Unit 6.3 Types of Chemical reactions

Most chemical reactions can be classified into one of five types of reactions. It depends on both the reactants used and the products formed. The possible chemical reactions are:

1. Combination Reaction or Synthesis Reaction
2. Decomposition Reaction
3. Single Replacement Reaction or Single Displacement Reaction
4. Double Replacement Reaction or Double Displacement Reaction
5. Combustion Reaction

Combination Reactions or Synthesis Reaction

A combination reaction is a reaction in which two or more substances combine to form a single new substance. Combination reactions can also be called synthesis reactions. The general form of a combination reaction is:

\[ A + B \rightarrow AB \]

One combination reaction is two elements combining to form a compound. Solid sodium metal (Na) reacts with chlorine gas (Cl\(_2\)) to produce solid sodium chloride (NaCl).

\[ 2 \text{Na} (s) + \text{Cl}_2 (g) \rightarrow 2 \text{NaCl} (s) \]

Notice that in order to write and balance the equation correctly, it is important to remember the seven elements that exist in nature as diatomic molecules. They are always written as H\(_2\), N\(_2\), O\(_2\), F\(_2\), Cl\(_2\), Br\(_2\), and I\(_2\).

One sort of combination reaction that occurs frequently is the reaction of an element with oxygen to form an oxide. Metals and nonmetals both react readily with oxygen under most conditions. Magnesium, (Mg) reacts rapidly and dramatically when heated, combining with oxygen (O\(_2\)) from the air to produce a fine powder of magnesium oxide (MgO).

\[ 2 \text{Mg} (s) + \text{O}_2 (g) \rightarrow 2 \text{MgO} (s) \]
Sulfur (S) reacts with oxygen (O\textsubscript{2}) in a combination reaction to form sulfur dioxide (SO\textsubscript{2}).

\[
\text{S} \text{(s)} + \text{O}_2 \text{(g)} \rightarrow \text{SO}_2 \text{(g)}
\]

When nonmetals react with one another, the product is a molecular compound. Often, the nonmetal reactants can combine in different ratios and produce different products. Sulfur (S) can also combine with oxygen (O\textsubscript{2}) to produce sulfur trioxide (SO\textsubscript{3}).

\[
2 \text{S} \text{(s)} + 3 \text{O}_2 \text{(g)} \rightarrow 2 \text{SO}_3 \text{(g)}
\]

Transition metals are capable of adopting multiple positive charges within their ionic compounds. Therefore, most transition metals are capable of forming different products in a combination reaction. Iron (Fe) reacts with oxygen (O\textsubscript{2}) to form both iron (II) oxide, (FeO, Ferrous oxide) and iron (III) oxide (Fe\textsubscript{2}O\textsubscript{3}, Ferric oxide).

\[
2 \text{Fe} \text{(s)} + \text{O}_2 \text{(g)} \rightarrow 2 \text{FeO} \text{(s)}
\]

\[
4 \text{Fe} \text{(s)} + 3 \text{O}_2 \text{(g)} \rightarrow 2 \text{Fe}_2\text{O}_3 \text{(s)}
\]
Sample Problem: Combination Reactions

Potassium is a very reactive alkali metal that must be stored under oil in order to prevent it from reacting with air. Write the balanced chemical equation for the combination reaction of potassium (K) with oxygen (O₂).

Step 1: Plan the problem

Make sure formulas of all reactants and products are correct before balancing the equation. Oxygen gas is a diatomic molecule. Potassium oxide is an ionic compound and so its formula is constructed by the crisscross method. Potassium as an ion becomes K⁺, while the oxide ion is O²⁻.

Step 2: Solve

Using Crisscross method, determine the formula for potassium oxide.

\[ K^+ \quad O^{\cdot-2} \quad K_2O \]

Step 3: Write the equation with reactants and products.

The skeleton (unbalanced) equation:

\[ K(s) \quad + \quad O_2(g) \quad \rightarrow \quad K_2O(s) \]

The equation is then easily balanced with coefficients.

\[ 4 \quad K(s) \quad + \quad O_2(g) \quad \rightarrow \quad 2 \quad K_2O(s) \]

Step 4: Think about your result.

Formulas are correct and the resulting combination reaction is balanced.
Combination reactions can also take place when an element reacts with a compound to form a new compound composed of a larger number of atoms. Carbon monoxide (CO) reacts with oxygen (O\textsubscript{2}) to form carbon dioxide (CO\textsubscript{2}) according to the equation:

\[ 2 \text{CO (g)} + \text{O}_2 (g) \rightarrow 2 \text{CO}_2 (g) \]

Two compounds may also react to form a more complex compound. A very common example is the reactions of oxides with water. Calcium oxide (CaO) reacts readily with water (H\textsubscript{2}O) to produce an aqueous solution of calcium hydroxide (Ca(OH)\textsubscript{2}). This reaction takes place when cement is made.

\[ \text{CaO (s)} + \text{H}_2\text{O (l)} \rightarrow \text{Ca(OH)}_2 (s) \]

This is also an example of a reaction that is exothermic. Heat is released as the reaction proceeds.

Sulfur trioxide (SO\textsubscript{3}) gas reacts with water (H\textsubscript{2}O) to form sulfuric acid (H\textsubscript{2}SO\textsubscript{4}). This is an unfortunately common reaction that occurs in the atmosphere in some places where oxides of sulfur are present as pollutants. The acid formed in the reaction falls to the ground as acid rain.

\[ \text{SO}_3 (g) + \text{H}_2\text{O (l)} \rightarrow \text{H}_2\text{SO}_4 (\text{l}) \]

This is an unfortunately common reaction that occurs in the atmosphere in some places where oxides of sulfur are present as pollutants. The acid formed in the reaction falls to the ground as acid rain.

Acid rain has severe consequences on both man-made objects and nature. Acid rain degrades marble statues like the one on the left. The trees in the forest on the right have been killed by acid rain.
Decomposition Reactions

A decomposition reaction is a reaction in which one compound breaks down into two or more simpler substances. The general form of a decomposition reaction is:

\[ AB \rightarrow A + B \]

Most decomposition reactions require an input of energy (endothermic) in the form of heat, light, or electricity.

Binary compounds are compounds composed of just two elements. The simplest kind of decomposition reaction is when a binary compound decomposes into its elements. Mercury (II) oxide (HgO), a red solid, decomposes when heated to produce mercury (Hg) and oxygen gas (O₂).

\[ 2 \text{HgO} \rightarrow 2 \text{Hg} + \text{O}_2 \]

Antoine Lavoisier is widely known as the “father of modern chemistry”. He was one of the first to study chemical reactions in detail. Lavoisier reacted mercury with oxygen to form mercuric oxide as part of his studies on the composition of the atmosphere. He was then able to show that the decomposition of mercuric oxide produced mercury and oxygen. The diagram above shows the apparatus used by Lavoisier to study the formation and decomposition of mercuric oxide.

A reaction is also considered to be a decomposition reaction even when one or more of the products are still compounds. A metal carbonate decomposes into a metal oxide and carbon dioxide gas. For example, calcium carbonate (CaCO₃) decomposes into calcium oxide (CaO) and carbon dioxide (CO₂).

\[ \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \]
Metal hydroxides decompose on heating to yield metal oxides and water. Sodium hydroxide (NaOH) decomposes to produce sodium oxide (Na₂O) and water (H₂O).

\[ 2 \text{NaOH} (s) \rightarrow \text{Na}_2\text{O} (s) + \text{H}_2\text{O} (g) \]

Some unstable acids decompose to produce nonmetal oxides and water. Carbonic acid (H₂CO₃) decomposes easily at room temperature into carbon dioxide (CO₂) and water (H₂O).

\[ \text{H}_2\text{CO}_3 (aq) \rightarrow \text{CO}_2 (g) + \text{H}_2\text{O} (l) \]

Carbonic acid is found in soft drinks. The gas coming out in the bubbles is CO₂.

**Sample Problem: Decomposition Reactions**

When an electric current is passed through pure water, it decomposes into its elements. Write a balanced equation for the decomposition of water.

**Step 1: Plan the problem**

Water is a binary compound composed of hydrogen and oxygen. The hydrogen (H₂) and oxygen (O₂) gases produced in the reaction are both diatomic molecules.

**Step 2: Solve**

The skeleton (unbalanced) equation:

\[ \text{H}_2\text{O} (l) \rightarrow \text{H}_2 (g) + \text{O}_2 (g) \]

Write as a balanced equation.

\[ 2 \text{H}_2\text{O} (l) \rightarrow 2 \text{H}_2 (g) + \text{O}_2 (g) \]

**Step 3: Think about your result.**

The products are elements and the equation is balanced.
Why is the silver dark? The cup shown to the left, provides an example of tarnish, a chemical reaction caused when silver metal reacts with hydrogen sulfide gas produced by some industrial processes or as a result of decaying animal or plant materials:

\[ 2 \text{Ag(s)} + \text{H}_2\text{S(g)} \rightarrow \text{Ag}_2\text{S(s)} + \text{H}_2(g) \]

The tarnish can be removed using a number of polishes, but the process also removes a small amount of silver along with the tarnish.

**Single-Replacement Reactions or Single Displacement Reaction**

A single-replacement reaction is a reaction in which one element replaces a similar element in a compound. The general form of a single-replacement or single-displacement reaction is:

\[ A + BC \rightarrow AC + B \]

In this general reaction, element A is a metal and replaces element B, also a metal, in the compound. When the element that is doing the replacing is a nonmetal, it must replace another nonmetal in a compound, and the general equation becomes:

\[ Y + XZ \rightarrow XY + Z \]

Y is a nonmetal and replaces the nonmetal Z in the compound with X.

**Metal Replacement**

Magnesium is a more reactive metal than copper. When a strip of magnesium metal is placed in an aqueous solution of copper (II) nitrate, the magnesium replaces the copper. The products of the reaction are aqueous magnesium nitrate and solid copper metal.

\[ \text{Mg(s)} + \text{Cu(NO}_3\text{)}_2 \text{aq) } \rightarrow \text{Mg(NO}_3\text{)}_2 \text{aq) } + \text{Cu(s)} \]

Many metals react easily with acids and when they do so, one of the products of the reaction is hydrogen gas. Zinc reacts with hydrochloric acid to produce aqueous zinc chloride and hydrogen.

\[ \text{Zn(s)} + 2 \text{HCl(aq) } \rightarrow \text{ZnCl}_2 \text{(aq) } + \text{H}_2(g) \]

In a hydrogen replacement reaction, the hydrogen in the acid is replaced by an active metal.
The element chlorine, a nonmetal, reacts with an aqueous solution of sodium bromide to produce aqueous sodium chloride and elemental bromine, another nonmetal.

\[
\text{Cl}_2 \text{(g)} + 2 \text{NaBr} \text{(aq)} \rightarrow 2 \text{NaCl} \text{(aq)} + \text{Br}_2 \text{(l)}
\]

These reactions release enough energy that the \( \text{H}_2 \text{(g)} \) ignites.

The reactivity of the halogen group (group 17) decreases from top to bottom within the group. Fluorine is the most reactive halogen, while iodine is the least. Since chlorine is above bromine, it is more reactive than bromine and can replace it in a halogen replacement reaction.

**Sample Problem: Single Replacement Reaction or Single Displacement Reaction**

When a copper wire is placed in a solution of silver nitrate, silver crystals appear and the copper goes into solution to form copper (II) nitrate.

**Step 1: Plan the problem**

Both silver nitrate and copper (II) nitrate are ionic compounds. Determine the formulas.

\[
2 \text{Na(s)} + 2 \text{H}_2\text{O(l)} \rightarrow 2 \text{NaOH(aq)} + \text{H}_2 \text{(g)}
\]

Some metals are so reactive that they are capable of replacing the hydrogen in water. The products of such a reaction are the metal hydroxide and hydrogen gas. All group 1 metals undergo this type of reaction. Sodium reacts vigorously with water to produce aqueous sodium hydroxide and hydrogen.

\[
2 \text{Na(s)} + 2 \text{H}_2\text{O(l)} \rightarrow 2 \text{NaOH(aq)} + \text{H}_2 \text{(g)}
\]

Notice that ( ) are used when more than one of a polyatomic ion is used.
Step 2: Solve

The skeleton (unbalanced) equation:

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

Write as a balanced equation.

\[ \text{Cu} (s) + 2 \text{AgNO}_3 (aq) \rightarrow 2 \text{Ag} (s) + \text{Cu(NO}_3)_2 (aq) \]

Step 3: Think about your result.

The products are elements and the equation is balanced.

Wanna trade? The practice of barter (trading one thing for another) has been in existence from the beginning of time. Items like chickens were bartered for newspapers. You have something I want, and I have something you want. So we trade and we each have something new. Some chemical reactions are like that. Compounds swap parts and you have new materials.

Double-Replacement Reactions or Double Displacement Reactions

A double-replacement reaction is a reaction in which the positive and negative ions of two ionic compounds exchange places to form two new compounds. These reactions usually occur with the reactant compounds dissolved in solution. The general form of a double-replacement or double-displacement reaction is:

\[ \text{AB} + \text{CD} \rightarrow \text{AD} + \text{CB} \]

In this reaction, A and C are positively-charged cations or metals, while B and D are negatively-charged anions or nonmetals. Double-replacement reactions generally occur between substances in aqueous solution. In order for a reaction to occur, one of the products is usually a solid precipitate, a gas, or a molecular compound such as water.
Formation of a Precipitate

A precipitate forms in a double-replacement reaction when the cations from one of the reactants combine with the anions from the other reactant to form an insoluble ionic compound. When aqueous solutions of potassium iodide and lead (II) nitrate are mixed, the following reaction occurs.

\[ 2 \text{KI}(aq) + \text{Pb(NO}_3\text{)}_2(aq) \rightarrow 2 \text{KNO}_3(aq) + \text{PbI}_2(s) \]

There are very strong attractive forces that occur between Pb\(^{2+}\) and I\(^{-}\) ions and the result is a brilliant yellow precipitate. The other product of the reaction, potassium nitrate, remains soluble.

Formation of a Gas

Some double-replacement reactions produce a gaseous product which then bubbles out of the solution and escapes into the air. When solutions of sodium sulfide and hydrochloric acid are mixed, the products of the reaction are aqueous sodium chloride and hydrogen sulfide gas.

\[ \text{Na}_2\text{S}(aq) + 2\text{HCl}(aq) \rightarrow 2\text{NaCl}(aq) + \text{H}_2\text{S}(g) \]

Formation of a Molecular Compound

Another kind of double-replacement reaction is one that produces a molecular compound as one of its products. Many examples in this category are reactions that produce water. When aqueous hydrochloric acid is reacted with aqueous sodium hydroxide, the products are aqueous sodium chloride and water.

\[ \text{HCl}(aq) + \text{NaOH}(aq) \rightarrow \text{NaCl}(aq) + \text{H}_2\text{O}(l) \]

Sample Problem: Double-Replacement Reactions

Write a complete and balanced chemical equation for the following double-replacement reactions. One product is indicated as a guide.

A. \[ \text{NaCN}(aq) + \text{HBr}(aq) \rightarrow \] (hydrogen cyanide gas is formed)

B. \[ (\text{NH}_4)_2\text{SO}_4(aq) + \text{Ba(NO}_3\text{)}_2(aq) \rightarrow \] (a precipitate of barium sulfate forms)
Step 1: Plan the problem

In A, the production of a gas drives the reaction.

In B, the production of a precipitate drives the reaction.

In both cases, use the ionic charges of both reactants to construct the correct formulas of the products.

Step 2: Solve

A. The cations of both reactants are +1 charged ions, while the anions are -1 charged ions.

\[
\begin{align*}
\text{Na}^{+} & \quad \text{Br}^{-} \\
\text{NaBr} & \\
\text{H}^{+} & \quad \text{CN}^{-} \\
\text{HCN} & \\
\end{align*}
\]

\[
\text{NaCN}_{(aq)} + \text{HBr}_{(aq)} \rightarrow \text{NaBr}_{(aq)} + \text{HCN}_{(g)}
\]

This equation is balanced as is!

B. Ammonium ion and nitrate ion are 1+ and 1− respectively, while barium and sulfate are 2+ and 2−. This must be taken into account when exchanging partners and writing the new formulas.

\[
\begin{align*}
\text{NH}_{4}^{+} & \quad \text{NO}_{3}^{-} \\
\text{NH}_4\text{NO}_3 & \\
\text{Ba}^{2+} & \quad \text{SO}_{4}^{2-} \\
\text{BaSO}_4 & \\
\end{align*}
\]

Remember that when writing formulas containing polyatomic ions, ( ) are used when using more than one of them, as in \((\text{NH}_4)_2\text{SO}_4\).

\[
\begin{align*}
(\text{NH}_4)_2\text{SO}_4_{(aq)} + \text{Ba(NO}_3)_2_{(aq)} & \rightarrow \text{NH}_4\text{NO}_3_{(aq)} + \text{BaSO}_4_{(s)}
\end{align*}
\]

Balance the equation:

\[
\begin{align*}
(\text{NH}_4)_2\text{SO}_4_{(aq)} + \text{Ba(NO}_3)_2_{(aq)} & \rightarrow 2\text{NH}_4\text{NO}_3_{(aq)} + \text{BaSO}_4_{(s)}
\end{align*}
\]
Step 3: Think about your result

Both are double-replacement reactions. All formulas are correct and the equations are balanced.

How do you cook the perfect marshmallow? Roasting marshmallows over an open fire is a favorite past-time for campers, outdoor cook-outs, and just gathering around a fire in the back yard. The trick is to get the marshmallow a nice golden brown without catching it on fire. Too often we are not successful and we see the marshmallow burning on the stick - a combustion reaction taking place right in front of us.

Combustion Reactions

A combustion reaction is a reaction in which a substance reacts with oxygen gas, releasing energy in the form of light and heat. Combustion reactions must involve $O_2$ as one reactant. Many combustion reactions occur with a hydrocarbon, a compound made up solely of carbon and hydrogen or a compound with carbon, hydrogen and oxygen. The products of the combustion of hydrocarbons are carbon dioxide and water.

$$C_xH_yO_z + O_2(g) \rightarrow CO_2(g) + H_2O(g)$$

Many hydrocarbons are used as fuel because their combustion releases very large amounts of heat energy. Propane ($C_3H_8$) is a gaseous hydrocarbon that is commonly used as the fuel source in gas grills.

$$C_3H_8(g) + 5 O_2(g) \rightarrow 3 CO_2(g) + 4 H_2O(g)$$

Notice that the fuel undergoing combustion is a hydrocarbon, containing only carbon and hydrogen.

The following is another combustion reaction showing a carbon, hydrogen, oxygen molecule combining with oxygen to produce carbon dioxide and water.

$$C_6H_{12}O_6(s) + 6 O_2(g) \rightarrow 6 CO_2(g) + 6 H_2O(g)$$
Practice Problem: Combustion Reactions

Ethanol can be used as a fuel source in an alcohol lamp. The formula for ethanol is $C_2H_5OH$. Write the balanced equation for the combustion of ethanol.

Step 1: Plan the problem

Ethanol and oxygen are the reactants. As with a hydrocarbon, the products of the combustion of an alcohol are carbon dioxide and water.

Step 2: Solve

Write the skeleton equation:

$$C_2H_5OH_{(l)} + O_2_{(g)} \rightarrow CO_2_{(g)} + H_2O_{(g)}$$

Balance the equation.

$$C_2H_5OH_{(l)} + 3O_2_{(g)} \rightarrow 2CO_2_{(g)} + 3H_2O_{(g)}$$

Step 3: Think about your result

Combustion reactions must have oxygen as a reactant. Note that the water that is produced is in the gas rather than the liquid state because of the high temperatures that accompany a combustion reaction.

Summary

- Combination reactions or synthesis reactions occur when two or more substances combine to form a new substance. $A + B \rightarrow AB$.
- Decomposition reactions begin with one large substance which breaks apart to form 2 or more smaller substances. $AB \rightarrow A + B$.
- Single replacement reactions or single displacement reactions occur in one of two ways:
  - A more active metal element replaces a less active metal in a compound.
    $A + BC \rightarrow AC + B$.
  - A more active nonmetal halogen replaces a less active nonmetal halogen in a compound.
    $X + YZ \rightarrow YX + Z$. 
Double replacement reactions or double displacement reactions are reactions in which the positive and negative ions of two ionic compounds exchange places to form two new compounds.

\[ AB + CD \rightarrow AD + CB \]

Products of double replacement reactions can include precipitate, gas, or molecular compounds.

Combustion reactions are defined as reactions in which a hydrocarbon, a hydrogen and carbon molecule or a hydrogen, carbon, oxygen molecule combines with oxygen to produce carbon dioxide and water.

\[ C_xH_yO_z + O_{2(g)} \rightarrow CO_{2(g)} + H_2O_{(g)} \]

**Review**

1. What are combination reactions?
2. What is a decomposition reaction?
3. What is usually needed for a decomposition reaction to take place?
4. What is a single replacement reaction?
5. Will a nonmetal replace a metal in a single replacement reaction?
6. What are the usual reactants in a double-replacement reaction?
7. What are the products of any combustion reaction involving a hydrocarbon?
8. List three types of products possible from a double-replacement reaction.
9. What type of reaction is each of the following?
   a. \[ H_2SO_4_{(aq)} \rightarrow H_2O_{(l)} + SO_3_{(g)} \]
   b. \[ 2 C_2H_2_{(g)} + 5 O_2_{(g)} \rightarrow 4 CO_{2(g)} + 2 H_2O_{(g)} \]
   c. \[ Ca(OH)_{2(aq)} + 2 HCl_{(aq)} \rightarrow CaCl_2_{(aq)} + 2 H_2O_{(l)} \]
   d. \[ 2 K_{(s)} + 2 H_2O_{(l)} \rightarrow 2 KOH_{(aq)} + H_2_{(g)} \]
   e. \[ 2 Mg_{(s)} + O_2_{(g)} \rightarrow 2 MgO_{(s)} \]

**Answers**

1. A **combination reaction** is a reaction in which two or more substances combine to form a single new substance.
2. A **decomposition reaction** is a reaction in which one compound breaks down into two or more simpler substances.
3. Most decomposition reactions require an input of energy (endothermic) in the form of heat, light, or electricity.
4. A **single-replacement reaction** is a reaction in which one element replaces a similar element in a compound.
5. No. A more active metal will replace a less active metal, or a more active nonmetal will replace a less active nonmetal.

6. Compounds that are dissolved in solution.

7. Carbon dioxide (CO$_2$) and water (H$_2$O).

8. Double replacement reaction products may be precipitates, liquids or gases.

9. What type of reaction is each of the following?
   a. Decomposition reaction $\text{H}_2\text{SO}_4{}_{\text{aq}} \rightarrow \text{H}_2\text{O}{}_{\text{l}} + \text{SO}_3{}_{\text{g}}$
   b. Combustion reaction $2\text{C}_2\text{H}_2{}_{\text{g}} + 5\text{O}_2{}_{\text{g}} \rightarrow 4\text{CO}_2{}_{\text{g}} + 2\text{H}_2\text{O}{}_{\text{g}}$
   c. Double replacement reaction $\text{Ca(OH)}_2{}_{\text{aq}} + 2\text{HCl}{}_{\text{aq}} \rightarrow \text{CaCl}_2{}_{\text{aq}} + 2\text{H}_2\text{O}{}_{\text{l}}$
   d. Single replacement reaction $2\text{K}{}_{\text{s}} + 2\text{H}_2\text{O}{}_{\text{l}} \rightarrow 2\text{KOH}{}_{\text{aq}} + \text{H}_2{}_{\text{g}}$
   e. Combination reaction $2\text{Mg}{}_{\text{s}} + \text{O}_2{}_{\text{g}} \rightarrow 2\text{MgO}{}_{\text{s}}$