonding and hydrophobic interactions.

Hydrogen Bonding

With its two polar O–H bonds, a water molecule is a polar molecule, with a slightly positive end and a slightly negative end. The slightly positive hydrogen atoms of one molecule of water are attracted to the slightly negative oxygen atoms of other water molecules. This type of intermolecular attraction is called a hydrogen bond, and it is weaker than an ionic or covalent bond. As shown in Figure 1.3, a hydrogen bond is represented by a dotted line to distinguish it from the stronger covalent bond. Many biological molecules have polar covalent bonds involving a hydrogen atom and an oxygen or nitrogen atom.

A hydrogen bond can occur between different molecules as well as within the same molecule. Since the cell is an aqueous environment, hydrogen bonding between biological molecules and water is very important. Although a hydrogen bond is more easily broken than a covalent bond, many hydrogen bonds added together can be very strong. Hydrogen bonds between molecules in cells help maintain the proper structure and function of the molecule. For example, the three-dimensional shape of DNA, which stores an organism’s genetic information, is maintained by numerous hydrogen bonds. The breaking and reforming of these bonds plays an important role in how DNA functions in the cell.

Figure 1.3 In water, hydrogen bonds (dotted lines) form between the partially positive hydrogen atoms of one molecule and the partially negative oxygen atoms on other molecules.
**Hydrophobic Interactions**

Non-polar molecules such as cooking oil and motor oil do not form hydrogen bonds. When non-polar molecules interact with polar molecules, the non-polar molecules have a natural tendency to clump together, rather than to mix with the polar molecules, as shown in Figure 1.4. (Think of the saying, “oil and water don’t mix.”) If the molecules had human emotions and motivations, it would appear as if the non-polar molecules were drawing or shying away from the polar molecules. Thus, in their interactions with water molecules, non-polar molecules are said to be **hydrophobic** (literally meaning “water-fearing”). Polar molecules, on the other hand, have a natural tendency to form hydrogen bonds with water and are said to be **hydrophilic** (literally meaning “water-loving”).

The natural clumping together of non-polar molecules in water is referred to as the **hydrophobic effect**. As you will see in this unit, the hydrophobic effect plays a central role in how cell membranes form and helps to determine the three-dimensional shape of biological molecules such as proteins.

**Ions in Biological Systems**

An atom can obtain a stable valence shell by losing or gaining electrons rather than sharing them. For example, the sodium atom, Na, has only one electron in its outer valence shell. Once this electron is given up, the electron shell closer to the sodium nucleus, which already contains eight electrons, becomes the valence shell. When an atom or group of atoms gains or loses electrons, it acquires an electric charge and becomes an **ion**. When an atom or group of atoms loses electrons, the resulting ion is positive and is called a **cation**. When an atom or group of atoms gains electrons, the resulting ion is negative and is called an **anion**. Ions can be composed of only one element, such as the sodium ion, Na\(^+\), or of several elements, such as the bicarbonate ion, HCO\(_3\)\(^-\).

Ions are an important part of living systems. For example, hydrogen ions, H\(^+\), are critical to many biological processes, including cellular respiration. Sodium ions, Na\(^+\), are part of transport mechanisms that enable specific molecules to enter cells. For biological processes in the cell, substances that form ions, such as sodium, are almost never considered in the form of **ionic compounds**, such as sodium chloride, NaCl(s). Since the cell is an aqueous environment, almost all ions are considered as free, or dissociated ions (Na\(^+\)(aq) and Cl\(^-\)(aq)) since they dissolve in water.

---

**Learning Check**

1. What is the relationship between elements and atoms?
2. Explain, with reference to subatomic particles and stability, the difference between carbon-12 and carbon-14.
3. Explain how a polar covalent bond is different from an ionic bond.
4. Use a water molecule to describe the relationships among all the following: polar and non-polar molecules, intramolecular and intermolecular forces, hydrophilic and hydrophobic interactions.

5. What is the hydrophobic effect?
6. Biochemistry is one of the many scientific disciplines that bridge the knowledge and understanding of one field of science with another. Identify at least two other “bridging” scientific disciplines, and explain how the knowledge and understanding of one field complements the knowledge and understanding of the other in each case.
1. The property that distinguishes one atom (carbon for example) from another atom (oxygen for example) is—
   a. The number of electrons
   b. The number of protons
   c. The number of neutrons
   d. The combined number of protons and neutrons

2. If an atom has one valence (outer energy level) electron, it will most likely form—
   a. One polar, covalent bond
   b. Two nonpolar, covalent bonds
   c. Two covalent bonds
   d. An ionic bond

3. An atom with a net positive charge must have—
   a. More protons than neutrons
   b. More protons than electrons
   c. More electrons than neutrons
   d. More electrons than protons

4. The isotopes C^{12} and C^{14} differ in—
   a. The number of neutrons
   b. The number of protons
   c. The number of electrons
   d. Both b and c

5. An atom with more electrons than protons is called—
   a. An element
   b. An isotope
   c. A cation
   d. An anion

6. Which of the following is NOT a property of the elements most commonly found in living organisms?
   a. The elements have a low atomic mass
   b. The elements have an atomic number less than 21
   c. The elements possess eight electrons in their outer energy level
   d. The elements are lacking one or more electrons from their outer energy level

7. Which of the following atoms would you predict could be a cation?
   a. Fluorine (F)
   b. Helium (He)
   c. Potassium (K)
   d. Boron (B)

8. Refer to the element pictured. How many covalent bonds could this atom form?
   a. Two
   b. Three
   c. Four
   d. None

9. Refer to the element pictured. How many covalent bonds could this atom form?
   a. Two
   b. Three
   c. Four
   d. None

10. An ionic bond is held together by
    a. shared valence electrons
    b. attractions between ions of the same charge
    c. charge attractions between valence electrons
    d. attractions between ions of opposite charge

11. How do polar covalent bonds differ from nonpolar covalent bonds?
    a. In a polar covalent bond the electrons are shared equally between the atoms.
    b. In a nonpolar covalent bond there is a charge attraction between the atomic nuclei.
    c. There is a large difference in electronegativity of the atoms in a nonpolar bond.
    d. There is a large difference in electronegativity of the atoms in a polar bond.

12. A hydrogen bond can form—
    a. when hydrogen is part of a polar covalent bond
    b. only in water
    c. between any large electronegative atoms like oxygen
    d. when two atoms of hydrogen share an electron

13. Which of the following properties of water is NOT a consequence of its ability to form hydrogen bonds?
    a. Cohesiveness
    b. High specific heat
    c. Ability to function as a solvent
    d. Neutral pH

14. A substance with a high concentration of hydrogen ions is—
    a. called a base
    b. called an acid
    c. has a high pH
    d. both b and c

---

**Challenge Questions**

1. Elements that form ions are important for a range of biological processes. You have learned about the cations, sodium (Na^+), calcium (Ca^{2+}) and potassium (K^+) in this chapter. Use your knowledge of the definition of a cation to identify other examples from the periodic table.

2. A popular theme in science fiction literature has been the idea of silicon-based life-forms in contrast to our carbon-based life. Evaluate the possibility of silicon-based life based on the chemical structure and potential for chemical bonding of a silicon atom.

3. Recent efforts by NASA to search for signs of life on Mars have focused on the search for evidence of liquid water in the planet’s history rather than looking directly for biological organisms (living or fossilized). Use your knowledge of the influence of water on life on Earth to construct an argument justifying this approach.