Unit 7.2 Molecular, Ionic and Net ionic equations

"Just a little rain..." One of the unfortunate by-products of our industrialized society is acid rain. Sulfur dioxide from burning coal and nitric oxides from vehicle emissions both form acids. When these acids react with limestone (calcium carbonate), reactions occur that dissolve the limestone and release water and carbon dioxide. Over a period of time, serious damage is caused to the structures.

Molecular and Ionic Equations

When ionic compounds are dissolved into water, the polar water molecules break apart the solid crystal lattice, resulting in the hydrated ions being evenly distributed through the water. This process is called dissociation and is the reason that all ionic compounds are strong electrolytes.

When two different ionic compounds that have been dissolved in water are mixed, a chemical reaction may occur between certain pairs of the hydrated ions.

Consider the double-replacement reaction that occurs when a solution of sodium chloride is mixed with a solution of silver nitrate.

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

White silver chloride precipitate instantly forms when a solution of silver nitrate is added to a solution of sodium chloride.

This is called a molecular equation. A molecular equation is an equation in which the formulas of the compounds are written as though all substances exist as molecules.
However, there is a more accurate way to show what is happening in this reaction. All of the aqueous compounds should be written as ions because they are present in the water as separated ions because of their dissociation.

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

This equation is called an ionic equation, an equation in which dissolved ionic compounds are shown as free ions. Solids and liquids must remain written as molecules since they do not dissociate into ions.

If you look carefully at the ionic equation, you will notice that the sodium ion and the nitrate ion appear unchanged on both sides of the equation. When the two solutions are mixed, neither the Na\(^{+}\) nor the NO\(_3\)\(^{-}\) ions participate in the reaction. They can be eliminated from the reaction.

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

A spectator ion is an ion that does not take part in the chemical reaction and is found in solution both before and after the reaction. In the above reaction, the sodium ion and the nitrate ion are both spectator ions. The equation can now be written without the spectator ions.

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

The net ionic equation is the chemical equation that shows only those elements, compounds, and ions that are directly involved in the chemical reaction. Notice that in writing the net ionic equation, the positively-charged silver cation was written first on the reactant side, followed by the negatively-charged chloride anion. This is somewhat customary because that is the order in which the ions must be written in the silver chloride product. However, it is not absolutely necessary to order the reactants in this way.

Net ionic equations must be balanced by both mass and charge. To balance by mass means making sure that there are equal numbers of each element. To balance by charge means making sure that the overall charge is the same on both sides of the equation. In the above equation, the overall charge is zero, or neutral, on both sides of the equation. As a general rule, if you balance the molecular equation properly, the net ionic equation will end up being balanced by both mass and charge.

**Sample Problem: Writing and Balancing Net Ionic Equations**

When aqueous solutions of copper (II) chloride and potassium phosphate are mixed, a precipitate of copper (II) phosphate is formed. Write a balanced molecular, ionic, and net ionic equation.
**Step 1: Plan the problem.**

Using the ions, determine the formulas for each molecule.

Write and balance the molecular equation.

Write the ionic equation, showing all aqueous substances as ions. Determine which ions are spectator ions.

Write the net ionic equation.

**Step 2: Solve.**

Through process of elimination, the missing product compound is the combination of potassium and chloride ions.

Copper (II) chloride  
Potassium phosphate  
Copper (II) phosphate  
Potassium chloride  

\[
\begin{align*}
\text{Cu}^{2+} & \quad \text{Cl}^{-} \\
\text{K}^{+} & \quad \text{PO}_{4}^{3-} \\
\text{CuCl}_{2} & \quad \text{K}_{3}\text{PO}_{4} \quad \text{Crisscross} \\
\text{Cu}^{2+} & \quad \text{PO}_{4}^{3-} \\
\text{K}^{+} & \quad \text{Cl}^{-} \\
\text{Cu}_{3}(\text{PO}_{4})_{2} & \quad \text{KCl}
\end{align*}
\]

Write the molecular equation:

\[
\text{CuCl}_{2} (aq) + \text{K}_{3}\text{PO}_{4} (aq) \rightarrow \text{Cu}_{3}(\text{PO}_{4})_{2} (s) + \text{KCl} (aq)
\]

Balance the molecular equation:

\[
3 \text{CuCl}_{2} (aq) + 2 \text{K}_{3}\text{PO}_{4} (aq) \rightarrow 3 \text{Cu}_{3}(\text{PO}_{4})_{2} (s) + 6 \text{KCl} (aq)
\]

Write the ionic equation:

\[
\text{Cu}^{2+} (aq) + \text{Cu}^{+} (aq) + \text{K}^{+} (aq) + \text{PO}_{4}^{3-} (aq) \rightarrow \text{Cu}_{3}(\text{PO}_{4})_{2} (s) + \text{K}^{+} (aq) + \text{Cl}^{-} (aq)
\]

Balance the ionic equation to match the amount of each substance in the molecular equation.

\[
3 \text{Cu}^{2+} (aq) + 6 \text{Cl}^{-} (aq) + 6 \text{K}^{+} (aq) + 2 \text{PO}_{4}^{3-} (aq) \rightarrow \text{Cu}_{3}(\text{PO}_{4})_{2} (s) + 6 \text{K}^{+} (aq) + 6 \text{Cl}^{-} (aq)
\]

Eliminate the spectator ions:

\[
3 \text{Cu}^{2+} (aq) + 6 \text{Cl}^{-} (aq) + 6 \text{K}^{+} (aq) + 2 \text{PO}_{4}^{3-} (aq) \rightarrow \text{Cu}_{3}(\text{PO}_{4})_{2} (s) + 6 \text{K}^{+} (aq) + 6 \text{Cl}^{-} (aq)
\]
Write the net ionic equation:

$$3 \text{Cu}^{2+} + 2 \text{PO}_4^{3-} \rightarrow \text{Cu}_3(\text{PO}_4)_2$$

**Step 3: Think about your result**

For a precipitation reaction, the net ionic equation always shows the two ions that come together to form the precipitate. The equation is balanced by mass and charge.

Some other double-replacement reactions do not produce a precipitate as one of the products. The production of a gas and/or a molecular compound such as water may also drive the reaction. For example, consider the reaction of a solution of sodium carbonate with a solution of hydrochloric acid (HCl). The products of the reaction are aqueous sodium chloride, carbon dioxide, and water.

The balanced molecular equation is:

$$\text{Na}_2\text{CO}_3 + 2 \text{HCl} \rightarrow 2 \text{NaCl} + \text{CO}_2 + \text{H}_2\text{O}$$

The ionic equation is:

$$2 \text{Na}^+ + \text{CO}_3^{2-} + 2 \text{H}^+ + 2 \text{Cl}^- \rightarrow 2 \text{Na}^+ + 2 \text{Cl}^- + \text{CO}_2 + \text{H}_2\text{O}$$

The net ionic equation is:

$$\text{CO}_3^{2-} + 2 \text{H}^+ \rightarrow \text{CO}_2 + \text{H}_2\text{O}$$

A single-replacement reaction is one in which an element replaces another element in a compound. An element is either the solid, liquid, or gas state and is not an ion. The example below shows the reaction of solid magnesium metal with aqueous silver nitrate to form aqueous magnesium nitrate and silver metal.

Write the balanced molecular equation:

$$\text{Mg} + 2 \text{AgNO}_3 \rightarrow \text{Mg(NO}_3)_2 + 2 \text{Ag}$$

Write the balanced ionic equation:

$$\text{Mg} + 2 \text{Ag}^+ + 2 \text{NO}_3^- \rightarrow \text{Mg}^{2+} + 2 \text{NO}_3^- + 2 \text{Ag}$$
Write the balanced net ionic equation:

\[
\text{Mg} (s) + 2 \text{Ag}^{+} (aq) + \text{NO}_3^{-} (aq) \rightarrow \text{Mg}^{2+} (aq) + (\text{NO}_3)^{-} (aq) + 2 \text{Ag} (s)
\]

This type of single-replacement reaction is called a metal replacement. Other common categories of single-replacement reactions are hydrogen replacement and halogen replacement.

**Summary**

- **Molecular equation** is an equation in which the formulas of the compounds are written as though all substances exist as molecules.
- **Ionic equation** is an equation in which dissolved ionic compounds are shown as free ions. Solids and liquids must remain written as molecules since they do not dissociate into ions.
- **Net Ionic equation** is an equation that shows only those elements, compounds, and ions that are directly involved in the chemical reaction. Net ionic equations do not include spectator ions.
- **Spectator Ions** are found as both reactants and products.

**Review**

1. What do the small letters in ( ) after the compounds indicate?
2. Why is it important to show the state of each compound?
3. What do ionic equations tell us?
4. What does the term "spectator ion" mean?
5. What is the difference between a molecule, ionic, and net ionic equation?
6. Write the molecular, ionic, and net ionic equation for: Ammonium carbonate solution reacting with a solution of calcium chloride, making a precipitate

**Answers**

1. s = solid, l = liquid, g = gas, aq = aqueous meaning dissolved in water
2. In the ionic and net ionic equations, solids, liquids, and gases remain written as molecules.
3. Ionic equations show all species that exist as ions. Solids, liquids, and gases will remain as molecules.
4. Spectator ions exist in the solution, but do not react. They are found before and after the reaction as the ions.
5. Molecular equations show all species as if they exist as molecules. Ionic equations show all species that are aqueous as ions, while solids, liquids, and gases remain unchanged. Net ionic equations show only what is reacting, eliminating all spectator ions.

6. Write the molecular, ionic, and net ionic equation for:

Ammonium carbonate solution reacting with a solution of calcium chloride, making a precipitate

\[(\text{NH}_4)_2\text{CO}_3\text{(aq)} + \text{CaCl}_2\text{(aq)} \rightarrow \text{CaCO}_3\text{(s)} + 2 \text{NH}_4\text{Cl}\text{(aq)}\]

\[2\text{NH}_4^+\text{(aq)} + \text{CO}_3^{2-}\text{(aq)} + \text{Ca}^{2+}\text{(aq)} + 2\text{Cl}^-\text{(aq)} \rightarrow \text{CaCO}_3\text{(s)} + 2\text{NH}_4^+\text{(aq)} + 2\text{Cl}^-\text{(aq)}\]

\[\text{Ca}^{2+}\text{(aq)} + \text{CO}_3^{2-}\text{(aq)} \rightarrow \text{CaCO}_3\text{(s)}\]