5.6: Kinds of Chemical Reactions

It is useful to place chemical reactions in various categories. The important categories of chemical reactions are addressed here.

The simplest kind of chemical reaction to visualize is a **combination reaction** in which two substances come together to form a new substance. The substances may be two elements, two compounds, or an element and a compound. An example of a combination reaction occurs when elemental carbon burns,

$$\mathrm{C + O_2 \rightarrow CO_2} \tag{5.6.1}$$

to produce carbon dioxide. Since this reaction generates only one product, it occurs with 100% atom economy. Another combination reaction occurs when calcium oxide, CaO, present in a bed of solid material in a fluidized bed furnace used to burn coal reacts with sulfur dioxide:

$$\mathrm{CaO + SO_2 \rightarrow CaSO_3} \tag{5.6.2}$$

The sulfur dioxide is a potential air pollutant produced from the burning of sulfur present in the coal. By injecting pulverized coal into a bed of CaO and other minerals kept in a fluid-like state by the injection of air, the sulfur dioxide produced has the opportunity to react with CaO and is not emitted as a pollutant with the stack gas.

In addition to being a combination reaction, the reaction above could also be called an **addition reaction** because the SO_2 adds to the CaO. Addition reactions are very desirable in the practice of green chemistry because they are 100% atom economical.

The opposite of a combination reaction is a **decomposition reaction**. An example of such a reaction occurs when a direct electrical current is passed between two electrodes through water to which a salt such as Na_2SO_4 has been added to make a solution in the water that is electrically conducting:

$$\mathrm{2\,H_2O(l) \xrightarrow{Electrolysis} 2\,H_2(g) + O_2(g)} \tag{5.6.3}$$

Reactions such as this that occur by the action of electricity passed through a solution are called **electrolysis** reactions. As written, the reaction is 100% atom economical. However, some side reactions may occur that reduce the efficiency. For example, impurity chloride ion, Cl^-, must be avoided in solution because it can produce some Cl_2 gas, a toxic, undesirable byproduct. Another inefficiency occurs because not all of the electricity passed through the solution is utilized to decompose water.

An example of a useful decomposition reaction is the high-temperature decomposition of methane,

$$\mathrm{CH_4(g) \xrightarrow{\Delta} C(s) + 2\,H_2(g)} \tag{5.6.4}$$

to produce elemental C and H_2 gas (where the triangle over the arrow shows that heat is applied —in this case to a temperature of 1260–1425°C — to make the reaction occur). The elemental carbon from this reaction is generated as a fine powder called **carbon black**. Carbon black is an ingredient of the paste in dry cells (such as those used in portable electronic devices); it is used as a filler in tires and to make electrodes for electrolysis processes such as the one by which aluminum metal is prepared.

Decomposition reactions do not always produce elements. For example, sodium bicarbonate mineral, $NaHCO_3$ may be heated,

$$\mathrm{2\,NaHCO_3(s) \xrightarrow{\Delta} Na_2CO_3(s) + CO_2(g) + H_2O(g)} \tag{5.6.5}$$

to produce sodium carbonate, Na_2CO_3, commonly used as an industrial chemical to treat water, in cleaning solutions, and as an ingredient of glass.

> **Example:** Using atomic masses Na 23.0, H 1.0, C 12.0, and O 16.0, calculate the percent atom economy of the above reaction for the production of Na_2CO_3.
>
> *Answer:* When 2 formula units of $NaHCO_3$ react, 1 formula unit of Na_2CO_3 is produced. The masses involved in atomic mass units, u, are the following:
>
> $\text{Mass } 2\mathrm{NaHCO_3} = 2 \times (23.0 + 1.0 + 12.0 + 3 \times 16.0) = 168 \text{ u}$
>
> $Na_2CO_3 = 2 \times 23.0 + 12.0 + 3 \times 16.0 = 106 \text{ u}$
>
> $\text{Percent atom economy} = \frac{160 \text{ u}}{168 \text{ u}} \times 100 = 63.1\%$

A **substitution** or **replacement** reaction is one such as the reaction of iron and sulfuric acid,

$$\mathrm{Fe(s) + H_2SO_4(aq) \rightarrow H_2(g) + FeSO_4(aq)} \tag{5.6.6}$$

in which Fe replaces H in H_2SO_4, a reaction shown earlier for the preparation of $FeSO_4$. This reaction also falls under the classification of reactions involving **evolution of a gas**, in this case evolution of hydrogen gas. A **double replacement** reaction, also called a **metathesis** reaction, is one in which two compounds trade ions or other groups. When dissolved calcium chloride reacts with dissolved sodium carbonate,

$$\mathrm{CaCl_2(aq) + Na_2CO_3(aq) \rightarrow CaCO_3(s) + 2\,NaCl(aq)} \tag{5.6.7}$$

the Ca^{2+} ion in calcium chloride simply switches places with the Na^+ ions in the sodium carbonate to produce solid calcium carbonate and NaCl in solution. This is also a **precipitation** reaction in which a solid material forms from two substances dissolved in water; the solid formed is a **precipitate**. The removal of calcium from water as shown by this reaction is a common water treatment process called **water softening**. It is done because excessive levels of calcium cause formation of scale that can clog water pipes and damage plumbing apparatus. Whenever an acid and a base react, as shown here for the reaction of hydrochloric acid with sodium hydroxide,

$$\mathrm{HCl(aq) + NaOH(aq) \rightarrow H_2O(l) + NaCl(aq)} \tag{5.6.8}$$

water and a salt are formed. Such a reaction is a **neutralization reaction** or simply an **acid-base** reaction.

> **Exercise:** Classify each of the following reactions as combination, decomposition, substitution, metathesis, neutralization, precipitation, or evolution of a gas. In some cases, a reaction will fit into more than one category.
>
> (a) $ce2Ca(s) + O2(g) \rightarrow 2CaO(s)$
>
> (b) $\mathrm{2\,KClO_3(s) \xrightarrow{\Delta} 2\,KCl(s) + 3\,O_2(g)}$
>
> (c) $\mathrm{SO_3(g) + H_2O(l) \rightarrow H_2SO_4(aq)}$
>
> (d) $\mathrm{MgCO_3(s) + 2\,HCl(aq) \rightarrow MgCl_2(aq) + H_2O(l) + CO_2(g)}$
>
> (e) $\mathrm{Zn(s) + CuCl_2(aq) \rightarrow Cu(s) + ZnCl_2(aq)}$
>
> (f) $\mathrm{KOH(aq) + Hcl(aq) \rightarrow KCl(aq) + H_2O(l)}$
>
> (g) $\mathrm{MgSO_4(aq) + 2\,KOH(aq) \rightarrow Mg(OH)_2(s) + K_2SO_4(aq)}$
>
> *Answers:* (a) Combination, (b) decomposition, evolution of a gas, (c) combination, (d)metathesis, evolution of a gas, (e) substitution, (f) neutralization, metathesis, (g) precipitation, metathesis