7.5: Classifying Chemical Reactions

Learning Objectives

- Classify a chemical reaction as a synthesis, decomposition, combustion, single replacement, double replacement reaction.
- Predict the products of simple reactions.

There are an infinite number of chemical reactions that are possible. How do chemists cope with this overwhelming diversity? How do they predict which compounds will react with one another and what products will be formed? The key to success is to find useful ways to categorize reactions. Familiarity with a few basic types of reactions will help you to predict the products that form when certain kinds of compounds or elements come in contact.

Many chemical reactions may be classified into one or more of five basic types: combination (or synthesis), decomposition, combustion, single replacement, and double replacement. It is important to note, however, that many reactions may classified in more than one way.

Combination Reactions

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

$$A + B \rightarrow AB$$

One type 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 reacts rapidly and dramatically when ignited, combining with oxygen from the air to produce a fine powder of magnesium oxide:

$$2\ Mg\ (s) + O_2\ (g) \rightarrow 2\ MgO\ (s)$$

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 (H_2, N_2, O_2, F_2, Cl_2, Br_2, and I_2). 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 can also combine with oxygen to form either sulfur dioxide or sulfur trioxide:

$$S\ (s) + O_2\ (g) \rightarrow SO_2\ (g)$$

$$2\ S\ (s) + 3\ O_2\ (g) \rightarrow 2\ SO_3\ (g)$$

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 reacts with oxygen to form both iron(II) oxide and iron(III) oxide:

$$2\ Fe\ (s) + O_2\ (g) \rightarrow 2\ FeO\ (s)$$

$$4\ Fe\ (s) + 3\ O_2\ (g) \rightarrow 2\ Fe_2O_3\ (s)$$

Combination reactions can also take place when two compounds react to form a more complex compound. A very common example is the reactions of oxides with water. Calcium oxide reacts readily with water to produce an aqueous solution of calcium hydroxide:

$$CaO\ (s) + H_2O\ (l) \rightarrow Ca(OH)_2\ (aq)$$

Sulfur trioxide gas reacts with water to form sulfuric acid. 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.

$$H_2O\ (l) + SO_3\ (g) \rightarrow H_2SO_4\ (aq)$$

Figure 7.5.1: Acid rain has severe consequences on both natural and manmade objects. The trees in the forest on the left have been killed by acid rain. Acid rain also degrades marble statues like the one on the right. (OpenStax, CC BY 4.0, via Wikimedia Commons)

Decomposition Reactions

A **decomposition reaction** is a reaction in which a 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 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, a red solid, decomposes when heated to produce mercury and oxygen gas:

$$2\ HgO\ (s) \rightarrow 2\ Hg\ (l) + O_2\ (g)$$

Video 7.5.1: Mercury(II) oxide is a red solid. When it is heated, it decomposes into mercury metal and oxygen gas.

A reaction is also considered to be a decomposition reaction even when one or more of the products are still compounds. For example, calcium carbonate decomposes into calcium oxide and carbon dioxide. Carbonic acid decomposes easily at room temperature into carbon dioxide and water:

$$CaCO_3\ (s) \rightarrow CaO\ (s) + CO_2\ (g)$$

$$H_2CO_3\ (aq) \rightarrow CO_2\ (g) + H_2O\ (l)$$

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. The products of a combustion reaction depend on the substance being burned. If the substance being burned contains carbon, one of the products will be carbon dioxide. If the substance being burned contains hydrogen, one of the products will be water. If the substance contains sulfur, one of the products will be sulfur dioxide.

The primary component of natural gas is methane, CH_4. The complete combustion of methane yields carbon dioxide and water:

$$CH_4\,(g) + 2\,O_2\,(g) \rightarrow CO_2\,(g) + 2\,H_2O\,(g)$$

When the supply of oxygen becomes limited, incomplete combustion typically occurs causing carbon monoxide, CO, to be produced in addition to carbon dioxide. In this text, complete combustion will always be assumed to occur unless otherwise specified. Combustion reactions are covered more extensively in Section 7.6.

Single Replacement Reactions

A third type of reaction is the single replacement reaction, in which one element replaces a similar element in a compound. One general form of a single-replacement reaction (also called a single-displacement reaction) is:

$$AB + C \rightarrow CB + A$$

In this general reaction, element C is a metal and replaces element A, also a metal, in the compound AB. One example is when a copper wire is placed into an aqueous solution of silver nitrate (see Figure 7.5.2 below). Silver leaves the solution forming crystals of silver metal, while copper metal goes into solution yielding the characteristic blue color of an aqueous copper(II) nitrate solution.

$$2\,AgNO_3\,(aq) + Cu\,(s) \rightarrow Cu(NO_3)_2\,(aq) + 2\,Ag\,(s)$$

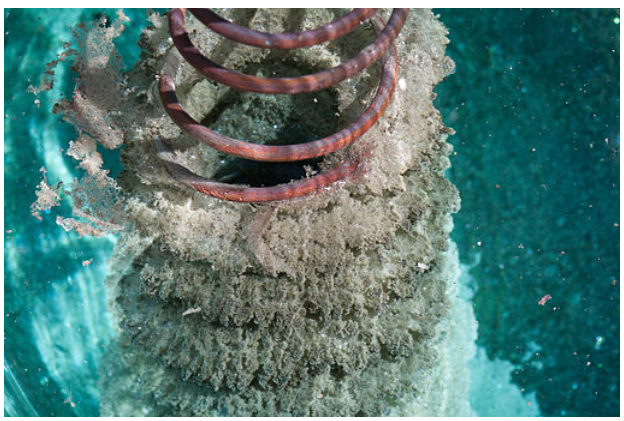

Figure 7.5.2: Crystals of silver metal form on a coil of copper wire that has been immersed into an aqueous solution of silver nitrate. The solution becomes progressively darker bluish-green as copper metal goes into solution forming copper(II) nitrate. (Tony Hudson via Wikipedia)

When the element that is doing the replacing is a nonmetal, it must replace another nonmetal in a compound, and the general equation becomes:

$$AB + C \rightarrow AC + B$$

where C is a nonmetal and replaces the nonmetal B in the compound AB. One example is when an aqueous solution of sodium bromide reacts with the element chlorine to produce aqueous sodium chloride and elemental bromine:

$$2\,NaBr\,(aq) + Cl_2\,(g) \rightarrow 2\,NaCl\,(aq) + Br_2\,(l)$$

The reactivity of the halogens (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.

Double Replacement Reactions

A **double-replacement reaction** (also called double-displacement reaction) is a reaction in which the positive and negative ions of two ionic compounds exchange places to form two new compounds. The general form of a double-replacement reaction is:

$$AB + CD \rightarrow AD + CB$$

In this reaction, A and C represent positively-charged cations, while B and D represent negatively-charged anions. 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.

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 lead(II) nitrate and potassium iodide are mixed, the following reaction occurs:

$$Pb(NO_3)_2\ (aq) + 2\ KI\ (aq) \rightarrow PbI_2\ (s) + 2\ KNO_3\ (aq)$$

There are very strong attractive forces that occur between Pb^{2+} and I^- ions and the result is a brilliant yellow precipitate (Figure 7.5.3). The other product of the reaction, potassium nitrate, remains soluble.

Figure 7.5.3: Lead(II) iodide precipitates when potassium iodide is mixed with lead(II) nitrate. (CC BY-SA 3.0; PRHaney).

Determining the products of precipitation reactions and predicting whether or not a precipitation reaction occurs is discussed more extensively in Section 7.8.

Table 7.5.1: A Summary of Chemical Reaction Classification

Name of Reaction	General Form	Examples
1. Combination (Synthesis)	$A + B \rightarrow AB$	$N_2\ (g) + 2\ O_2\ (g) \rightarrow 2\ NO_2\ (g)$ $CO_2\ (g) + H_2O\ (l) \rightarrow H_2CO_3\ (aq)$
2. Decomposition	$AB \rightarrow A + B$	$CaCO_3\ (s) \rightarrow CaO\ (s) + CO_2\ (g)$
3. Combustion	burning in the presence of $O_2\ (g)$	$C_7H_{16}\ (l) + 11\ O_2\ (g) \rightarrow 7\ CO_2\ (g) + 8\ H_2O\ (g)$
4. Single Replacement	$AB + C \rightarrow CB + A$ $AB + C \rightarrow AC + B$	$ZnCl_2\ (aq) + Mg\ (s) \rightarrow MgCl_2\ (aq) + Zn\ (s)$ $2\ KI\ (aq) + Cl_2\ (aq) \rightarrow 2\ KCl\ (aq) + I_2\ (aq)$
5. Double Replacement	$AB + CD \rightarrow AD + CB$	$BaCl_2\ (aq) + Na_2SO_4\ (aq) \rightarrow BaSO_4\ (s) + 2\ NaCl\ (aq)$

The classification scheme is by no means complete. Other reaction classifications include oxidation-reduction reactions (also called redox reactions), acid-base reactions, and condensation reactions, to name a few. In this text, determining the products of combustion reactions and double replacement reacts (specifically precipitation reactions) will be most emphasized. These reactions are covered in the next few sections.

✏️ Exercise 7.5.1

Classify the following reactions as combination, decomposition, combustion, single replacement, or double replacement.

A. $\mathrm{Mg}(s) + \mathrm{Cu(NO_3)_2}(aq) \rightarrow \mathrm{Mg(NO_3)_2}(aq) + \mathrm{Cu}(s)$
B. $4\ \mathrm{V}\ (s)\ +\ 5\ \mathrm{O_2}\ (g)\ \rightarrow\ 2\ \mathrm{V_2O_5}\ (s)$
C. $\mathrm{(NH_4)_2SO_4}\ (aq)\ +\ \mathrm{Ba(NO_3)_2}\ (aq)\ \rightarrow\ \mathrm{BaSO_4}\ (s)\ +\ 2\ \mathrm{NH_4NO_3}\ (aq)$
D. $\mathrm{C_6H_{12}O_6}\ (s)\ +\ 6\ \mathrm{O_2}\ (g)\ \rightarrow\ 6\ \mathrm{CO_2}\ (s)\ +\ 6\ \mathrm{H_2O}\ (l)$
E. $2\ \mathrm{H_2O_2}\ (aq)\ \xrightarrow{\mathrm{MnO_2}}\ 2\ \mathrm{H_2O}\ (l)\ +\ \mathrm{O_2}\ (g)$

Answer A

single replacement

Answer B

combination

Answer C

double replacement

Answer D

combustion

Answer E

decomposition

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