11.3 Reactions in Aqueous Solution

Connecting to Your World

The beauty of a limestone cavern is the result of chemical reactions involving water. Limestone caverns form as calcium carbonate reacts with carbon dioxide dissolved in water and forms soluble calcium hydrogen carbonate. Additional carbon dioxide then converts the calcium hydrogen carbonate back into calcium carbonate. The calcium carbonate precipitates and forms dramatic stalactites and stalagmites. In this section, you will learn to predict the formation of precipitates and write equations to describe the reactions that produce them.

Net Ionic Equations

Your world is water-based. More than 70% of Earth’s surface is covered by water, and about 66% of the adult human body is water. It is not surprising, then, that many important chemical reactions take place in water—that is, in aqueous solution.

The reaction of aqueous solutions of silver nitrate with sodium chloride to form solid silver chloride and aqueous sodium nitrate is a double-replacement reaction. The reaction is shown in Figure 11.11.

\[
\text{AgNO}_3(aq) + \text{NaCl}(aq) \rightarrow \text{AgCl}(s) + \text{NaNO}_3(aq)
\]

This is the way you have been writing equations involving aqueous solutions of ionic compounds. However, the equation does not show that like most ionic compounds, the reactants and one of the products dissociate, or separate, into cations and anions when they dissolve in water. For example, when sodium chloride dissolves in water, it separates into sodium ions (Na\(^+\)(aq)) and chloride ions (Cl\(^-\)(aq)). Similarly, silver nitrate dissociates into silver ions (Ag\(^+\)(aq)) and nitrate ions (NO\(_3^\)(aq)). You can use these ions to write a complete ionic equation, an equation that shows dissolved ionic compounds as dissociated free ions.

\[
\text{Ag}^+(aq) + \text{NO}_3^-(aq) + \text{Na}^+(aq) + \text{Cl}^-(aq) \rightarrow \text{AgCl}(s) + \text{Na}^+(aq) + \text{NO}_3^-(aq)
\]

Notice that the nitrate ion and the sodium ion appear unchanged on both sides of the equation. The equation can be simplified by eliminating these ions because they don’t participate in the reaction.

\[
\text{Ag}^+(aq) + \text{NO}_3^-(aq) + \text{Na}^+(aq) + \text{Cl}^-(aq) \rightarrow \text{AgCl}(s) + \text{Na}^+(aq) + \text{NO}_3^-(aq)
\]
An ion that appears on both sides of an equation and is not directly involved in the reaction is called a spectator ion. When you rewrite an equation leaving out the spectator ions, you have the net ionic equation. The net ionic equation is an equation for a reaction in solution that shows only those particles that are directly involved in the chemical change.

\[ \text{Ag}^+ (aq) + \text{Cl}^- (aq) \rightarrow \text{AgCl}(s) \]

In writing balanced net ionic equations, you must make sure that the ionic charge is balanced. For the previous reaction, the net ionic charge on each side of the equation is zero and is therefore balanced. But consider the skeleton equation for the reaction of lead with silver nitrate.

\[ \text{Pb}(s) + \text{AgNO}_3(aq) \rightarrow \text{Ag}(s) + \text{Pb(NO}_3)_2(aq) \]

The nitrate ion is the spectator ion in this reaction. The net ionic equation is this.

\[ \text{Pb}(s) + \text{Ag}^+ (aq) \rightarrow \text{Ag}(s) + \text{Pb}^{2+} (aq) \quad \text{(unbalanced)} \]

Why is this equation unbalanced? Notice that a single unit of positive charge is on the reactant side of the equation. Two units of positive charge are on the product side. Placing the coefficient 2 in front of Ag\(^+\) (aq) balances the charge. A coefficient of 2 in front of Ag(s) rebalances the atoms.

\[ \text{Pb}(s) + 2\text{Ag}^+ (aq) \rightarrow 2\text{Ag}(s) + \text{Pb}^{2+} (aq) \quad \text{(balanced)} \]

A net ionic equation shows only those particles involved in the reaction and is balanced with respect to both mass and charge.

### Conceptual Problem 11.9

**Writing and Balancing Net Ionic Equations**

In the photograph, aqueous solutions of iron(III) chloride and potassium hydroxide are mixed. A precipitate of iron(III) hydroxide forms.

\[ \text{FeCl}_3(aq) + 3\text{KOH}(aq) \rightarrow \text{Fe(OH)}_3(s) + 3\text{KCl}(aq) \]

Write a balanced net ionic equation for the reaction.

**Practice Problems**

28. Write the balanced net ionic equation for this reaction.

\[ \text{Ca}^{2+} (aq) + \text{OH}^- (aq) + \text{H}^+ (aq) + \text{PO}_4^{3-} (aq) \rightarrow \text{Ca}_3(\text{PO}_4)_2(s) + \text{H}_2\text{O}(l) \]

29. Write the complete ionic equation and net ionic equation for the reaction of aqueous calcium hydroxide with phosphoric acid. The products are calcium phosphate and water.

### Word Origins

Spectator comes from the Latin verb spectare, meaning “to watch.” Thus a spectator ion can be thought of as only watching a reaction, not participating. During a football game, what analogy can you draw to the people in the seats and the football players on the field?

**Answers**

28. \( \text{OH}^- (aq) + \text{H}^+ (aq) \rightarrow \text{H}_2\text{O}(l) \)

29. complete ionic equation:

\[ 3\text{Ca}^{2+} (aq) + 6\text{OH}^- (aq) + 6\text{H}^+ (aq) + 2\text{PO}_4^{3-} (aq) \rightarrow \text{Ca}_3(\text{PO}_4)_2(s) + 6\text{H}_2\text{O}(l) \]

**Word Origins**

The spectators at a football game are present at the game, but they don’t participate in it.

**Relate**

If any students have visited underground caves such as Carlsbad Caverns, have them describe what they saw. Explain that the caverns form when carbonic acid dissolves the calcium carbonate (calcite) in limestone. The icicle-like deposits on the roof of the cavern are called stalactites. The deposits on the floor are called stalagmites. Both form when dissolved calcium carbonate precipitates from groundwater.

**Discuss**

Explain to students that a net ionic equation differentiates between ions that react to form a solid precipitate, a gas, or water, and ions that simply remain in aqueous solution. It is important to note, however, that spectator ions are not completely unaffected by the reaction. They end up paired with different anions or cations than they were paired with when the reaction began.
Predicting the Formation of a Precipitate

Discuss

On the board, write the products only of several double-replacement reactions; challenge students to fill in the reactants. Examples include: $\text{AgBr}(s) + \text{KNO}_3(aq) \rightarrow \text{BaSO}_4(s) + 2\text{NaCl}(aq)$, and $2\text{KCl}(aq) + \text{CaSO}_4(s). (\text{KBr}(aq) + \text{AgNO}_3(aq), \text{BaCl}_2(aq) + \text{Na}_2\text{SO}_4(aq), \text{and} \text{CaCl}_2(aq) + K_2\text{SO}_4(aq))$ Remind students that in a double-replacement reaction, the positive ions (cations) of one compound trade places with the positive ions of another compound.

### Assess

Evaluate Understanding

To evaluate students’ understanding of complete ionic equations, net ionic equations, and the formation of precipitates, write the reactants in some precipitation reactions on the board. Include at least one example for which no reaction occurs. Have students write complete and net ionic equations.

Re-Teach

Review with students the writing and balancing of complete and net ionic equations and the use of solubility rules to predict the outcome of double-replacement reactions. Stress that it is important to note the physical states of reactants and products in precipitation reactions.

### Elements Handbook

In the formation of limestone caves, calcium carbonate dissolves in carbonic acid (H$_2$CO$_3$). Another reaction occurs when stalagmites form: Ca$^{2+}(aq) + 2\text{HCO}_3^-(aq) \rightarrow \text{CaCO}_3(s) + \text{CO}_2(g) + \text{H}_2\text{O}(l)$

### Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 11.3.

---

### Table 11.3

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Solubility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salts of alkali metals and ammonia</td>
<td>Soluble</td>
</tr>
<tr>
<td>Nitrate salts and chloride salts</td>
<td>Soluble</td>
</tr>
<tr>
<td>Sulfate salts, except compounds</td>
<td>Soluble</td>
</tr>
<tr>
<td>with Pb$^{2+}$, Ag$^+$, Hg$^{2+}$, Sr$^{2+}$, and Ca$^{2+}$</td>
<td></td>
</tr>
<tr>
<td>Chloride salts, except compound</td>
<td>Soluble</td>
</tr>
<tr>
<td>with Ag$^+$, Pb$^{2+}$, and Hg$^{2+}$</td>
<td></td>
</tr>
<tr>
<td>Carbonates, phosphates,</td>
<td>Most are</td>
</tr>
<tr>
<td>sulfides, and hydroxides</td>
<td>insoluble</td>
</tr>
</tbody>
</table>

### Section 11.3 Assessment

#### 30. Key Concept
What is a net ionic equation?

#### 31. Key Concept
How can you predict the formation of a precipitate in a double-replacement reaction?

#### 32.
Write a balanced net ionic equation for each reaction.

- a. Pb(NO$_3$_2)(aq) + H$_2$SO$_4$(aq) $\rightarrow$ PbSO$_4$(s) + HNO$_3$(aq)
- b. Pb(C$_2$H$_3$O$_2$_2)(aq) + HCl(aq) $\rightarrow$ PbCl$_2$(s) + H$_2$C$_2$H$_3$O$_2$(aq)
- c. Na$_2$PO$_4$(aq) + FeCl$_3$(aq) $\rightarrow$ NaCl(aq) + FePO$_4$(s)
- d. (NH$_4$_)$_2$SO$_4$(aq) + Co(NO$_3$_3)(aq) $\rightarrow$ Co(SO$_4$_3) + NH$_4$NO$_3$(aq)

#### 33.
Write a balanced net ionic equation for each reaction.

- a. HCl(aq) + AgNO$_3$(aq) $\rightarrow$
- b. Pb(C$_2$H$_3$O$_2$_2)(aq) + LiCl(aq) $\rightarrow$
- c. Na$_2$PO$_4$(aq) + CrCl$_3$(aq) $\rightarrow$

#### 34.
Identify the precipitate formed when solutions of these ionic compounds are mixed.

- a. H$_2$SO$_4$ + BaCl$_2$
- b. Al$_2$(SO$_4$_3) + NH$_3$OH
- c. AgNO$_3$ + H$_2$S

#### 35.
Will a precipitate form when the following aqueous solutions of ionic compounds are mixed?

- a. AgNO$_3$ and Na$_2$SO$_4$
- b. NH$_4$Cl and Ba(NO$_3$_3)
- c. CaCl$_2$ and K$_2$SO$_4$
- d. Pb(NO$_3$_3) and HCl

#### 33.
A net ionic equation shows only those particles involved in the reaction and is balanced with respect to both mass and charge.

#### 31.
Use the general rules for solubility of ionic compounds (Table 11.3).

- a. Pb$^{2+}(aq) + SO_4^{2-}(aq) \rightarrow$ PbSO$_4(s)$
- b. Pb$^{2+}(aq) + 2Cl^- (aq) \rightarrow$ PbCl$_2(s)$
- c. Fe$^{3+}(aq) + PO_4^{3-}(aq) \rightarrow$ FePO$_4(s)$
- d. Co$^{2+}(aq) + S^{2-}(aq) \rightarrow$ CoS(s)

#### 34.
Identify the precipitate formed when solutions of these ionic compounds are mixed.

- a. Ag$^+(aq) + Cl^- (aq) \rightarrow$ AgCl(s); spectator ions are H$^+$(aq) and NO$_3^-(aq)$
- b. Pb$^{2+}(aq) + 2Cl^-(aq) \rightarrow$ PbCl$_2(s)$; spectator ions are Li$^+(aq)$ and C$_2$H$_3$O$_2^-(aq)$
- c. Cr$^{3+}(aq) + PO_4^{3-}(aq) \rightarrow$ CrPO$_4(s)$; spectator ions are Na$^+(aq)$ and Cl$^-(aq)$

#### 35.
Identify the precipitate formed when solutions of these ionic compounds are mixed.

- a. yes; Ag$_2$SO$_4(s)$
- b. no
- c. yes; CaSO$_4(s)$
- d. yes; PbCl$_2$
## Precipitation Reactions: Formation of Solids

### Purpose
To observe, identify, and write balanced equations for precipitation reactions.

### Materials
- pencil
- paper
- ruler
- reaction surface
- chemicals shown in the grid below

### Procedure
Copy the grid on two sheets of paper. Make each square grid space 2 cm on each side. Draw large black Xs on one of the grids. Place a reaction surface over the grid with black Xs and add the chemicals as shown. Use the other grid as a data table to record your observations for each solution.

### Analyze
Using your experimental data, record your answers to the following in the space below your data table.

### Expected Outcome
See below.

### Analyze

1. **You’re The Chemist**
   - **Objective**
   - **Preparation**
   - **Expected Outcome**

2. **Solution**
   - **Preparation**
   - **Analyse**
     - **You’re The Chemist**

3. **For Enrichment**
   - **Have students design and conduct an experiment to determine which soaps and detergents form the least amount of precipitate when added to “hard” water. (Soaps form precipitates; detergents do not.)**

4. **You’re The Chemist**
   - **1.**
   - **2.**
   - **3.**

5. **For Enrichment**
   - **Have students design and conduct an experiment to determine which soaps and detergents form the least amount of precipitate when added to “hard” water. (Soaps form precipitates; detergents do not.)**