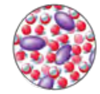
Chapter 7

How Molecules Mix

THE MAIN IDEA



Molecules are "sticky."

^ Water in these hot springs is loaded with calcium carbonate, a mineral whose solubility decreases with increasing temperature resulting in these spectacular pools of Pamukkale, Turkey.

In Chapter 6, we focused on how atoms bond together to form ionic or covalent compounds. You understand from earlier chapters that the formation of these compounds is a chemical change. In this chapter, we look at how the ions of ionic compounds and the molecules of covalent compounds—once created—interact to form mixtures, which, as you know, is a physical change.

So, when you stir sugar into water, the sugar crystals disappear, but where do they go? What does it mean to say that one solution is more concentrated, while another is more dilute? Why does a warm soda fizzle in your mouth more than a cold one does? How does soap remove water-resistant grime? What is "hard water," and why does it hinder soap from working? How is water made safe for drinking, and why is it so difficult to create fresh water from ocean water? The answers to these sorts of questions involve an understanding of mixtures.

7.1 Dipole Attractions

Recall from Chapter 6 that compounds can have a *dipole*. This means the electrons tend to congregate preferentially to one side of the compound. An extreme case occurs within an ionic compound such as sodium chloride, NaCl, where the bonding electrons spend most all of their time with the chlorine, which becomes the negatively charged chloride ion, Cl^-, while the sodium becomes a positively charged sodium ion, Na^+. Sodium chloride, NaCl, has a rather high melting point of 801°C and boiling point of 1465°C because of the strong attractions among all the highly charged sodium and chloride ions.

A milder form of a dipole occurs with water where the oxygen side of the water molecule slightly negative, while the hydrogen side is slightly positive. A molecule with such a dipole is said to be a *polar molecule.* Water has a relatively high boiling point of 100°C because of the electrical attractions among all the polar water molecules.

We begin this chapter by describing molecular attractions involving dipoles, as shown in **Table 7.1**. Each is electrical in nature, involving the attraction between positive and negative charges.

TABLE 7.1 Molecular Attractions

ATTRACTION	RELATIVE STRENGTH
Ion–dipole	Strongest
Dipole–dipole	↑
Dipole–induced dipole	
Induced dipole–induced dipole	Weakest

Ion–Dipole Attractions

What happens to polar molecules, such as water molecules, when they are near an ionic compound, such as sodium chloride? The opposite charges electrically attract one another. A positive sodium ion attracts the negative side of a water molecule, and a negative chloride ion attracts the positive side of a water molecule. This phenomenon is illustrated in **Figure 7.1.** Such an attraction between an ion and the dipole of a polar molecule is called an ion–dipole attraction.

Ion–dipole attractions are much weaker than ionic bonds. However, a large number of ion–dipole attractions can act collectively to disrupt ionic bonds. This is what happens to sodium chloride in water. Attractions exerted by the water molecules break the ionic bonds and pull the ions away from one another. The result, represented in **Figure 7.2**, is a solution of sodium chloride in water. (A solution in water is called an *aqueous solution*.)

Dipole–Dipole Attractions

An attraction between two polar molecules is called a *dipole–dipole attraction*. An unusually strong dipole–dipole attraction is the **hydrogen bond**. This attraction occurs between molecules that have a hydrogen atom covalently bonded to a small, highly electronegative atom, usually nitrogen, oxygen, or fluorine. Recall from Section 6.7 that the electronegativity of an atom describes how well that atom is able to pull bonding electrons toward itself. The greater the atom's electronegativity, the better it can attract bonding electrons and become negatively charged.

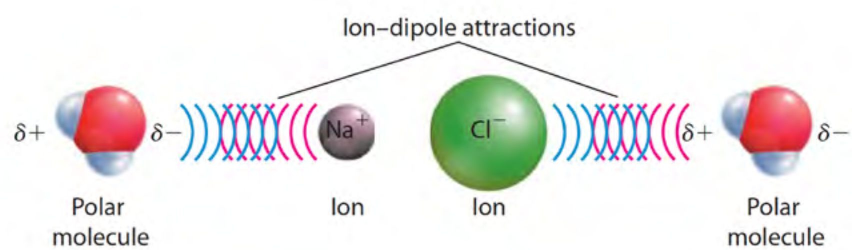


Figure 7.1 >

Electrical attractions are shown as a series of overlapping arcs. The blue arcs indicate negative charge, and the red arcs indicate positive charge.

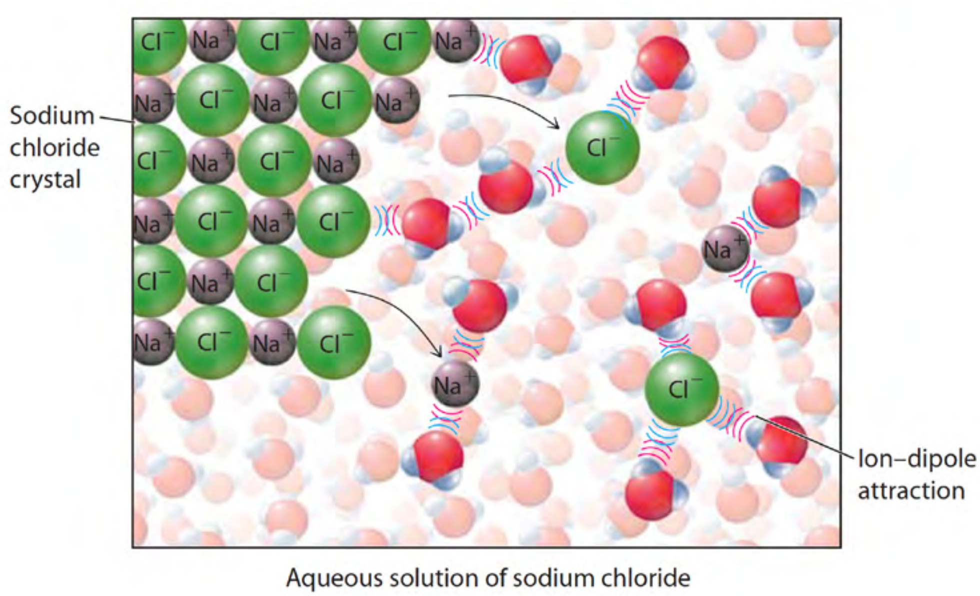


Figure 7.2 >

Sodium and chloride ions tightly bound in a crystal lattice are separated from one another by the collective attraction exerted by many water molecules to form an aqueous solution of sodium chloride.

Look at **Figure 7.3** to see how hydrogen bonding works. The hydrogen side of a polar molecule (water, in this example) has a partial positive charge because the more electronegative oxygen atom pulls more strongly on the electrons of the covalent bond. The hydrogen is therefore electrically attracted to a pair of non-bonding electrons on the partially negatively charged atom of another molecule (in this case, another water molecule). This mutual attraction between hydrogen and the negatively charged atom of another molecule is a hydrogen bond.

Even though the hydrogen bond is much weaker than any covalent or ionic bond, the effects of hydrogen bonding can be very pronounced. As we explore in Chapter 8, water owes many of its properties to hydrogen bonds. The hydrogen bond is also of great importance in the chemistry of the large molecules, such as DNA and proteins, which we discuss in Chapter 13.

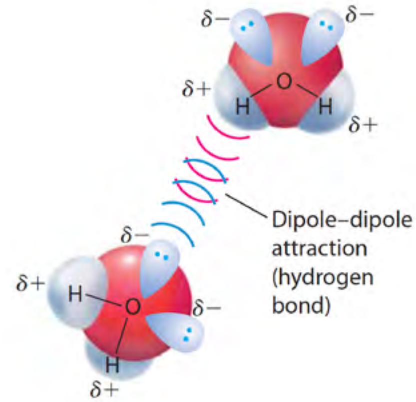


Figure 7.3

The dipole–dipole attraction between two water molecules is a hydrogen bond because it involves hydrogen atoms bonded to highly electronegative oxygen atoms.

Dipole–Induced Dipole Attractions

In many molecules, the electrons are distributed evenly, so there is no dipole. The oxygen molecule, O_2, is an example. Such a nonpolar molecule can be induced to become a *temporary dipole*, however, when it is brought close to a water molecule (or to any other polar molecule), as **Figure 7.4** illustrates. The slightly negative side of the water molecule pushes the electrons in the oxygen molecule away. The result is a temporarily uneven distribution of electrons called an **induced dipole**. The resulting attraction between the permanent dipole (water) and the induced dipole (oxygen) is a *dipole–induced dipole* attraction.

Remember, induced dipoles are only temporary. If the water molecule in **Figure 7.4b** were removed, the oxygen molecule would return to its normal, non-polar state. In general, dipole–induced dipole attractions are much weaker than dipole–dipole attractions. But dipole–induced dipole attractions are strong enough to hold relatively small quantities of oxygen dissolved in water, as depicted in **Figure 7.5**. This attraction between water and molecular oxygen is vital for fish and other forms of aquatic life that rely on molecular oxygen dissolved in water.

Dipole–induced dipole attractions are also responsible for holding plastic wrap to glass, as shown in **Figure 7.6**. These wraps are made of very long non- polar molecules that are induced to have dipoles when placed in contact with glass, which is highly polar. As we will discuss next, the molecules of a nonpolar material, such as plastic wrap, can also induce dipoles among themselves. This explains why plastic wrap sticks not only to polar materials such as glass but also to itself.

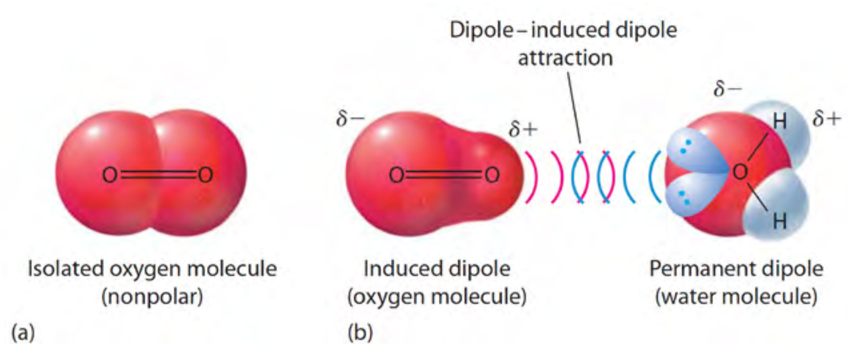
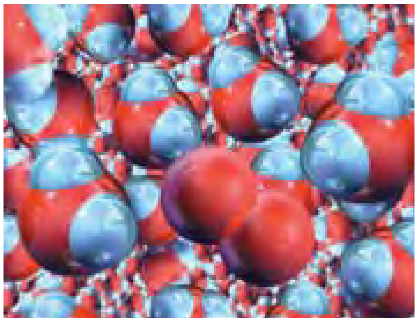


Figure 7.4

(a) An isolated oxygen molecule has no dipole; its electrons are distributed evenly. (b) An adjacent water molecule induces a redistribution of electrons in the oxygen molecule. (The slightly negative side of the oxygen molecule is shown as larger than the slightly positive side because the slightly negative side contains more electrons.)



Λ Figure 7.5

The electrical attraction between water and oxygen molecules is relatively weak, which explains why not much oxygen is able to dissolve in water. For example, water fully aerated at room temperature contains only about 1 oxygen molecule for every 200,000 water molecules. The gills of a fish, therefore, must be highly efficient at extracting this molecular oxygen from water.

Λ Figure 7.6

Temporary dipoles induced in the normally nonpolar molecules in plastic wrap make it stick to glass.

CONCEPT **CHECK**

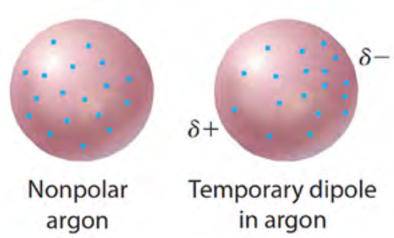
How does the electron distribution in an oxygen molecule change when the hydrogen side of a water molecule is nearby?

CHECK YOUR ANSWER

Because the hydrogen side of the water molecule is slightly positive, the electrons in the oxygen molecule are pulled toward the water molecule, inducing a temporary dipole in the oxygen molecule.

READING CHECK

Is it possible for the electrons of an atom or a nonpolar molecule to be bunched to one side?



Λ Figure 7.7

The electron distribution in an atom is normally even. At any given moment, however, the electron distribution may be somewhat uneven, resulting in a temporary dipole.

Induced Dipole–Induced Dipoles Attractions

Individual atoms and nonpolar molecules, on average, have a fairly even distribution of electrons. Because of the randomness of electron distribution, however, at any given moment, the electrons in an atom or a nonpolar molecule may be bunched to one side. The result is a temporary dipole, as shown in **Figure 7.7**.

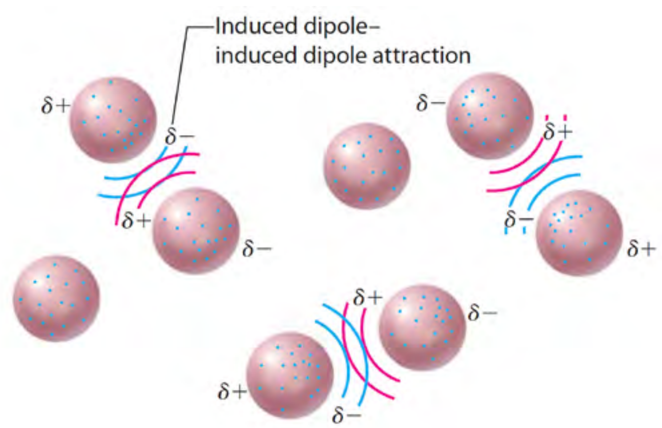
Just as the permanent dipole of a polar molecule can induce a dipole in a nonpolar molecule, a temporary dipole can do the same thing. This gives rise to the relatively weak *induced dipole–induced dipole* attraction, illustrated in **Figure 7.8**.

Induced dipole–induced dipole attractions (sometimes called *dispersion forces*) help explain why natural gas is a gas at room temperature but gasoline is a liquid. The major component of natural gas is methane, CH_4, and one of the major components of gasoline is octane, C_8H_{18}. We can see in **Figure 7.9** that the number of induced dipole–induced dipole attractions between two methane molecules is appreciably less than the number between two octane molecules. You know that two small pieces of Velcro are easier to pull apart than two long pieces. Like short pieces of Velcro, methane molecules can be pulled apart with little effort. That's why methane has a low boiling point, −161°C, and is a gas at room temperature. Octane molecules, like long strips of Velcro, are relatively difficult to pull apart because of the larger number of induced dipole–induced dipole attractions. The boiling point of octane, 125°C, is therefore much higher than that of methane, and octane is a liquid at room temperature. (The greater mass of octane also plays a role in making its boiling point higher.)

Induced dipole–induced dipole attractions also explain how the gecko can race up a glass wall and support its entire body weight with only a single toe. A gecko's feet are covered with billions of microscopic hairs called *spatulae*, each of which is about 1/300 as thick as a human hair. The

CONCEPT **CHECK**
Distinguish between a dipole–dipole attraction and a dipole–induced dipole attraction.

CHECK YOUR ANSWER
The dipole–dipole attraction is stronger and involves two permanent dipoles. The dipole–induced dipole attraction is weaker and involves a permanent dipole and a temporary one.

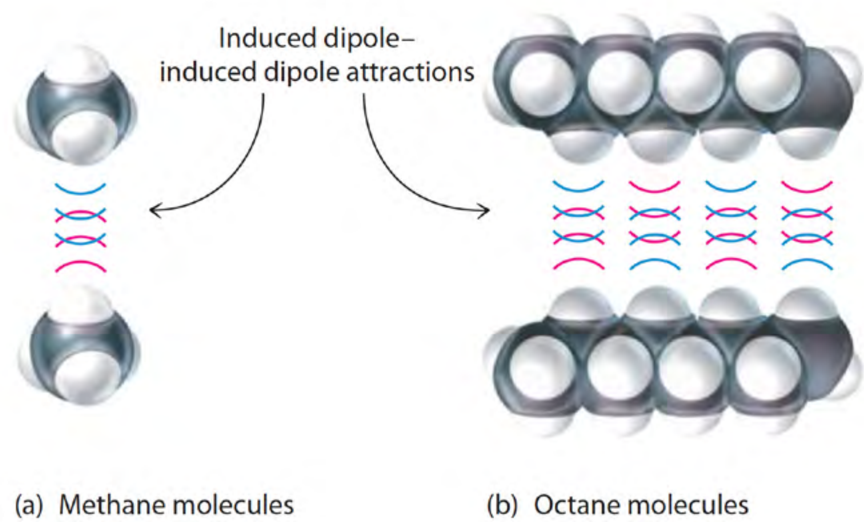


< Figure 7.8

Because the normally even distribution of electrons in atoms can momentarily become uneven, atoms can be attracted to one another through induced dipole–induced dipole attractions.

force of attraction between these hairs and the wall is the weak induced dipole–induced dipole attraction. But because there are so many hairs, the surface area of contact is relatively great; hence, the total force of attraction is enough to prevent the gecko from falling (**Figure 7.10**). Look for synthetic dry glue and dry, yet sticky, fabrics (allowing humans to stick to walls) based on the principle of gecko adhesion.

Temporary dipoles are more significant for larger atoms. A reason for this is that their outermost electrons are relatively far from the nucleus as well as from each other. As a result, these electrons are easily "pushed around," as described in **Figure 7.11.** Thus, larger atoms are sometimes described as "soft"—more like a marshmallow than a marble. The technical term for this property is *polarizability*. We say that a larger atom is more "polarizable," which means it can form an induced dipole more easily.



< Figure 7.9

Two nonpolar methane molecules are attracted to each other by induced dipole–induced dipole attractions, but there is only one attraction per molecule. (b) Two nonpolar octane molecules are similar to methane molecules, but they are longer. The number of induced dipole–induced dipole attractions between these two molecules is therefore greater.

FOR YOUR INFORMATION

Dipole–induced dipole attractions are sometimes called Debye forces, while induced dipole–induced dipole attractions are sometimes called London dispersion forces, or more simply London forces. Each of these are the last names of the 20th-century scientists who first described them.

Figure 7.10 >

If the gecko's foot is so sticky, how does the gecko keep its feet clean? Answer: The gecko's foot is extremely nonpolar. Dirt may stick to it briefly, but after a few steps, the dirt sticks better to the surface upon which the gecko walks.

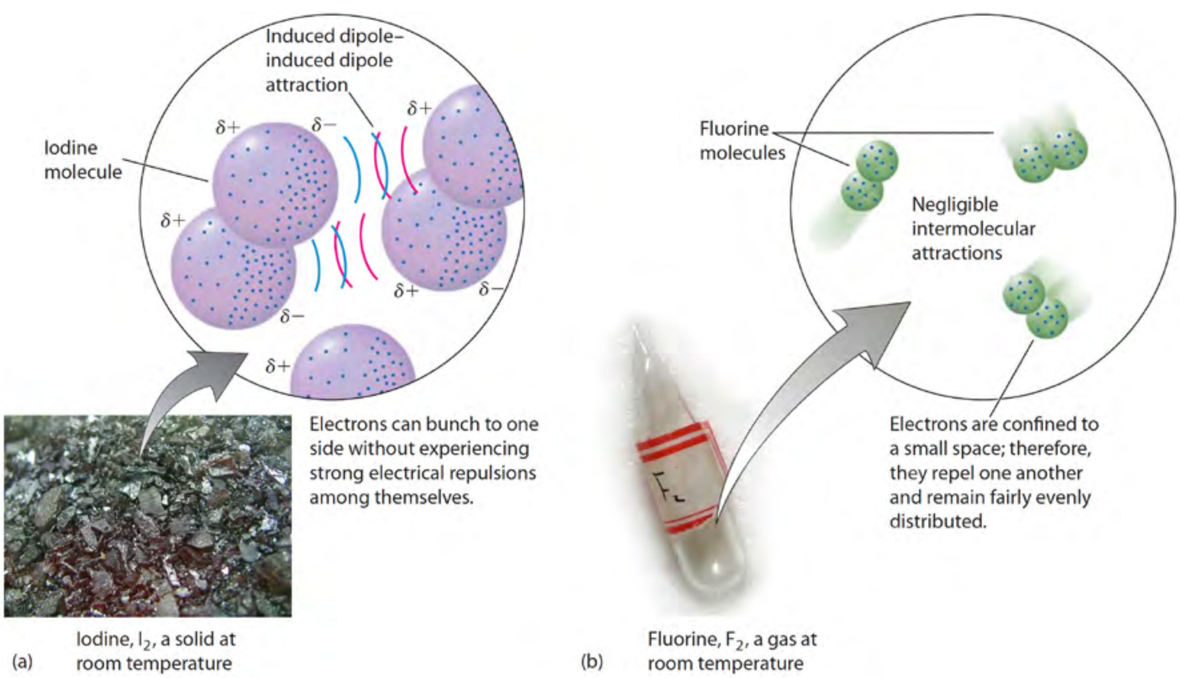
Fluorine is one of the smallest atoms, which means it is a "hard" atom (like a marble) and not very polarizable. Nonpolar molecules made with fluorine atoms exhibit only very weak induced dipole–induced dipole attractions. This is the principle behind the Teflon® nonstick surface. The Teflon® molecule, part of which is shown in **Figure 7.12**, is a long chain of carbon atoms chemically bonded to fluorine atoms, and the fluorine atoms exert essentially no attractions on any material in contact with the Teflon® surface—scrambled eggs in a frying pan, for instance.

CONCEPT **CHECK**

Distinguish between a dipole–induced dipole attraction and an induced dipole–induced dipole attraction.

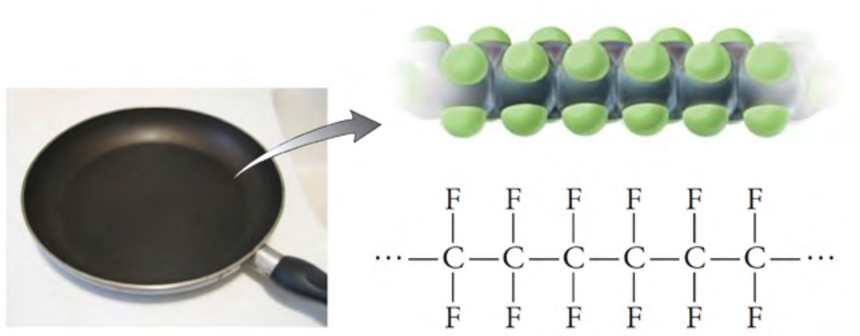
CHECK YOUR ANSWER

The dipole–induced dipole attraction is stronger and involves a permanent dipole and a temporary one. The induced dipole–induced dipole attraction is weaker and involves two temporary dipoles.



∧ Figure 7.11

(a) Temporary dipoles form more readily in larger atoms, such as those in an iodine molecule, because in larger atoms, electrons are more loosely held and can bunch to one side and still be relatively far apart from one another. (b) In smaller atoms, such as those in a fluorine molecule, electrons are tightly held and cannot bunch to one side so well because the repulsive electric force increases as the electrons get closer together.



^ Figure 7.12

Few things stick to Teflon® because of the high proportion of fluorine atoms that it contains. The structure depicted here is only a portion of the full length of the molecule.

CONCEPT **CHECK**

Molecules of methanol, CH_3OH are not much larger than molecules of methane, CH_4. Methanol, however, is a liquid at room temperature while methane is a gas. Suggest why.

CHECK YOUR ANSWER

The polar oxygen–hydrogen covalent bond in each methanol molecule leads to hydrogen bonding between molecules. These relatively strong interparticle attractions hold methanol molecules together as a liquid at room temperature.