Chemical Reactions

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CHAPTER 1 Chemical Reactions

CHAPTER OUTLINE

Chemical reactions can be recognized by careful observations. The production of a precipitate, a color change, evolution of a gas, or a transfer of energy are all clues that a chemical change is occurring. In the picture above, a copper sheet has been placed into a colorless solution of silver nitrate. The reaction slowly produces silver metal, which clings to the surface of the copper sheet. The other product of the reaction is aqueous copper(II) nitrate, which is blue in color. In this chapter, we begin to advance beyond simply recognizing chemical reactions by writing chemical equations that describe how the reactants in a given reaction are converted into products. Classifying chemical reactions into several distinctive categories will aid you in predicting the products of many different chemical reactions.

1.1 Chemical Equations

Lesson Objectives

- Describe chemical reactions using word equations.
- Know the correct symbols to use in order to write skeleton equations for chemical reactions.
- Use coefficients to balance chemical equations so that the law of conservation of mass is followed.

Lesson Vocabulary

- balanced equation
- chemical equation
- coefficient
- skeleton equation

Check Your Understanding

Recalling Prior Knowledge

- What kinds of observations indicate that a chemical reaction may be occurring?
- What are chemical reactions according to the principles detailed by John Dalton?
- What are reactants and products?
- What is the law of conservation of mass?

Writing Chemical Equations

Chemical reactions are occurring all around you. Plants use sunlight to drive their photosynthetic process and produce energy. Cars and other vehicles burn gasoline in order to power their engines. Batteries use electrochemical reactions to produce energy and power many everyday devices. Many chemical reactions are going on inside you as well, especially during the digestion of food.

In math class, you have written and solved many mathematical equations. Chemists keep track of chemical reactions by writing equations as well. In any chemical reaction one or more substances, called reactants, are converted into one or more new substances, called products. The general form of the equation for such a process looks like this.

$$\text{Reactants} \rightarrow \text{Products}$$

Unlike in a math equation, a chemical equation does not use an equal sign. Instead the arrow is called a yield sign and so the equation is described as "reactants yield products."

Word Equations

You can describe a chemical reaction by writing a word equation. When silver metal is exposed to sulfur it reacts to form silver sulfide. Silver sulfide is commonly known as tarnish and turns the surface of silver objects dark and streaky black (**Figure** 1.1). The sulfur that contributes to tarnish can come from traces of sulfur in the air or from food such as eggs. The word equation for the process is:

Silver + sulfur $\rightarrow$ Silver sulfide

The silver and the sulfur are the reactants in the equation, while the silver sulfide is the product.

FIGURE 1.1
The coffee percolator on the left has been tarnished from exposure to sulfur. Tarnish is the chemical compound silver sulfide. The same percolator on the right has been polished with a tarnish removal product in order to restore its silver finish.

Another common chemical reaction is the burning of methane gas. Methane is the major component of natural gas and is commonly burned on a gas stove or in a Bunsen burner (**Figure** 1.2). Burning is a chemical reaction in which some type of fuel is reacted with oxygen gas. The products of the reaction in the burning of methane as well as other fuels are carbon dioxide and water. The word equation for this reaction is:

Methane + oxygen $\rightarrow$ carbon dioxide + water

FIGURE 1.2
A Bunsen burner is commonly used to heat substances in a chemistry lab. Methane is reacted with oxygen to form carbon dioxide and water.

Chemical Equations

Word equations are time-consuming to write and will not prove to be convenient for many of the things that chemists need to do with equations. A **chemical equation** *is a representation of a chemical reaction that displays the reactants and products with chemical formulas*. The chemical equation for the reaction of methane with oxygen is shown:

$$CH_4 + O_2 \rightarrow CO_2 + H_2O$$

The equation above, called a **skeleton equation**, *is an equation that shows only the formulas of the reactants and products with nothing to indicate the relative amounts*. The first step in writing an accurate chemical equation is to write the skeleton equation, making sure that the formulas of all substances involved are written correctly. All reactants are written to the left of the yield arrow, separated from one another by a plus sign. Likewise, products are written to the right of the yield arrow, also separated with a plus sign.

It is often important to know the physical states of the reactants and products taking part in a reaction. To do this, put the appropriate symbol in parentheses after each formula: (s) for solid, (l) for liquid, (g) for gas, and (aq) for an aqueous (water-based) solution. At room temperature, the components of the previous reaction are in the following states:

$$CH_4(g) + O_2(g) \rightarrow CO_2(g) + H_2O(l)$$

The table below (**Table** 1.1) shows a listing of symbols used in chemical equations. Some, such as the double arrow which represents equilibrium, and the use of a catalyst in a reaction, will be treated in detail in later chapters.

TABLE 1.1: Symbols Used In Chemical Equations

Symbol	Description
+	used to separate multiple reactants or products
$\rightarrow$	yield sign; separates reactants from products
$\rightleftharpoons$	replaces the yield sign for reversible reactions that reach equilibrium
(s)	reactant or product in the solid state
(l)	reactant or product in the liquid state
(g)	reactant or product in the gas state
(aq)	reactant or product in an aqueous solution (dissolved in water)
$\xrightarrow{Pt}$	formula written above the arrow is used as a catalyst in the reaction
$\xrightarrow{\Delta}$	triangle indicates that the reaction is being heated

Balancing Chemical Equations

Suppose you were to write a word equation for building the ideal ham sandwich (**Figure** 1.3). Perhaps you might come up with this:

Ham + cheese + tomato + pickles + bread $\rightarrow$ ham sandwich

The reactants are the "parts" or ingredients of the ham sandwich while the sandwich itself is the product. There is something missing from your equation, however. There is no indication how many of each "reactant" is required to make the "product." For one thing, you would certainly need two slices of bread to make a conventional sandwich.

FIGURE 1.3
A ham sandwich can be thought of as the product of a reaction while all the individual ingredients are the reactants.

Let's say that the perfect ham sandwich (HS) is composed of 2 slices of ham (H), a slice of cheese (C), 1 slice of tomato (T), 5 pickles (P), and 2 slices of bread (B). Accounting for the numbers of each reactant, as well as substituting symbols for words, your equation would become:

$$2\text{H} + \text{C} + \text{T} + 5\text{P} + 2\text{B} \rightarrow \text{HS}$$

This now shows the correct quantities of the reactants. As one final improvement, we will change the "formula" of the product. Since the final sandwich contains all the reactants that went into it, its formula should reflect that.

$$2\text{H} + \text{C} + \text{T} + 5\text{P} + 2\text{B} \rightarrow \text{H}_2\text{CTP}_5\text{B}_2$$

The subscript after each symbol in the product stands for the number of that particular reactant found on the reactant side of the equation: 2 for H, 1 for C, etc.

Since the equation now shows equal numbers of each sandwich part on both sides of the equation, we say that the equation is balanced. Chemical equations must also be balanced in a similar way. A **balanced equation** *is a chemical equation in which mass is conserved and there are equal numbers of atoms of each element on both sides of the equation*. We can write a chemical equation for the reaction of carbon with hydrogen gas to form methane (CH_4).

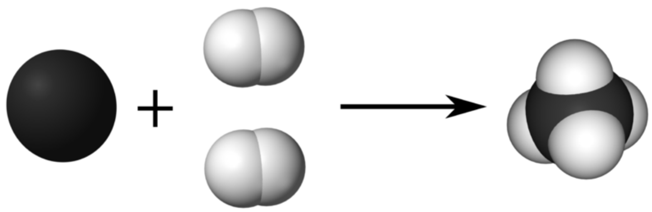
$$\underset{1\text{ C atom}}{?\ \ \text{C}(s)} + \underset{2\text{ H atoms}}{?\ \ \text{H}_2(g)} \rightarrow \underset{1\text{ C atom, }4\text{ H atoms}}{?\ \ \text{CH}_4(g)}$$

In order to write a correct equation, you must first write the correct skeleton equation with the correct chemical formulas. Recall that hydrogen is a diatomic molecule and so is written as H_2. When we count the number of atoms of both elements, shown under the equation, we see that the equation is not balanced. There are only 2 atoms of hydrogen on the reactant side of the equation, while there are 4 atoms of hydrogen on the product side. This violates the law of conservation of mass, which states that mass must be conserved in any chemical reaction or physical process. Another common way to express the law of conservation of mass is that matter cannot be created or destroyed.

As we saw in the chapter *Atomic Structure*, John Dalton's atomic theory stated that chemical reactions are separations, combinations, or rearrangements of atoms. Atoms themselves cannot be created or destroyed. Dalton's theory explains the law of conservation of mass and the process of balancing an equation ensures that the law is followed. We can balance the above equation by adding a coefficient of 2 in front of the formula for hydrogen.

$$C(s) + 2H_2(g) \rightarrow CH_4(g)$$

A **coefficient** *is a small whole number placed in front of a formula in an equation in order to balance it*. The 2 in front of the H_2 means that there are a total of $2 \times 2 = 4$ atoms of hydrogen as reactants. Visually, the reaction looks like:



In the balanced equation, there is one atom of carbon and four atoms of hydrogen on both sides of the arrow. Below are guidelines for writing and balancing chemical equations.

1. Determine the correct chemical formulas for each reactant and product.
2. Write the skeleton equation by placing the reactant(s) on the left side of the yield sign (→) and the product(s) on the right side. If there is more than one reactant or product, separate with plus signs.
3. Count the number of atoms of each element that appears as a reactant and as a product. If a polyatomic ion is unchanged on both sides of the equation, count it as a unit.
4. Balance each element one at a time by placing coefficients in front of the formulas. No coefficient is written for a 1. It is best to begin by balancing elements that only appear in one formula on each side of the equation. You can only balance equations by using coefficients; NEVER change the subscripts in a chemical formula that you already know is correct.
5. Check each atom or polyatomic ion to be sure that they are equal on both sides of the equation.
6. Make sure that all coefficients are in the lowest possible ratio. If necessary, reduce to the lowest ratio.

Sample Problem 11.1: Balancing Chemical Equations

Aqueous solutions of lead(II) nitrate and sodium chloride are mixed. The products of the reaction are an aqueous solution of sodium nitrate and a solid precipitate of lead(II) chloride.

Step 1: Plan the problem.

Follow the steps for writing and balancing a chemical equation.

Step 2: Solve.

Write the skeleton equation with the correct formulas.

$$Pb(NO_3)_2(aq) + NaCl(aq) \rightarrow NaNO_3(aq) + PbCl_2(s)$$

Count the number of each atom or polyatomic ion on both sides of the equation (**Table** 1.2).

TABLE 1.2: Unbalanced Reactants/Products

reactants	products
1 Pb atom	1 Pb atom
2 NO_3^-	1 NO_3^-
1 Na atoms	1 Na atoms
1 Cl atom	2 Cl atoms

The nitrate ions and the chlorine atoms are unbalanced. Start by placing a 2 in front of the NaCl. This increases the reactant counts to 2 Na atoms and 2 Cl atoms. Then place a 2 in front of the $NaNO_3$. The result is:

$$Pb(NO_3)_2(aq) + 2NaCl(aq) \rightarrow 2NaNO_3(aq) + PbCl_2(s)$$

The new count for each atom and polyatomic ion becomes (**Table** 1.3):

TABLE 1.3: Balanced Reactants/Products

reactants	products
1 Pb atom	1 Pb atom
2 $NO_3{}^-$	2 $NO_3{}^-$
2 Na atoms	2 Na atoms
2 Cl atom	2 Cl atoms

Step 3: Think about your result.

The equation is now balanced since there are equal numbers of atoms of each element on both sides of the equation.

Practice Problems

1. Balance the following equations.
   a. $Zn(s) + HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$
   b. $Li(s) + N_2(g) \rightarrow Li_3N(s)$
2. Create a balanced chemical equation from the following word equations.
   a. Potassium + water → potassium hydroxide + hydrogen gas
   b. Sodium phosphate + calcium chloride → sodium chloride + calcium phosphate

Some equations provide a challenge to balancing when one or more of the elements can't be balanced by simply using one coefficient. Aluminum reacts with oxygen gas to form aluminum oxide according to the equation:

$$Al(s) + O_2(g) \rightarrow Al_2O_3(s)$$

Since there are 2 oxygen atoms on the reactant side and 3 oxygen atoms on the product side, no single whole-number coefficient will balance the oxygen atoms. Find the lowest common multiple of 2 and 3, which is 6. Placing a 3 in front of the O_2 and a 2 in front of the Al_2O_3 will result in 6 oxygen atoms on both sides. Finish by balancing the aluminum with a 4.

$$4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(s)$$

The equation is balanced with 4 Al atoms and 6 O atoms on each side.

Finally, we will return to the equation from earlier where methane was reacted with oxygen to form carbon dioxide and water.

$$CH_4(g) + O_2(g) \rightarrow CO_2(g) + H_2O(l)$$

The element oxygen appears in two different places on the product side of the equation, so you should not start by trying to balance the oxygen. Instead, balance the carbon and the hydrogen first. The carbon is already balanced, but the hydrogen is balanced by placing a 2 in front of the water.

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

Now count the total number of oxygen atoms on the product side: two from the CO_2 and two from the $2H_2O$ to give a total of four. Place a 2 in front of the O_2.

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

Balancing difficult equations can be a trial-and-error process and is a skill that requires practice. If you find that one particular strategy with a tough equation isn't working, start over and balance a different element first. Persistence will lead you to the correct balanced equation.

You can watch a video lecture about balancing chemical equations at http://www.khanacademy.org/science/chemistry/chemical-reactions-stoichiometry/v/balancing-chemical-equations .

If you want to practice and develop your skills at balancing chemical equations, you can download a simulation at http://phet.colorado.edu/en/simulation/balancing-chemical-equations .

You can also play a game called "Balancing Act" at http://education.jlab.org/elementbalancing/index.html .

Lesson Summary

- Chemical reactions can be described as the process of one or more reactants being transformed into one or more products. In a word equation, the names of the reactants are separated from the names of the products by a yield arrow.
- A skeleton equation shows the chemical formulas and physical states of the reactants and products, but it does not account for their relative amounts.
- Chemical reactions result solely from the rearrangement of atoms, so the law of conservation of mass must be observed. Coefficients are placed in front of chemical formulas to balance a chemical equation, meaning that the same quantities of each kind of atom are present on each side of the equation.

Lesson Review Questions

Reviewing Concepts

1. Identify the reactants and products in each chemical reaction.
   a. In photosynthesis, carbon dioxide and water react to form glucose and oxygen.
   b. Magnesium oxide forms when magnesium is exposed to oxygen gas.
2. What is the relationship between an equal sign and a yield sign?
3. Write sentences that completely describe the chemical reactions shown in the skeleton equations below.
   a. $H_2O_2(l) \overset{MnO_2}{\rightarrow} H_2O(l) + O_2(g)$
   b. $CuCO_3(s) \overset{\Delta}{\rightarrow} CuO(s) + CO_2(g)$
   c. $Cs(s) + H_2O(l) \rightarrow CsOH(aq) + H_2(g)$
4. How many atoms of each element are represented by the following combinations of coefficients and chemical formulas?
   a. $5Br_2$
   b. $2NH_3$

c. $4(NH_4)_2SO_4$
d. $2CH_3COOH$
e. $3Fe(NO_3)_3$
f. $2K_3PO_4$

5. The skeleton equation for the reaction of nitrogen gas with oxygen gas to form dinitrogen monoxide is shown below. Explain why the equation below is not a correctly balanced equation for this reaction.

Problems

6. Balance each of the following equations.
   a. $KClO_3 \rightarrow KCl + O_2$
   b. $Ca(OH)_2 + HBr \rightarrow CaBr_2 + H_2O$
   c. $C_4H_{10} + O_2 \rightarrow CO_2 + H_2O$
   d. $NH_3 + CuO \rightarrow Cu + N_2 + H_2O$
7. Write and balance chemical equations for each of the following word equations.
   a. sodium carbonate → sodium oxide + carbon dioxide
   b. tetraphosphorus decoxide + water → phosphoric acid
   c. lead + nitrogen → lead(II) nitride
   d. ammonium carbonate → ammonia + water + carbon dioxide
8. Write and balance chemical equations from the following descriptions. Include symbols for the physical states of each reaction component.
   a. Solid barium oxide is reacted with water and forms aqueous barium hydroxide.
   b. Aqueous lithium phosphate reacts with aqueous iron(III) nitrate to form aqueous lithium nitrate and solid iron(III) phosphate.
   c. Aluminum metal is reacted with an aqueous solution of zinc chloride to form aqueous aluminum chloride and solid zinc.
   d. Iron(III) oxide solid reacts with carbon monoxide gas to produce iron and carbon dioxide gas.
9. The following equations are incorrect in some way. Identify and correct each error, and then balance the corrected equation.
   a. $K + O_2 \rightarrow KO_2$
   b. $Ag_2O \rightarrow Ag_2 + O$
   c. $NaCl + F_2 \rightarrow NaF_2 + Cl$

Further Reading / Supplemental Links

- Balancing Chemical Equations, (http://www.mpcfaculty.net/mark_bishop/balancing_equations_tutorial.htm)

Points to Consider

It is important for a chemist to be able to predict the products of chemical reactions. This task is made easier by placing known reactions into specific categories based on the ways in which the substances behave in those reactions.

- What are combination and decomposition reactions?
- What are single replacement and double replacement reactions?

- What is a combustion reaction?

1.2 Types of Chemical Reactions

Lesson Objectives

- Define and give general equations for combination, decomposition, single-replacement, and double-replacement reactions.
- Classify a reaction as combination, decomposition, single-replacement, double-replacement, or combustion.
- Use the activity series to correctly predict whether a given reaction will occur.
- Predict the products of simple reactions, given only the reactants.

Vocabulary

- activity series
- combination reaction
- combustion reaction
- decomposition reaction
- double-replacement reaction
- single-replacement reaction

Check Your Understanding

Recalling Prior Knowledge

- What is the difference between an element and a compound?
- What is the crisscross method, and how does it help one to write correct formulas for ionic compounds?
- What are the steps to balancing a chemical equation?

Many chemical reactions can be classified as one of five basic types. Having a thorough understanding of these types of reactions will be useful for predicting the products of an unknown reaction. The five basic types of chemical reactions are combination, decomposition, single-replacement, double-replacement, and combustion. Analyzing the reactants and products of a given reaction will allow you to place it into one of these categories. Some reactions will fit into more than one category.

Combination Reactions

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 reacts with chlorine gas to produce solid sodium chloride.

$$2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$$

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).

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 reacts rapidly and dramatically when ignited, combining with oxygen from the air to produce a fine powder of magnesium oxide. This reaction can be seen in the following video: http://www.youtube.com/watch?v=NnFzHt6l4z8 (0:37).

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

MEDIA

Click image to the left or use the URL below.

URL: http://www.ck12.org/flx/render/embeddedobject/65507

Sulfur reacts with oxygen to form sulfur dioxide.

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

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 can also combine with oxygen to produce sulfur trioxide.

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

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.

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

Sample Problem 11.2: 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 with oxygen.

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 O^{2-}.

Step 2: Solve.

The skeleton (unbalanced) equation: $K(s) + O_2(g) \rightarrow K_2O(s)$

The equation is then easily balanced with coefficients.

$4K(s) + O_2(g) \rightarrow 2K_2O(s)$

Step 3: Think about your result.

The formulas are correct and the resulting combination reaction is balanced.

Practice Problems

1. Write a balanced equation for the combination reactions.
   a. aluminum and oxygen
   b. calcium and bromine
2. Write a balanced equation showing the formation of copper(II) nitride from its elements.

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 reacts with oxygen to form carbon dioxide according to the equation:

$2CO(g) + O_2(g) \rightarrow 2CO_2(g)$

Two compounds may also react to from 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 (**Figure** 1.4).

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

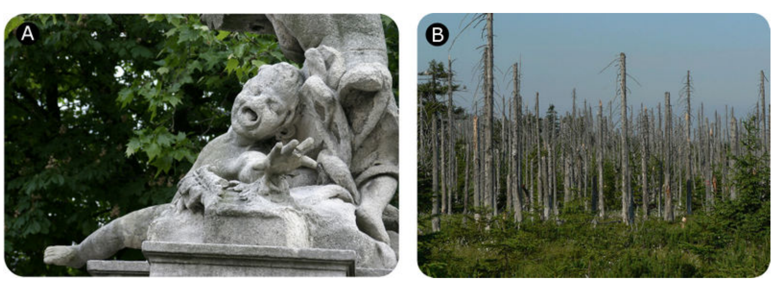


FIGURE 1.4
Acid rain has severe consequences on both nature as well as on man-made objects. (A) Acid rain degrades marble statues like the one on the left. (B) The trees in the forest on the right have been killed by acid rain.

For additional help and examples of combination reactions, also known as synthesis reactions, go to http://www.chemteam.info/Equations/Synthesis.html .

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.

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

View a video of the decomposition of mercury(II) oxide at http://www.youtube.com/watch?v=_Y1alDuXm6A (1:12).

MEDIA

Click image to the left or use the URL below.

URL: http://www.ck12.org/flx/render/embeddedobject/59229

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

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

Metal hydroxides decompose on heating to yield metal oxides and water. Sodium hydroxide decomposes to produce sodium oxide and water.

$2NaOH(s) \rightarrow Na_2O(s) + H_2O(g)$

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

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

Sample Problem 11.3: 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 and oxygen gases produced in the reaction are both diatomic molecules.

Step 2: Solve.

The skeleton (unbalanced) equation: $H_2O(l) \stackrel{elec}{\rightarrow} H_2(g) + O_2(g)$

Note the abbreviation "elec" above the arrow to indicate the passage of an electric current to initiate the reaction. Balance the equation.

$2H_2O(l) \stackrel{elec}{\rightarrow} 2H_2(g) + O_2(g)$

Step 3: Think about your result.

The products are elements and the equation is balanced.

Practice Problem

3. Write balanced equations for the decomposition of the following compounds.
   (a) strontium phosphide
   (b) silver carbonate
   (c) aluminum hydroxide

For more information on decomposition reactions, go to http://www.chemteam.info/Equations/Decomposition.html .

Single-Replacement Reactions

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 (also called 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, it replaces the copper. The products of the reaction are aqueous magnesium nitrate and solid copper metal.

$$\mathrm{Mg}(s) + \mathrm{Cu(NO_3)_2}(aq) \rightarrow \mathrm{Mg(NO_3)_2}(aq) + \mathrm{Cu}(s)$$

This subcategory of single-replacement reactions is called a metal replacement reaction because it is a metal that is being replaced (copper).

You can view a two part video experiment of a metal replacement occurring over a period of time.

- Part 1 video: http://www.youtube.com/watch?v=gqGrpd5smtI
  - The document that goes with part 1 is at http://www.dlt.ncssm.edu/core/Chapter1-Introduction/Chapter1-Labs/Iron_Nail_Observation_Activity.doc .
- Part 2 video: http://www.youtube.com/watch?v=yWcSzvJ6Kcw

Hydrogen Replacement

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 (**Figure** 1.5).

$$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$$

In a hydrogen replacement reaction, the hydrogen in the acid is replaced by an active metal.

FIGURE 1.5
Zinc metal reacts with hydrochloric acid to give off hydrogen gas in a single-replacement reaction.

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 (**Figure** 1.6).

$$2Na(s) + 2H_2O(l) \rightarrow 2NaOH(aq) + H_2(g)$$

View an animation of a metal replacing hydrogen at http://www.dlt.ncssm.edu/core/Chapter5-Moles-Molarity-Reaction_Types/Chapter5-Animations/SingleDisp_Reaction-MetalToAcid.html .

Halogen Replacement

The element chlorine reacts with an aqueous solution of sodium bromide to produce aqueous sodium chloride and elemental bromine.

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

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.

You can view a halogen replacement experiment at http://www.dlt.ncssm.edu/core/Chapter5-Moles-Molarity-Reaction_Types/l2hexane-lg.htm .

FIGURE 1.6
Pictured here is about 3 pounds of sodium metal reacting with water. Sodium metal reacts vigorously when dropped into a container of water, giving off hydrogen gas. A large piece of sodium will often generate so much heat that the hydrogen will ignite.

The Activity Series

Single-replacement reactions only occur when the element that is doing the replacing is more reactive than the element that is being replaced. Therefore, it is useful to have a list of elements in order of their relative reactivities. The **activity series** *is a list of elements in decreasing order of their reactivity*. Since metals replace other metals, while nonmetals replace other nonmetals, they each have a separate activity series. Listed below (**Table** 1.4) is an activity series of most common metals, and of the halogens.

TABLE 1.4: Activity Series

Activity of Metals		Activity of Halogens
Li K Ba Sr Ca Na	React with cold water, replacing hydrogen.	F_2 Cl_2 Br_2 I_2
Mg Al Zn Cr Fe Cd	React with steam, but not cold water, replacing hydrogen.	
Co Ni Sn Pb	Do not react with water. React with acids, replacing hydrogen.	
H_2		

TABLE 1.4: (continued)

Activity of Metals		Activity of Halogens
Cu Hg Ag Pt Au	Unreactive with water or acids.	

For a single-replacement reaction, a given element is capable of replacing an element that is below it in the activity series. This can be used to predict if a reaction will occur. Suppose that small pieces of the metal nickel were placed into two separate aqueous solutions: one of iron(III) nitrate and one of lead(II) nitrate. Looking at the activity series, we see that nickel is below iron, but above lead. Therefore, the nickel metal will be capable of replacing the lead in a reaction, but will not be capable of replacing iron.

$$Ni(s) + Pb(NO_3)_2(aq) \rightarrow Ni(NO_3)_2(aq) + Pb(s)$$
$$Ni(s) + Fe(NO_3)_3(aq) \rightarrow \text{NR (no reaction)}$$

In the descriptions that accompany the activity series of metals, a given metal is also capable of undergoing the reactions described below that section. For example, lithium will react with cold water, replacing hydrogen. It will also react with steam and with acids, since that requires a lower degree of reactivity.

Sample Problem 11.4: Single-Replacement Reactions

Use the activity series to predict if the following reactions will occur. If not, write NR. If the reaction does occur, write the products of the reaction and balance the equation.

1. $Al(s) + Zn(NO_3)_2(aq) \rightarrow$
2. $Ag(s) + HCl(aq) \rightarrow$

Step 1: Plan the problem.

For 1, compare the placements of aluminum and zinc on the activity series. For 2, compare the placements of silver and hydrogen.

Since aluminum is above zinc, it is capable of replacing it and a reaction will occur. The products of the reaction will be aqueous aluminum nitrate and solid zinc. Take care to write the correct formulas for the products before balancing the equation. Aluminum adopts a 3+ charge in an ionic compound, so the formula for aluminum nitrate is $Al(NO_3)_3$. The balanced equation is:

$$2Al(s) + 3Zn(NO_3)_2(aq) \rightarrow 2Al(NO_3)_3(aq) + 3Zn(s)$$

Since silver is below hydrogen, it is not capable of replacing hydrogen in a reaction with an acid.

$$Ag(s) + HCl(aq) \rightarrow \text{NR}$$

Step 3: Think about your result.

The equation for 1 is balanced and follows the activity series. Silver, a coinage and jewelry metal, is unreactive toward acids.

Practice Problem

4. Complete and balance the reactions for the following single-replacement reactions. Use the activity series. If no reaction will occur, write NR.
   (a) $Fe(s) + MgCl_2(aq) \rightarrow$
   (b) $F_2(g) + KI(aq) \rightarrow$
   (c) $Sn(s) + Cu(NO_3)_2(aq) \rightarrow$

Watch a video experiment of halogen activity series at http://www.dlt.ncssm.edu/core/Chapter8-Atomic_Str_Part2/bleachoverlay-lg.htm .

For more explanation and examples of single-replacement reactions go to http://www.chemteam.info/Equations/SingleReplacement.html .

Double-Replacement 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*. The general form of a double-replacement (also called double-displacement) reaction is:

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

In this reaction, *A* and *C* are positively-charged cations, while *B* and *D* are 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.

For more information and examples on double-replacement reactions go to http://www.chemteam.info/Equations/DoubleReplacement.html .

Formation of a Precipitate

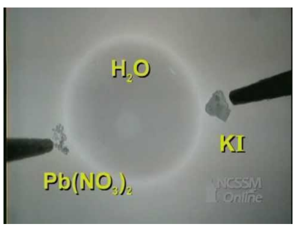
A precipitate forms in a double-replacement reaction when the cations from one of the reactants combine with the anions from the other reactant to form an insoluble ionic compound. When aqueous solutions of potassium iodide and lead(II) nitrate are mixed, the following reaction occurs.

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

There are very strong attractive forces that occur between Pb^{2+} and I^- ions and the result is a brilliant yellow precipitate (**Figure** 1.7). The other product of the reaction, potassium nitrate, remains soluble. Rules for predicting the water solubility of ionic compounds and how to apply those rules to reactions are covered in a later chapter.

Watch a video of the reaction between lead(II) nitrate and potassium iodide on the microscopic level at http://www.youtube.com/watch?v=ncRj5qIoRRg (0:43).

FIGURE 1.7
When a few drops of lead(II) nitrate are added to a solution of potassium iodide, a yellow precipitate of lead(II) iodide immediately forms in a double-replacement reaction.



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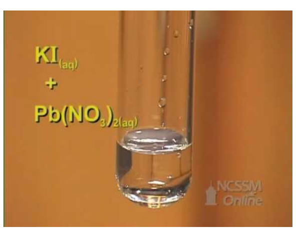
Click image to the left or use the URL below.
URL: http://www.ck12.org/flx/render/embeddedobject/60858

You can watch the above reaction without a microscope at http://www.youtube.com/watch?v=X2mB-q2NQXY (0:38).



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Click image to the left or use the URL below.
URL: http://www.ck12.org/flx/render/embeddedobject/60859

You can view an animation of a double-replacement precipitation reaction at http://www.dlt.ncssm.edu/core/Chapter5-Moles-Molarity-Reaction_Types/Chapter5-Animations/DoubleDisp_Reaction-Precipitation.html .

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.

$$Na_2S(aq) + 2HCl(aq) \rightarrow 2NaCl(aq) + H_2S(g)$$

Watch a video experiment that shows the production of hydrogen sulfide gas from sodium sulfide and hydrochloric acid at http://www.youtube.com/watch?v=os8Yr-rindU .

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.

$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$$

Sample Problem 11.5: Double-Replacement Reactions

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

1. $NaCN(aq) + HBr(aq) \rightarrow$ (hydrogen cyanide gas is formed)
2. $(NH_4)_2SO_4(aq) + Ba(NO_3)_2(aq) \rightarrow$ (a precipitate of barium sulfate forms)

Step 1: Plan the problem.

In 1, the production of a gas drives the reaction. In 2, 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.

1. The cations of both reactants are 1+ charged ions, while the anions are 1− charged ions. After exchanging partners, the balanced equation is: $NaCN(aq) + HBr(aq) \rightarrow NaBr(aq) + HCN(g)$
2. 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. Then, the equation is balanced. $(NH_4)_2SO_4(aq) + Ba(NO_3)_2(aq) \rightarrow 2NH_4NO_3(aq) + BaSO_4(s)$

Step 3: Think about your result.

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

Practice Problem

5. Complete and balance the double-replacement reactions.
   (a) $H_3PO_4(aq) + KOH(aq) \rightarrow$ (water is formed)
   (b) $AgNO_3(aq) + CaCl_2(aq) \rightarrow$ (silver chloride precipitate forms)

Occasionally, a reaction will produce both a gas and a molecular compound. The reaction of a sodium carbonate solution with hydrochloric acid produces aqueous sodium chloride, carbon dioxide gas, and water.

$$Na_2CO_3(aq) + 2HCl(aq) \rightarrow 2NaCl(aq) + CO_2(g) + H_2O(l)$$

Combustion Reactions

A **combustion reaction** *is a reaction in which a substance reactants with oxygen gas, releasing energy in the form of light and heat*. Combustion reactions must involve O_2 as one reactant. The combustion of hydrogen gas produces water vapor (**Figure** 1.8).

$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$

Notice that this reaction also qualifies as a combination reaction.

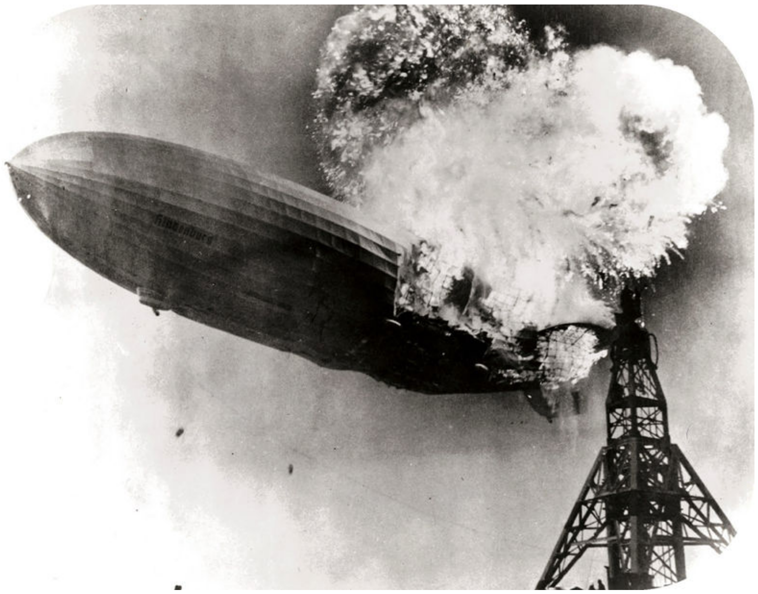

FIGURE 1.8
Hindenburg was a hydrogen-filled airship that suffered an accident upon its attempted landing in New Jersey in 1937. The hydrogen immediately combusted in a huge fireball, destroying the airship and killing 36 people. The chemical reaction was a simple one: hydrogen combining with oxygen to produce water.

Many combustion reactions occur with a hydrocarbon, a compound made up solely of carbon and hydrogen. The products of the combustion of hydrocarbons are carbon dioxide and water. 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.

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

Practice Problem 11.6: 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.

Practice Problem

6. Write and balance combustion reactions for the following compounds.
   (a) octane (C_8H_{18})
   (b) sucrose ($C_{12}H_{22}O_{11}$)

For more information and practice on combustion reactions, go to http://www.chemteam.info/Equations/Combustion.html .

Lesson Summary

- The five general types of chemical reactions are combination, decomposition, single-replacement, double-replacement, and combustion.
- In a combination reaction, two simple substances combine to from a single product.
- In a decomposition reaction, a compound breaks down into two or more simpler substances.
- In a single-replacement reaction, one element takes the place of another similar element in a compound. Common types of single-replacement reactions include metal replacement, hydrogen replacement, and halogen replacement. The activity series can be used to predict whether a given reaction will occur.
- In a double-replacement reaction, two ionic compounds react by exchanging cation-anion partners. A double-replacement reaction generally produces an ionic precipitate, a gas, or a molecular compound.
- In a combustion reaction, a substance reacts with oxygen gas, giving off energy as light and heat.

Lesson Review Questions

Reviewing Concepts

1. Write a general reaction for each reaction type below.
   a. double-replacement
   b. decomposition
   c. single-replacement
   d. combination
2. Which type of reaction generally takes place only between substances in aqueous solution?
3. What do all combustion reactions have in common?
4. Where on an activity series are the most reactive elements located?
5. Classify the following reactions according to the five basic reaction types.
   a. $Cd(s) + H_2SO_4(aq) \rightarrow CdSO_4(aq) + H_2(g)$
   b. $2Fe(s) + 3Cl_2(g) \rightarrow 2FeCl_3(s)$
   c. $C_7H_8(l) + 9O_2(g) \rightarrow 7CO_2(g) + 4H_2O(g)$
   d. $2NH_4NO_3(s) \rightarrow 2N_2(g) + O_2(g) + 4H_2O(g)$
   e. $2CoCl_3(aq) + 3Pb(NO_3)_2(aq) \rightarrow 2Co(NO_3)_3(aq) + 3PbCl_2(s)$

Problems

6. Write balanced chemical equations for the following combination reactions.
   a. $Sr(s) + S(s) \rightarrow$
   b. $Zn(s) + O_2(g) \rightarrow$
   c. $Li_2O(s) + H_2O(l) \rightarrow$
7. Write balanced chemical equations for the following decomposition reactions.
   a. $Na_3N(s) \xrightarrow{\Delta}$
   b. $SnCO_3(s) \xrightarrow{\Delta}$
   c. $NCl_3(l) \rightarrow$
   d. $Mg(OH)_2(s) \xrightarrow{\Delta}$
8. Use the activity series to write a balanced chemical equation for the following single-replacement reactions. Write NR if no reaction occurs.
   a. $Cl_2(g) + NaF(aq) \rightarrow$
   b. $Ca(s) + H_2O(l) \rightarrow$
   c. $Pt(s) + H_2SO_4(aq) \rightarrow$
   d. $Al(s) + NiBr_2(aq) \rightarrow$
9. Write balanced chemical equations for the following double-replacement reactions.
   a. $Ca(NO_3)_2(aq) + K_3PO_4(aq) \rightarrow$ (calcium phosphate precipitates)
   b. $HI(aq) + Mg(OH)_2(aq) \rightarrow$
   c. $FeS(s) + HCl(aq) \rightarrow$ (aqueous iron(II) chloride is one product)
   d. $CuBr_2(aq) + KOH(aq) \rightarrow$ (copper(II) hydroxide precipitates)
10. Write balanced equations for the combustion of the following compounds.
   a. ethyne (C_2H_2)
   b. acetic acid (CH_3COOH)
   c. hexane (C_6H_{14})

Further Reading / Supplemental Links

- Reaction Identification Practice, (http://www.sciencegeek.net/Chemistry/taters/EquationIdentification.htm)
- MHS Chemistry: Predicting Reaction Products, (http://dbooth.net/mhs/chem/predictingproducts01.html)
- You can view several examples of metals reacting with various solutions at http://www.harpercollege.edu/tm-ps/chm/100/dgodambe/thedisk/series/3perform.htm . After choosing a metal and a solution, you will be shown a picture of the resulting reaction.

Synthesis reactions:

- Simulation of the synthesis of water: http://www.dlt.ncssm.edu/core/Chapter5-Moles-Molarity-Reaction_Types/Chapter5-Animations/Synthesis.html
- A video of the synthesis reaction that produces magnesium oxide can be found at http://www.youtube.com/watch?v=kx72te_jAfw
- Watch the synthesis of a metal hydroxide at http://www.youtube.com/watch?v=AP79_srafmE
- Watch the synthesis of carbonic acid at http://www.youtube.com/watch?v=kJC8NHiXc9c
- View the synthesis of calcium oxide at http://www.youtube.com/watch?v=dszSKIM5rqk
- View the reaction between copper and chlorine gas at http://www.youtube.com/watch?v=edLpxdERQZc

- A video of the combination reaction between chlorine gas and iron can be found at http://www.youtube.com/watch?v=ygLDJKG_QSY
- An animation of a combination reaction between nitrogen gas and oxygen gas can be found at http://www.dlt.ncssm.edu/core/Chapter6-Stoichiometry/Chapter6-Animations/Stoichiometry-1.html

Decomposition reactions:

- An animation of the decomposition of a metal hydrogen carbonate can be viewed at http://www.dlt.ncssm.edu/core/Chapter5-Moles-Molarity-Reaction_Types/Chapter5-Animations/Decomposition.html
- A video of the decomposition of a metal hydrogen carbonate can be seen at http://www.youtube.com/watch?v=GPXRY3MPUMY
- Watch the decomposition of copper(II) oxide at http://www.youtube.com/watch?v=Ar07zUf52Tc
- Watch the decomposition of a metal hydroxide at http://www.youtube.com/watch?v=dFYJ7a7-wIc
- Watch the decomposition of hydrogen peroxide at http://www.youtube.com/watch?v=oX5FyaqNx54
- Watch the decomposition of potassium chlorate at http://www.youtube.com/watch?v=svRIg_kzE68

Metal replacement:

- An animation of a metal replacement reaction can be found at http://www.dlt.ncssm.edu/core/Chapter5-Moles-Molarity-Reaction_Types/Chapter5-Animations/SingleDisp_Reaction-MetalToMetal.html
- A video experiment showing what happens at the microscopic level when copper replaces silver in a reaction between copper wire and silver nitrate can be seen at http://www.youtube.com/watch?v=dVK6B-56MYs
- A video of the reaction between copper wire and silver nitrate without the use of a microscope can be found at http://www.youtube.com/watch?v=k8UtR7akNec

Hydrogen replacement:

- A video experiment of hydrogen replacement by calcium can be seen at http://www.youtube.com/watch?v=hjB96do_fRw
- A video experiment of magnesium metal reacting with hydrochloric acid can be viewed at http://www.youtube.com/watch?v=OBdgeJFzSec

Double-replacement reaction:

- Watch an animation of a double-replacement reaction at http://www.dlt.ncssm.edu/core/Chapter5-Moles-Molarity-Reaction_Types/Chapter5-Animations/DoubleDisp_Reaction-AcidToBase.html
- View a double-replacement reaction between sodium hydroxide and hydrochloric acid at http://www.youtube.com/watch?v=HQfXzbZJhgg

Formation of a precipitate:

- A video experiment in which a precipitate is formed by reacting sodium chloride with silver nitrate can be seen at http://www.youtube.com/watch?v=eGG3EI4mwok
- A video of the double-replacement reaction between calcium chloride and sodium phosphate can be viewed at http://www.youtube.com/watch?v=aFFC6vtI-rY
- A video of the double-replacement reaction between copper(II) sulfate and sodium sulfide can be viewed at http://www.youtube.com/watch?v=KkKBDcFfZWo
- A video of the double-replacement reaction between sodium sulfate and barium chloride can be viewed at http://www.youtube.com/watch?v=XaMyfjYLhxU

Formation of a gas:

- When metal carbonates are involved in a double-replacement reaction, the carbonate ion frequently breaks apart after the displacement and forms carbon dioxide. View an animation of this type of reaction at http://www.dlt.ncssm.edu/core/Chapter5-Moles-Molarity-Reaction_Types/Chapter5-Animations/DoubleDisp_Reaction-GasProduction.html .
- Watch a video experiment of a double-replacement reaction between a metal carbonate and an acid at http://www.youtube.com/watch?v=TJYOxGHNTzg
- Watch a video experiment of a double-replacement reaction between sodium bicarbonate and hydrochloric acid at http://www.youtube.com/watch?v=xRfPvDEs2gM
- Watch a video experiment that shows the production of ammonia gas from ammonium chloride and sodium hydroxide at http://www.youtube.com/watch?v=LUEakMDNRsM
- Watch a video experiment that shows the production of sulfurous acid from the double-replacement reaction between sodium sulfite and hydrochloric acid at http://www.youtube.com/watch?v=BlpjKceHF3g
- Watch a video experiment in which two gases undergo a double-replacement reaction to produce a solid at http://www.youtube.com/watch?v=60vtFe42sGs

Combustion reactions:

- View an in-depth explanation of the combustion reaction that occurs when you strike a match at http://www.pbs.org/wgbh/nova/cigarette/onfire.html .
- View an exciting video demonstration that confirms the importance of oxygen in a combustion reaction at http://education.jlab.org/frost/live_candle.html .
- View another video demonstration that confirms the importance of oxygen in a combustion reaction at http://education.jlab.org/frost/combustion.html .

Points to Consider

Balanced equations allow chemists to control reactions quantitatively. The coefficients in a balanced equation represent the ideal molar ratio for the reactants in the given reaction.

- How can a balanced chemical equation be used to calculate how much of a certain product will be formed in a reaction or how much of a certain reactant will be needed to perform the reaction?

1.3 References

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