

## 9.1.3: Aqueous Solutions and Solubility - Compounds Dissolved in Water

### Learning Objectives

- Know how to use solubility rules.

Water and other polar molecules are attracted to ions, as shown in Figure 9.1.3.2. The electrostatic attraction between an ion and a molecule with a dipole is called an ion-dipole attraction. These attractions play an important role in the dissolution of ionic compounds in water.

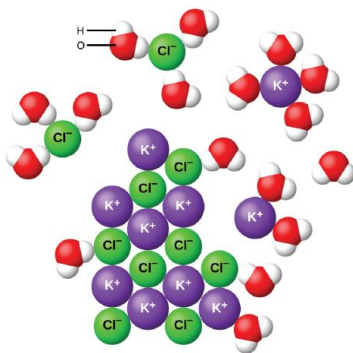


Figure 9.1.3.2: As potassium chloride (KCl) dissolves in water, the ions are hydrated. The polar water molecules are attracted by the charges on the  $K^+$  and  $Cl^-$  ions. Water molecules in front of and behind the ions are not shown.

When ionic compounds dissolve in water, the ions in the solid separate and disperse uniformly throughout the solution because water molecules surround and solvate the ions, reducing the strong electrostatic forces between them. This process represents a physical change known as dissociation. Under most conditions, ionic compounds will dissociate nearly completely when dissolved, and so they are classified as strong electrolytes.

Let us consider what happens at the microscopic level when we add solid KCl to water. Ion-dipole forces attract the positive (hydrogen) end of the polar water molecules to the negative chloride ions at the surface of the solid, and they attract the negative (oxygen) ends to the positive potassium ions. The water molecules penetrate between individual  $K^+$  and  $Cl^-$  ions and surround them, reducing the strong interionic forces that bind the ions together and letting them move off into solution as solvated ions, as Figure 9.1.3.2 shows. The reduction of the electrostatic attraction permits the independent motion of each hydrated ion in a dilute solution, resulting in an increase in the disorder of the system, as the ions change from their fixed and ordered positions in the crystal to mobile and much more disordered states in solution. This increased disorder is responsible for the dissolution of many ionic compounds, including KCl, which dissolve with absorption of heat.

In other cases, the electrostatic attractions between the ions in a crystal are so large, or the ion-dipole attractive forces between the ions and water molecules are so weak, that the increase in disorder cannot compensate for the energy required to separate the ions, and the crystal is insoluble. Such is the case for compounds such as calcium carbonate (limestone), calcium phosphate (the inorganic component of bone), and iron oxide (rust).

### Solubility Rules

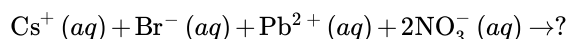
Some combinations of aqueous reactants result in the formation of a solid precipitate as a product. However, some combinations will not produce such a product. If solutions of sodium nitrate and ammonium chloride are mixed, no reaction occurs. One could write a molecular equation showing a double-replacement reaction, but both products, sodium chloride and ammonium nitrate, are soluble and would remain in the solution as ions. Every ion is a spectator ion and there is no net ionic equation at all. It is useful to be able to predict when a precipitate will occur in a reaction. To do so, you can use a set of guidelines called the **solubility rules** (Tables 9.1.3.1 and 9.1.3.2).

Table 9.1.3.1: Solubility Rules for Soluble Substances

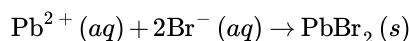
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Compounds containing these ions are generally soluble (aq)	... except combinations described below are insoluble (s)
Group 1 ( $\text{Li}^+$ , $\text{Na}^+$ , $\text{K}^+$ , etc.), $\text{NH}_4^+$	<b>Except</b> $\text{Li}^+$ is slightly soluble with $\text{CO}_3^{2-}$ , $\text{PO}_4^{3-}$ , and $\text{F}^-$ .
$\text{ClO}_4^-$ , $\text{ClO}_3^-$ , $\text{NO}_3^-$ , $\text{C}_2\text{H}_3\text{O}_2^- / \text{CH}_3\text{COO}^-$	None.
$\text{Cl}^-$ , $\text{Br}^-$ , $\text{I}^-$	<b>Except</b> for those containing $\text{Ag}^+$ , $\text{Hg}_2^{2+}$ , and $\text{Pb}^{2+}$ .
$\text{F}^-$	<b>Except</b> for those containing $\text{Mg}^{2+}$ , $\text{Ca}^{2+}$ , $\text{Sr}^{2+}$ , $\text{Ba}^{2+}$ , and $\text{Pb}^{2+}$ .
$\text{SO}_3^{2-}$ , $\text{SO}_4^{2-}$	<b>Except</b> for those containing $\text{Ca}^{2+}$ , $\text{Sr}^{2+}$ , $\text{Ba}^{2+}$ , $\text{Ag}^+$ , and $\text{Pb}^{2+}$ .
Compounds containing these ions are generally insoluble (s)	... except combinations described below are soluble (aq)
$\text{CO}_3^{2-}$ , $\text{PO}_4^{3-}$	<b>Except</b> those of Group 1 and $\text{NH}_4^+$ .
$\text{CrO}_4^{2-}$ , $\text{C}_2\text{O}_4^{2-}$	<b>Except</b> those of Group 1 and $\text{NH}_4^+$ .
$\text{O}^{2-}$ , $\text{S}^{2-}$	<b>Except</b> those of Group 1, $\text{NH}_4^+$ , $\text{Ca}^{2+}$ , $\text{Sr}^{2+}$ , and $\text{Ba}^{2+}$ .
$\text{OH}^-$	<b>Except</b> those of Group 1, $\text{NH}_4^+$ . <b>Except</b> $\text{OH}^-$ is slightly soluble with $\text{Ca}^{2+}$ , $\text{Sr}^{2+}$ , and $\text{Ba}^{2+}$ .

As an example on how to use the solubility rules, predict if a precipitate will form when solutions of cesium bromide and lead (II) nitrate are mixed.



The potential precipitates from a double-replacement reaction are cesium nitrate and lead (II) bromide. According to the solubility rules table, cesium nitrate is soluble because all compounds containing the nitrate ion, as well as all compounds containing the alkali metal ions, are soluble. Most compounds containing the bromide ion are soluble, but lead (II) is an exception. Therefore, the cesium and nitrate ions are spectator ions and the lead (II) bromide is a precipitate. The balanced net ionic reaction is:



#### ✓ Example 9.1.3.1: Solubility

Classify each compound as soluble or insoluble

- $\text{Zn}(\text{NO}_3)_2$
- $\text{PbBr}_2$
- $\text{Sr}_3(\text{PO}_4)_2$

#### Solution

- All nitrates are soluble in water, so  $\text{Zn}(\text{NO}_3)_2$  is soluble.
- All bromides are soluble in water, except those combined with  $\text{Pb}^{2+}$ , so  $\text{PbBr}_2$  is insoluble.
- All phosphates are insoluble, so  $\text{Sr}_3(\text{PO}_4)_2$  is insoluble.

#### ? Exercise 9.1.3.1: Solubility

Classify each compound as soluble or insoluble.

- $\text{Mg}(\text{OH})_2$
- $\text{KBr}$
- $\text{Pb}(\text{NO}_3)_2$

**Answer a**

insoluble

**Answer b**

soluble

**Answer c**

soluble

## Summary

Substances that dissolve in water to yield ions are called electrolytes. Nonelectrolytes are substances that do not produce ions when dissolved in water. Solubility rules allow prediction of what products will be insoluble in water.

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