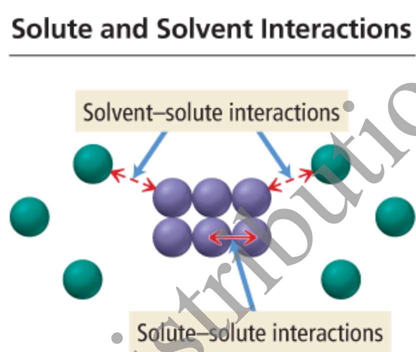
Pearson

8.4: Types of Aqueous Solutions and Solubility

Consider two familiar aqueous solutions: saltwater and sugar water. Saltwater is a homogeneous mixture of NaCl and H_2O, and sugar water is a homogeneous mixture of $C_{12}H_{22}O_{11}$ and H_2O. You may have made these solutions yourself by adding table salt or sugar to water. As you stir either of these two substances into the water, the substance seems to disappear. However, you know that the original substance is still present because you can taste saltiness or sweetness in the water. How do solids such as salt and sugar dissolve in water?

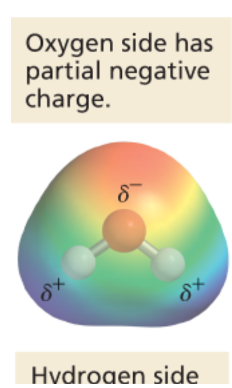
When we put a solid into a liquid solvent, the attractive forces that hold the solid together (the solute–solute interactions) compete with the attractive forces between the solvent molecules and the particles that compose the solid (the solvent–solute interactions), as shown in Figure 8.5.

Figure 8.5 **Solute and Solvent Interactions**



For example, when we add sodium chloride to water, there is a competition between the attraction of Na^+ cations and Cl^- anions to each other (due to their opposite charges) and the attraction of Na^+ and Cl^- to water molecules. The attraction of Na^+ and Cl^- to water is based on the *polar nature* of the water molecule (see Section 5.10). The oxygen atom in water is electron-rich, giving it a partial negative charge (δ^-), as shown in Figure 8.6. The hydrogen atoms, in contrast, are electron-poor, giving them a partial positive charge (δ^+). As a result, the positively charged sodium ions are strongly attracted to the oxygen side of the water molecule, and the negatively charged chloride ions are attracted to the hydrogen side of the water molecule, as shown in Figure 8.7. In the case of NaCl, the attraction between the separated ions and the water molecules overcomes the attraction of sodium and chloride ions to each other, and the sodium chloride dissolves in the water (Figure 8.8).

Figure 8.6 **Electrostatic Potential Map of a Water Molecule**



has partial
positive charge.

Figure 8.7 Solute and Solvent Interactions in a Sodium Chloride Solution

When sodium chloride is put into water, the attraction of Na^+ and Cl^- ions to water molecules competes with the attraction among the oppositely charged ions themselves.

Interactions in a Sodium Chloride Solution

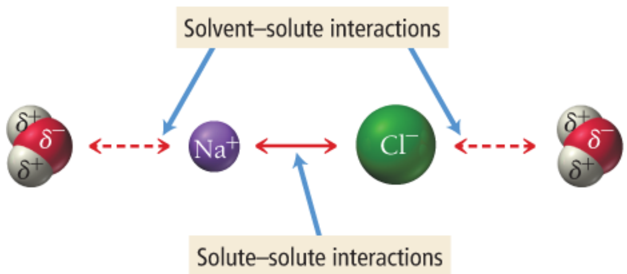
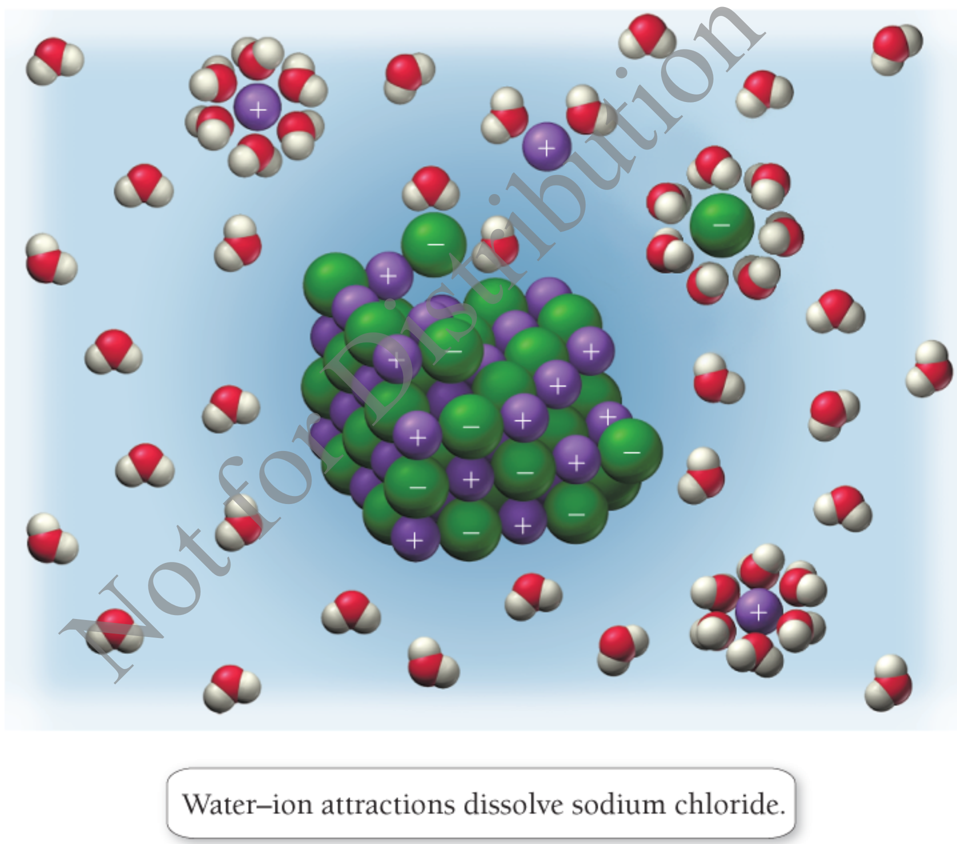


Figure 8.8 Sodium Chloride Dissolving in Water

Dissolution of an Ionic Compound



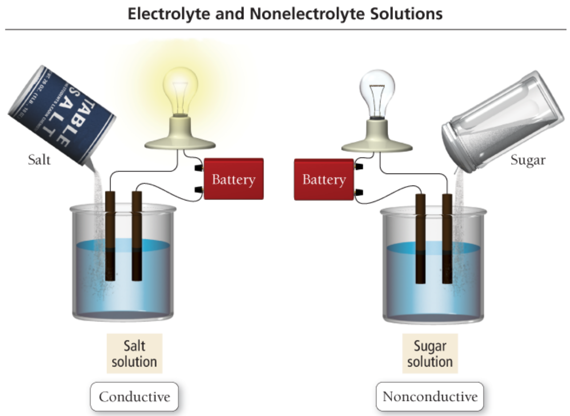
Electrolyte and Nonelectrolyte Solutions

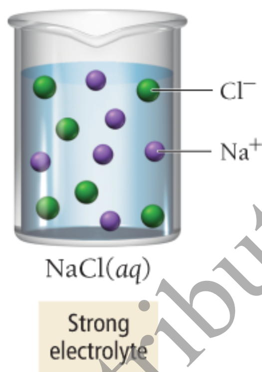
As Figure 8.9 illustrates, a salt solution conducts electricity while a sugar solution does not. The difference between the way that salt (an ionic compound) and sugar (a molecular compound) dissolve in water illustrates a fundamental difference between types of solutions. Ionic compounds such as the sodium chloride in the previous example (or the calcium chloride used for spherification in molecular gastronomy discussed in Section 8.1), dissociate into their component ions when they dissolve in water. An NaCl solution, represented as

NaCl(aq), does not contain any NaCl units, but rather dissolved Na^+ ions and Cl^- ions.

Figure 8.9 Electrolyte and Nonelectrolyte Solutions

A solution of salt (an electrolyte) conducts electrical current. A solution of sugar (a nonelectrolyte) does not.



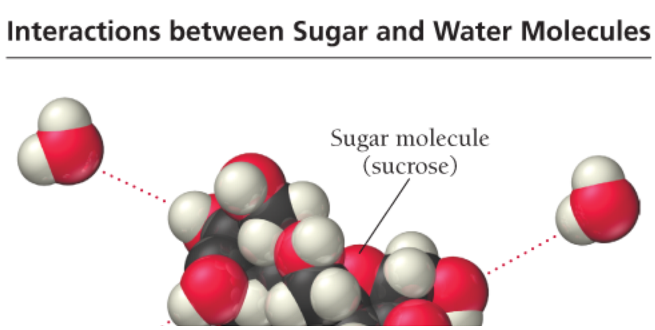


The dissolved ions act as charge carriers, allowing the solution to conduct electricity. Substances that dissolve in water to form solutions that conduct electricity are **electrolytes**. Substances such as sodium chloride that completely dissociate into ions when they dissolve in water are **strong electrolytes**, and the resulting solutions are strong electrolyte solutions.

In contrast to sodium chloride, sugar is a molecular compound. Most molecular compounds—with the important exception of acids, which we discuss shortly—dissolve in water as intact molecules. Sugar dissolves because the attraction between sugar molecules and water molecules, shown in Figure 8.10, overcomes the attraction of sugar molecules to each other (Figure 8.11). So unlike a sodium chloride solution (which is composed of dissociated ions), a sugar solution is composed of intact $C_{12}H_{22}O_{11}$ molecules homogeneously mixed with the water molecules.

Figure 8.10 Sugar and Water Interactions

Partial charges on sugar molecules and water molecules (discussed more fully in Chapter 13) result in attractions between the sugar molecules and water molecules.



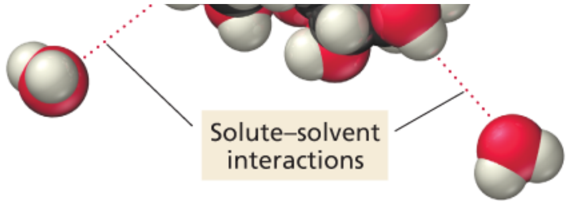
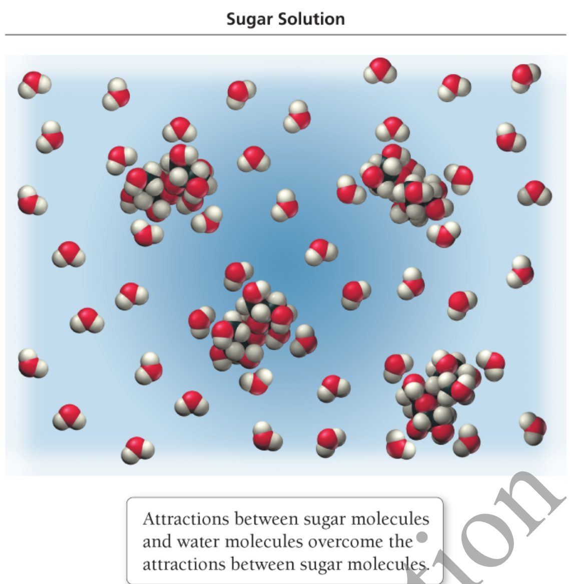
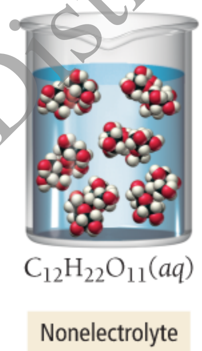


Figure 8.11 A Sugar Solution

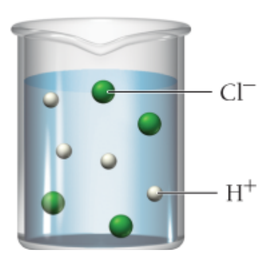


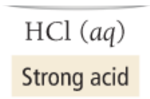
Compounds such as sugar that do not dissociate into ions when dissolved in water are **nonelectrolytes**, and the resulting solutions—called *nonelectrolyte solutions*—do not conduct electricity.

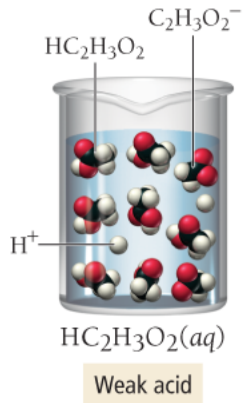


Acids are molecular compounds that ionize to form H^+ ions when they dissolve in water. Hydrochloric acid (HCl), for example, ionizes into H^+ and Cl^- when it dissolves in water. HCl is an example of a **strong acid**, one that completely ionizes in solution. Since strong acids completely ionize in solution, they are also strong electrolytes. We represent the complete ionization of a strong acid with a single reaction arrow between the acid and its ionized form:

$$HCl(aq) \rightarrow H^+(aq) + Cl^-(aq)$$





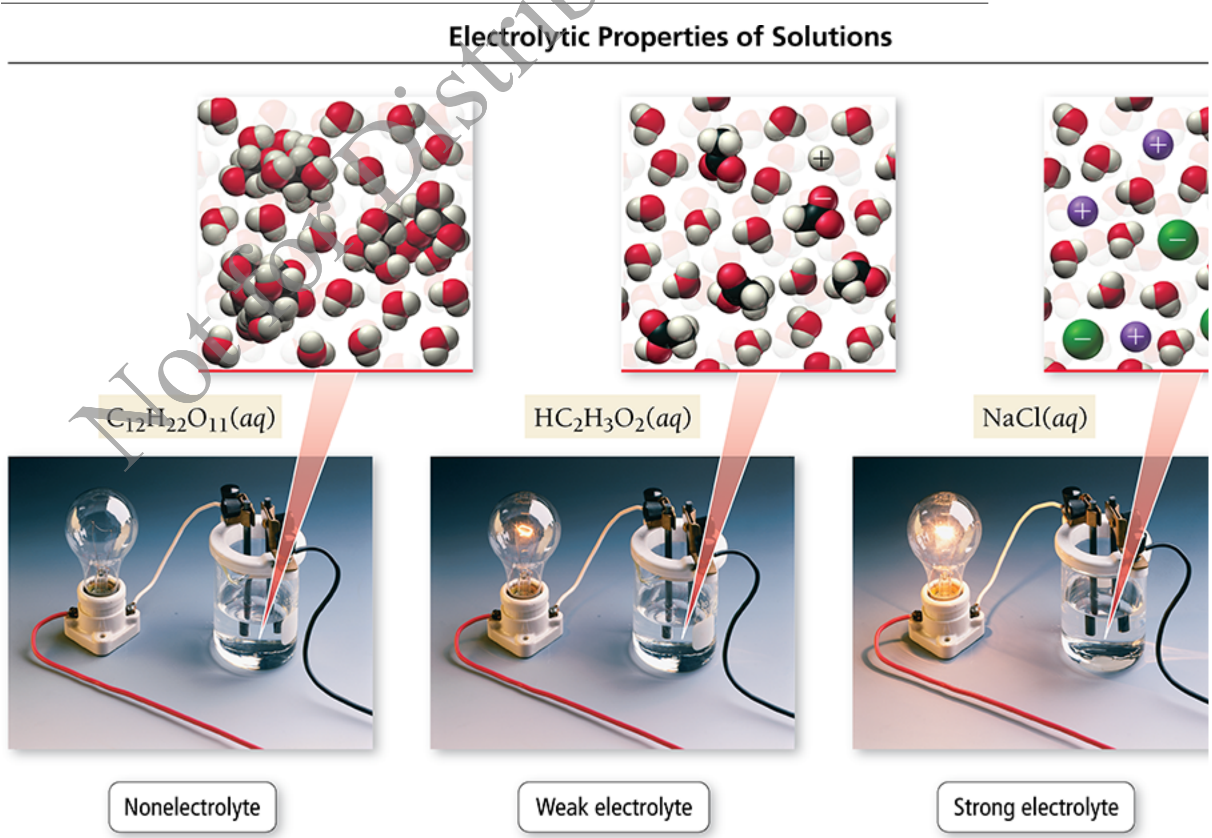


Many acids are **weak acids**; they do not completely ionize in water. For example, acetic acid ($HC_2H_3O_2$), the acid in vinegar, is a weak acid. A solution of a weak acid is composed mostly of the nonionized acid—only a small percentage of the acid molecules ionize. We represent the partial ionization of a weak acid with opposing half arrows between the reactants and products:

$$HC_2H_3O_2\,(aq) \rightleftharpoons H^+\,(aq) + C_2H_3O_2^-\,(aq)$$

Weak acids are **weak electrolytes**, and the resulting solutions—called *weak electrolyte solutions*—conduct electricity only weakly. Figure 8.12 summarizes the electrolytic properties of solutions.

Figure 8.12 Electrolytic Properties of Solutions

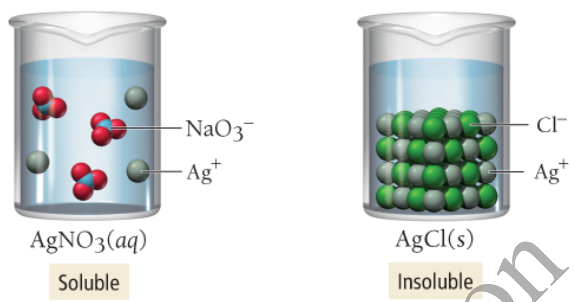


The Solubility of Ionic Compounds

As we have just discussed, when an ionic compound dissolves in water, the resulting solution contains, not the intact ionic compound itself, but its component ions dissolved in water. However, not all ionic compounds dissolve in water. If we add AgCl to water, for example, it remains solid and appears as a white powder at the bottom of the water.

In general, a compound is termed **soluble** if it dissolves in water and **insoluble** if it does not. However, these classifications are a bit of an oversimplification. In reality, solubility is a continuum and even "insoluble" compounds dissolve to some extent, though usually orders of magnitude less than soluble compounds. Nonetheless, this oversimplification is useful in allowing us to systematically categorize a large number of compounds. (See Karl Popper's quote at the beginning of this chapter.)

As an example, consider silver nitrate, which is soluble. If we mix solid $AgNO_3$ with water, it dissolves and forms a strong electrolyte solution. Silver chloride, on the other hand, is almost completely insoluble. If we mix solid AgCl with water, virtually all of it remains as a solid within the liquid water.



AgCl does not dissolve in water; it remains as a white powder at the bottom of the beaker.

Whether a particular compound is soluble or insoluble depends on several factors. In Section 13.3, we will examine more closely the energy changes associated with solution formation. For now, however, we can follow a set of empirical rules that chemists have inferred from observations on many ionic compounds. Table 8.1 summarizes these *solubility rules*.

Table 8.1 Solubility Rules for Ionic Compounds in Water

Compounds Containing the Following Ions Are Generally Soluble	Exceptions

Ions Are Generally Soluble	Exceptions
Li^+, Na^+, K^+, and NH_4^+	None
NO_3^- and $C_2H_3O_2^-$	None
Cl^-, Br^-, and I^-	When these ions pair with Ag^+, Hg_2^{2+}, or Pb^{2+}, the resulting compounds are insoluble.
SO_4^{2-}	When SO_4^{2-} pairs with Sr^{2+}, Ba^{2+}, Pb^{2+}, Ag^+, or Ca^{2+}, the resulting compound is insoluble.
Compounds Containing the Following Ions Are Generally Insoluble	**Exceptions**
OH^- and S^{2-}	When these ions pair with Li^+, Na^+, K^+, or NH_4^+, the resulting compounds are soluble.
	When S^{2-} pairs with Ca^{2+}, Sr^{2+}, or Ba^{2+}, the resulting compound is soluble.
	When OH^- pairs with Ca^{2+}, Sr^{2+}, or Ba^{2+}, the resulting compound is slightly soluble.
CO_3^{2-} and PO_4^{3-}	When these ions pair with Li^+, Na^+, K^+, or NH_4^+, the resulting compounds are soluble.

The solubility rules state that compounds containing the sodium ion are soluble. That means that compounds such as $NaBr$, $NaNO_3$, Na_2SO_4, $NaOH$, and Na_2CO_3 all dissolve in water to form strong electrolyte solutions. Similarly, the solubility rules state that compounds containing the NO_3^- ion are soluble. That means that compounds such as $AgNO_3$, $Pb(NO_3)_2$, $NaNO_3$, $Ca(NO_3)_2$, and $Sr(NO_3)_2$ all dissolve in water to form strong electrolyte solutions. Notice that when compounds containing polyatomic ions such as NO_3^- dissolve, the polyatomic ions remain as intact units.

The solubility rules also state that, with some exceptions, compounds containing the CO_3^{2-} ion are insoluble. Therefore, compounds such as $CuCO_3$, $CaCO_3$, $SrCO_3$, and $FeCO_3$ do not dissolve in water. Note that the solubility rules contain many exceptions. For example, compounds containing CO_3^{2-} *are* soluble when paired with Li^+, Na^+, K^+, or NH_4^+. Thus Li_2CO_3, Na_2CO_3, K_2CO_3, and $(NH_4)_2CO_3$ are all soluble.

Example 8.5 Predicting Ionic Compound Solubility

Predict whether each compound is soluble or insoluble.

a. $PbCl_2$
b. $CuCl_2$
c. $Ca(NO_3)_2$
d. $BaSO_4$

SOLUTION

a. Insoluble. Compounds containing Cl^- are normally soluble but Pb^{2+} is an exception.
b. Soluble. Compounds containing Cl^- are normally soluble and Cu^{2+} is not an exception.
c. Soluble. Compounds containing NO_3^- are always soluble.
d. Insoluble. Compounds containing SO_4^{2-} are normally soluble but Ba^{2+} is an exception.

FOR PRACTICE 8.5 Predict whether each compound is soluble or insoluble.

a. NiS
b. $Mg_3(PO_4)_2$
c. Li_2CO_3

d. NH_4Cl