Topic 3.1

Intermolecular Forces

Learning Objectives

- Define London dispersion forces and identify the types of molecules that interact through these forces.
- Describe dipole-dipole intermolecular interactions and list the properties of these interactions.
- Describe ion-dipole interactions and identify the types of atoms and molecules that form ion-dipole interactions.
- Define hydrogen bonding and identify the atoms involved in hydrogen bonding interactions.
- Describe how intermolecular forces impact biological systems.

Topic Questions

- What are London dispersion forces and what types of molecules interact through these forces?
- What is the relationship between polarizability and London dispersion forces?
- What is the difference between a dipole-dipole interaction and a dipole–induced dipole interaction?
- What is an ion-dipole interaction and what types of atoms and molecules form ion-dipole interactions?
- Why do biological systems tend to have separate polar and nonpolar environments?

3.1.01 London Dispersion Forces

[SAP-5.A.1]

The types of intermolecular forces experienced by the particles of a chemical substance depend on the nature of the interactions between the particles. The simplest forces are London dispersion forces, which are attractions between **temporary distortions** in the orbitals (ie, electron "clouds") around two nearby atoms or molecules. These distortions are caused when the random motion of electrons in an orbital form an instantaneous electric dipole with a separation of partial positive and partial negative charges (δ^+, δ^-).

As two atoms move closer together, a distortion in one atom can produce a distortion in the neighboring atom. This causes a momentary induced dipole to form in the other atom. The resulting attraction between the opposite partial charges of the two momentary dipoles produces a London dispersion force, as illustrated in Figure 3.1.

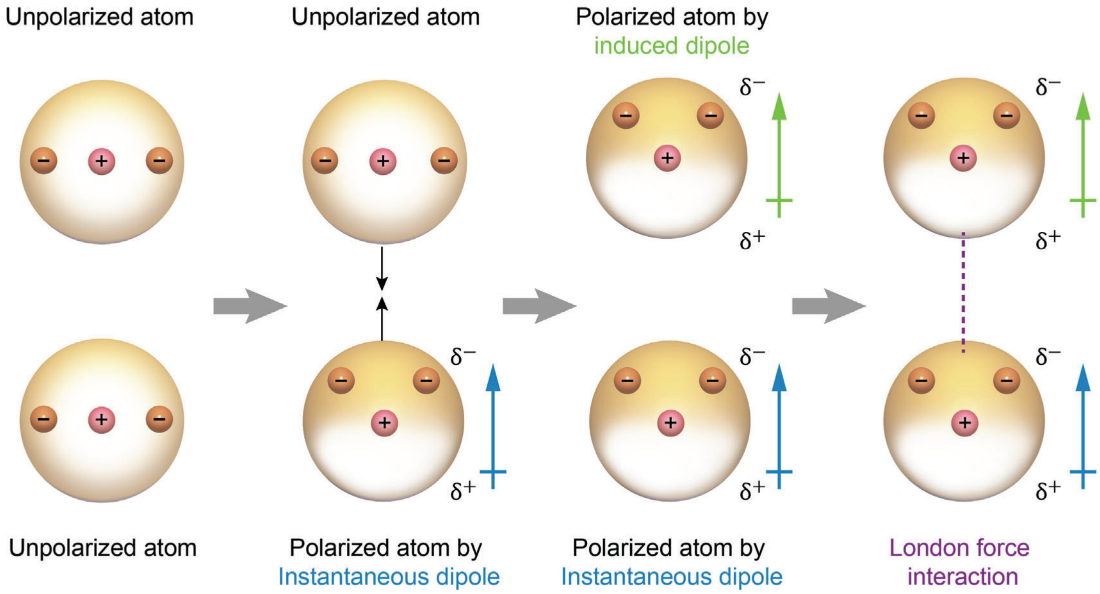

Figure 3.1 London dispersion force interaction between two adjacent helium atoms.

The strength of the London dispersion forces in an atom or molecule depends on its polarizability, which is a measure of how easily its electron cloud can be distorted. Larger atoms and molecules are more polarizable than smaller ones because larger atoms and molecules have more electrons and larger electron clouds that are more easily distorted. Essentially, larger and longer molecules are more polarizable and have stronger London dispersion forces than smaller and shorter molecules. This is because larger molecules have more contact area for orbital interactions, as illustrated in Figure 3.2.

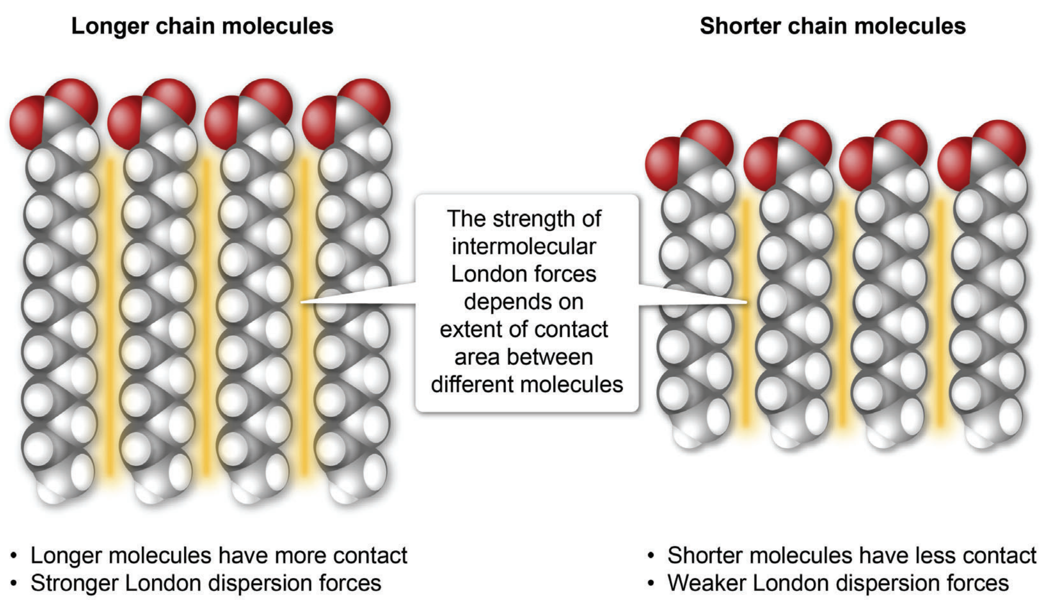

Figure 3.2 The strength of London dispersion forces is greater for larger or longer molecules.

Because all atoms and molecules have polarizable electron orbitals, all chemical compounds can participate in some amount of London forces. However, molecules consisting only of nonpolar covalent bonds between atoms with similar electronegativities experience no other types of intermolecular forces. Although each individual London force is relatively weak compared to other types of intermolecular forces, the cumulative effect of many London force interactions can be one of the strongest overall influences on physical properties, especially in larger nonpolar molecules.

3.1.02 Dipole-Dipole Interactions

[SAP-5.A.2 SAP-5.A.3]

As Sub-Topic 2.7.01 explains, a molecule with a significant net dipole moment is considered polar. Polar molecules have a partial positive charge (δ^+) on one part of the molecule and a partial negative charge (δ^-) on another part of the same molecule. Because opposite charges are attracted to each other, the partial positive end of a polar molecule is attracted to the partial negative ends of any nearby polar molecules and vice versa. The intermolecular forces resulting from these attractions are called dipole-dipole forces (Figure 3.3).

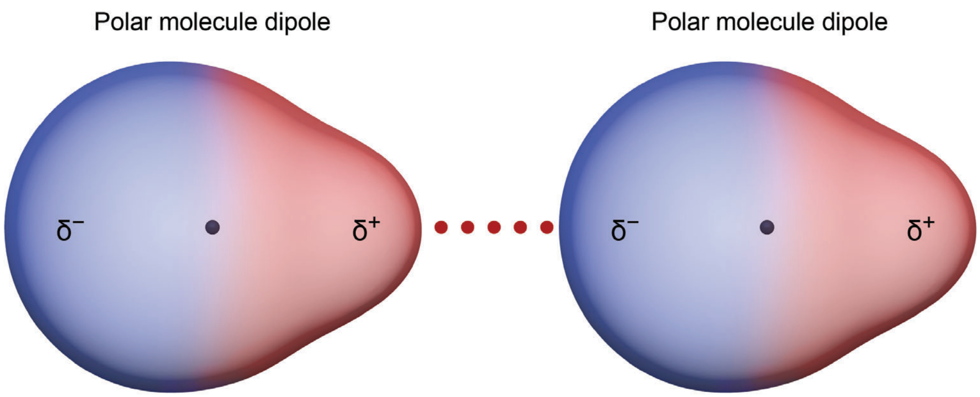

Figure 3.3 Dipole-dipole interaction between the permanent dipoles of two polar molecules.

Compared to the small, temporary dipoles that cause London dispersion forces, the dipoles in polar molecules are both larger and permanent. Therefore, dipole-dipole interactions between polar molecules are much stronger than London dispersion forces between nonpolar molecules of similar size.

When a nonpolar molecule is more polarizable, it can interact with the permanent dipoles of polar molecules. These dipole–induced dipole interactions happen when the permanent dipole of a polar molecule induces a weak temporary dipole in a nearby nonpolar molecule, as shown in Figure 3.4. As such, a dipole–induced dipole interaction is weaker than a dipole-dipole interaction but stronger than London dispersion forces (ie, interactions between two induced dipoles).

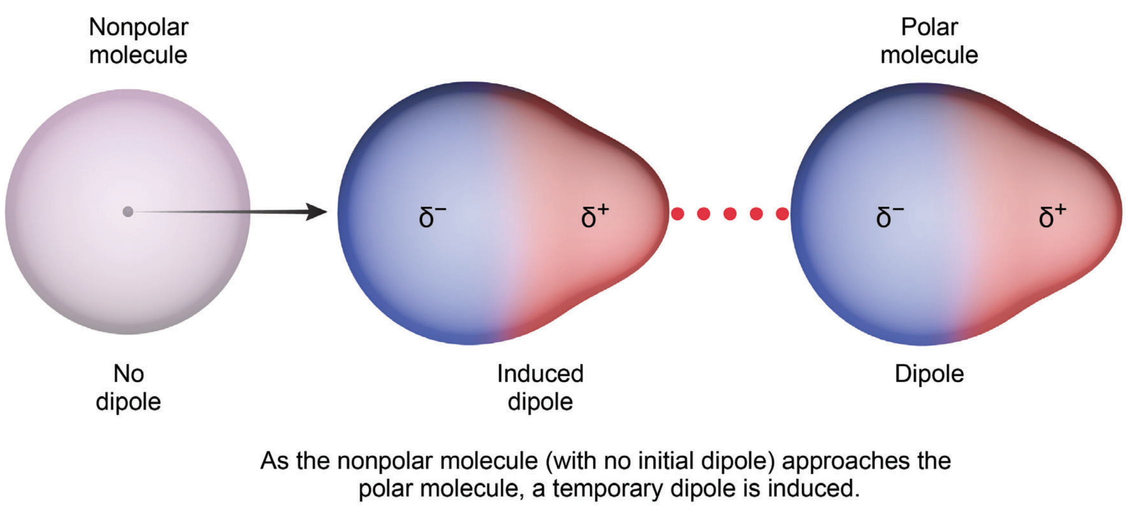

Figure 3.4 Dipole–induced dipole interaction between the permanent dipole of a polar molecule and a temporary, induced dipole in a polarizable nonpolar molecule.

3.1.03 Ion-Dipole Interactions

[SAP-5.A.2 SAP-5.A.3]

Intermolecular forces result from the electrostatic attractions between opposite charges on particles of chemical species. As a result, the partial charges of the permanent dipoles in polar molecules are readily attracted to fully charged ions and form ion-dipole interactions, as shown in Figure 3.5.

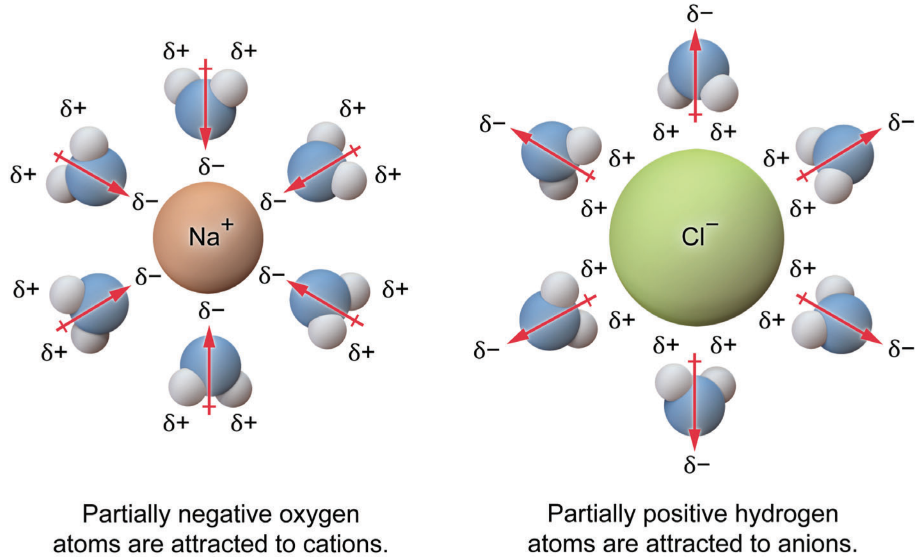

Figure 3.5 Ion-dipole interactions between positively and negatively charged ions and dipoles of polar molecules.

When ionic compounds such as table salt (NaCl) dissolve in water, the compound separates into its individual ions, and the ions form ion-dipole interactions with the partially charged oxygen and hydrogen atoms of the polar water molecules. The positive sodium ions (Na^+) interact with the partially negative oxygen atoms, and the negative chlorine ions (Cl^-) interact with the partially positive hydrogen atoms (Figure 3.5).

Coulomb's law (see Sub-Topic 1.5.02) shows that smaller ions with greater charges produce stronger ion-dipole interactions than larger ions with lesser charges. An ion with a larger ionic radius will cause a greater separation *r* between the charge centers and will result in a weaker attractive force.

In a NaCl(*aq*) solution (Figure 3.5), the Na^+ and Cl^- ions both have a charge magnitude of 1, but the Na^+ ions have a smaller ionic radius than the Cl^- ions. As a result, the ion-dipole interaction between the Na^+ ions and water is stronger than that between the Cl^- ions and water. However, a stronger interaction would be formed if more highly charged ions such as Mg^{2+} were dissolved, as summarized in Figure 3.6.

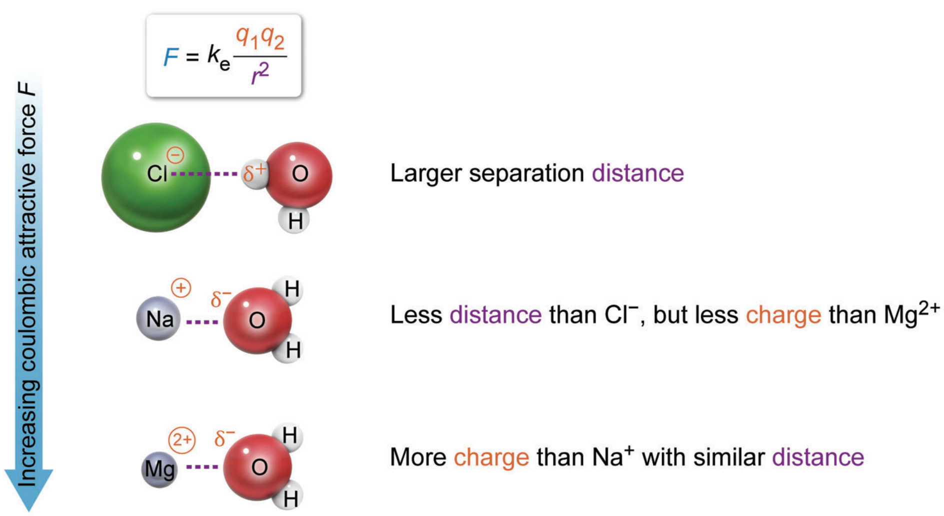

Figure 3.6 Effects of ionic radius and charge on the strength of ion-dipole interactions.

3.1.04 Hydrogen Bonding

[SAP-5.A.4]

Hydrogen bonding is a particularly strong type of dipole-dipole interaction that forms between a **hydrogen bond donor** (ie, an H–O, H–N, or H–F bond) and a **hydrogen bond acceptor** (ie, an O, N, or F atom with a lone pair of electrons), as shown in Figure 3.7.

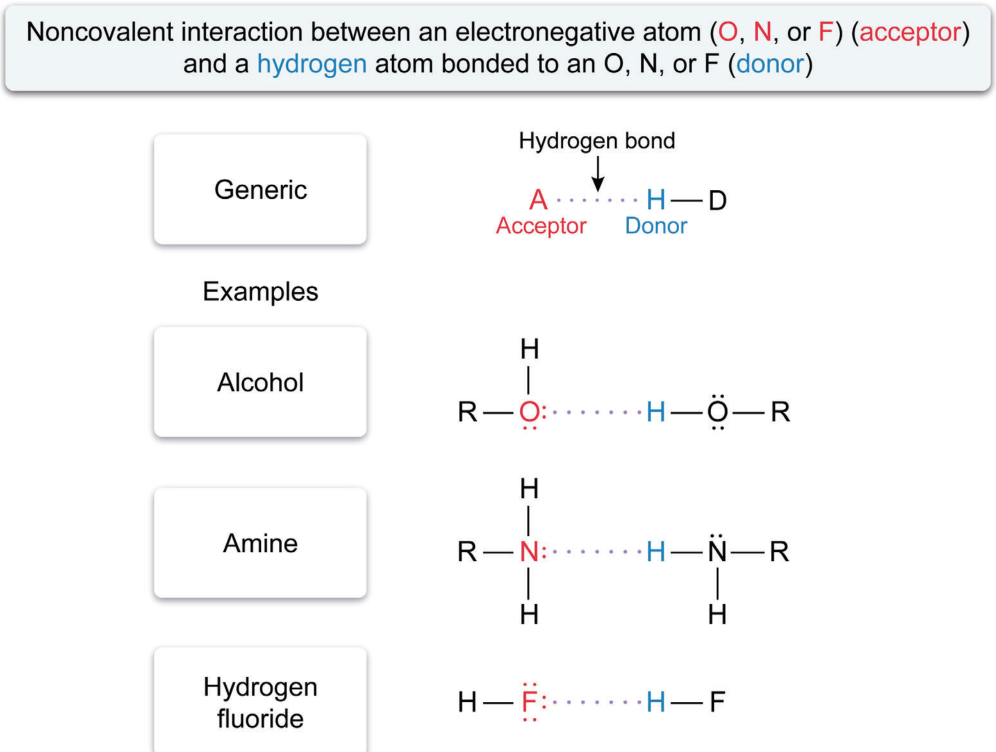

Figure 3.7 Examples of hydrogen bonding.

The large electronegativity difference between H and O, N, or F produces a strong dipole in which the H atom has a partial positive charge (δ^+) and the O, N, or F atom has a partial negative charge (δ^-). These opposite partial charges experience a noncovalent attraction that forms a hydrogen bond.

3.1.05 Intermolecular Forces Impacting Biological Systems

[SAP-5.A.5]

Intermolecular forces are weak, noncovalent attractive or repulsive interactions between molecules. Although these noncovalent interactions often form between chemical groups on two different molecules, large biomolecules can bend and fold. This allows the chemical groups from one part of the molecule to form interactions with other chemical groups on another part of the same molecule.

For example, the biomolecules called proteins are made of long chains of amino acids linked by peptide bonds. The type of intermolecular interactions that occur within the protein depend on the structures of the chemical groups (also called functional groups) of the amino acids, which can be broadly classified as polar, nonpolar, or charged. A summary of the common amino acids and their functional groups is shown in Figure 3.8.

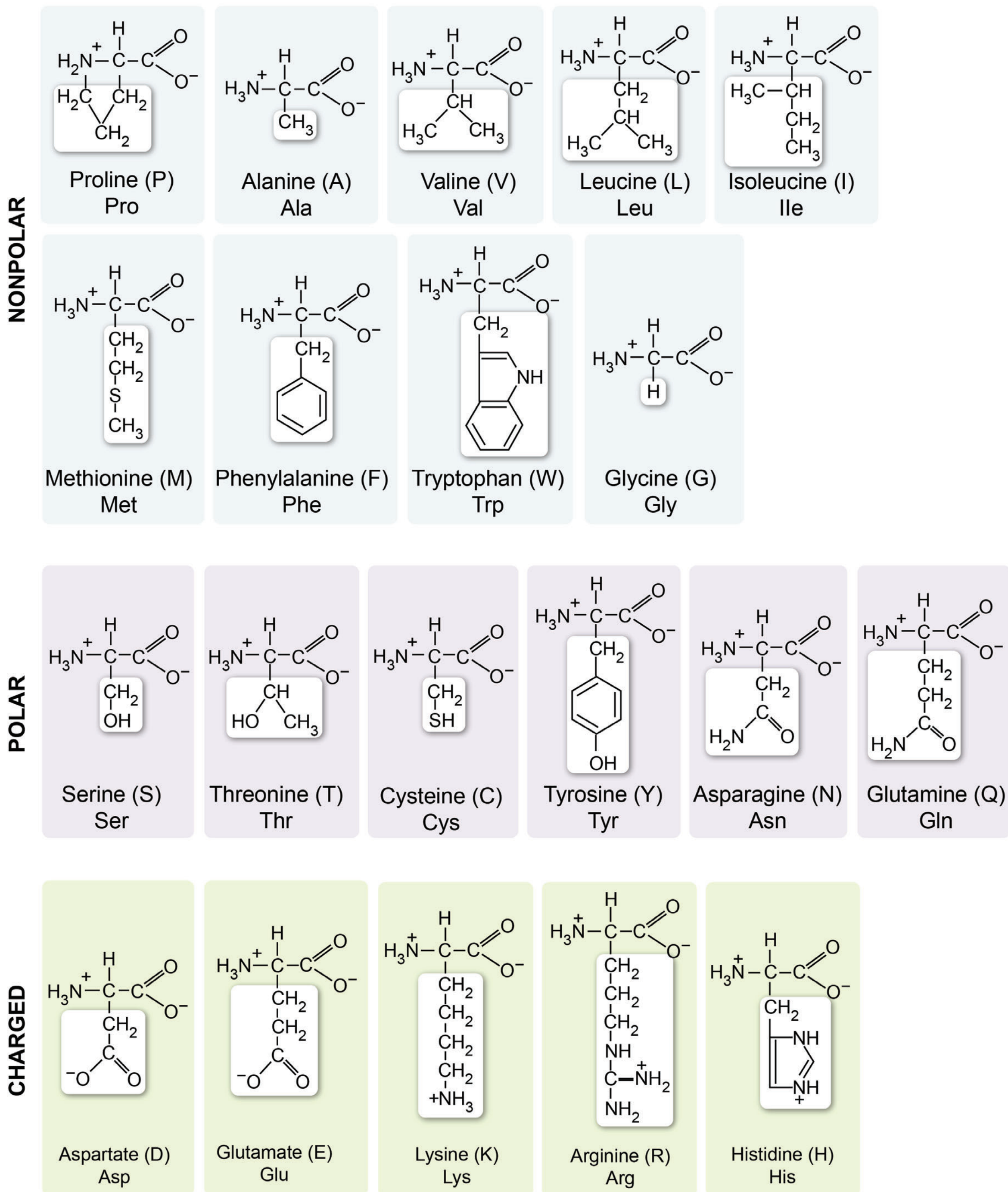

Figure 3.8 Common amino acids classified according to their side chain functional groups.

Molecules and chemical groups that experience similar types of intermolecular forces tend to interact well with each other. In biological systems, this helps separate and align molecules into specific environments.

Because oxygen and nitrogen are among the most electronegative elements, chemical groups that contain these atoms tend to be **polar**. Polar chemical groups primarily interact through dipole-dipole interactions (including hydrogen bonding) and readily interact with water (a polar molecule). In contrast, **nonpolar** chemical groups interact primarily through London dispersion forces. These types of chemical groups interact poorly with polar molecules and tend to be found in nonpolar environments, away from water.

In a protein, these types of interactions cause the polar, hydrophilic (ie, "water-loving") units (called residues) of its amino acid chain to face outwardly toward regions where water is present. On the other hand, the nonpolar, hydrophobic (ie, "water-fearing") portions of the chain face inwardly toward each other to form regions shielded from water. The combined effects of these forces cause proteins to fold into specific three-dimensional shapes, as illustrated in Figure 3.9.

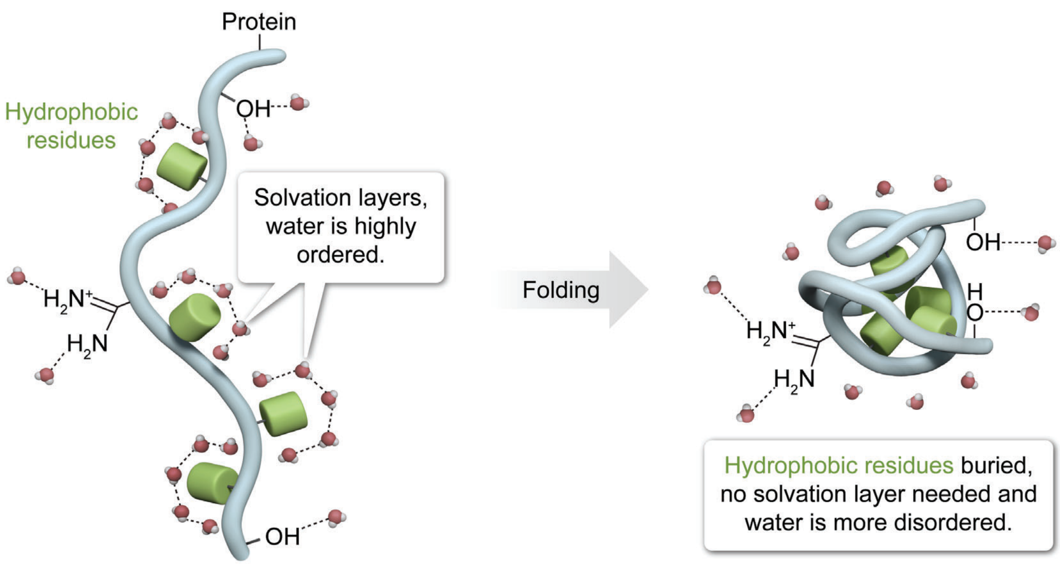

Figure 3.9 Nonpolar hydrophobic and polar hydrophilic interactions cause protein folding.

Oppositely charged amino acids (Figure 3.8) can also play a role in protein folding by strong mutual attractions that form ion-ion interactions called salt bridges. The specific shapes formed by protein folding depend on the particular amino acid sequence and the surrounding conditions.

Intermolecular forces also help separate molecules into specific environments. For instance, biological membranes consist of **hydrocarbons**, which are nonpolar molecules that contain only carbon and hydrogen. Figure 3.10 shows how the hydrocarbon interior of biological membranes (white structures) interacts with nonpolar cholesterol molecules (gold structures), resulting in the migration of these nonpolar molecules away from regions containing water.

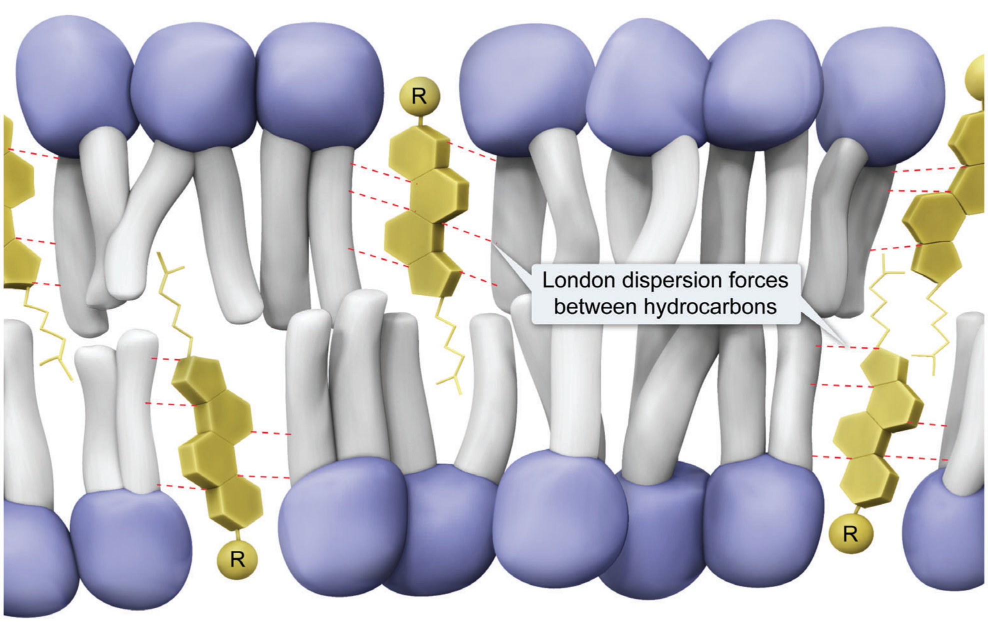

Figure 3.10 Interactions between nonpolar molecules and the nonpolar structures inside a biological membrane.

Topic 3.1 Intermolecular Forces

Check for Understanding Quiz

1. Which of the following can form hydrogen bonds with water (H_2O)?
   A. H_2S
   B. HBr
   C. NaCl
   D. NH_3

2. What type of intermolecular interactions result from temporary, induced dipoles?
   A. Dipole-dipole forces
   B. Ion-dipole forces
   C. London dispersion forces
   D. Hydrogen bonding

Note: Answers to this quiz are in the back of the book (appendix).