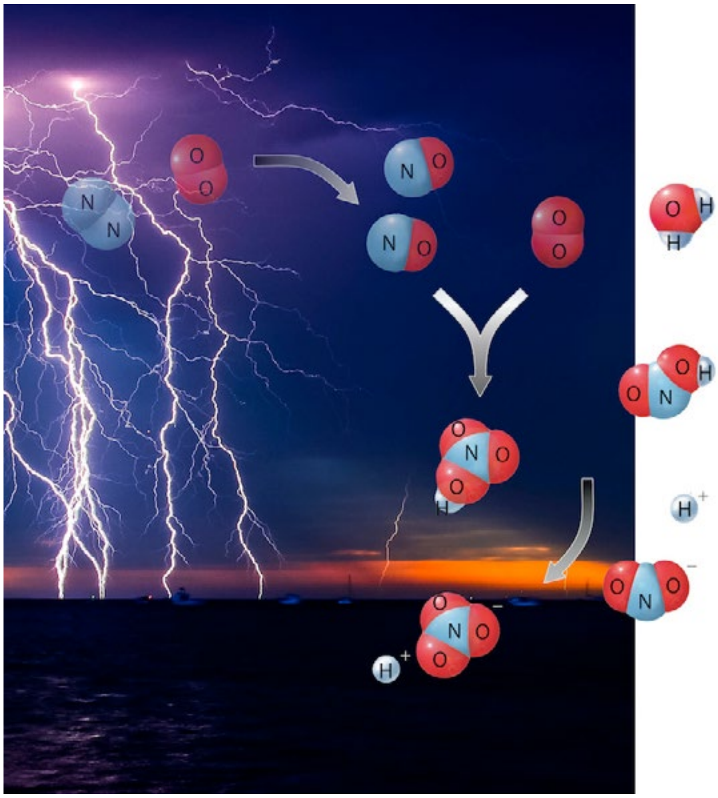

Chapter 9

How Chemicals React

THE MAIN IDEA

Atoms change partners during a chemical reaction.

Λ The atmosphere is awash with chemicals such as water, nitrogen, and oxygen, that are forced to undergo chemical changes during a high-energy lightning bolt.

Chemists have learned how to control chemical reactions to produce many useful materials— nitrogen-based fertilizers from the atmosphere, metals from rocks, plastics and pharmaceuticals from petroleum. These materials and the thousands of others produced by chemical reactions have dramatically improved our standard of living, as has the abundant energy released when fossil fuels take part in the chemical reaction called combustion. What happens in a chemical reaction? Why are new materials produced? Why must chemical equations always be balanced? If two molecules meet, will they always react to form new molecules? What is a catalyst, and what role do catalysts play in our environment? Why do some chemical reactions, such as the burning of wood, produce energy, while other reactions, such as those occurring in the cooking of food, require the input of energy? What is the ultimate driving force for all chemical reactions? The goal of this chapter is to provide you with a stronger handle on the basics of chemical reactions introduced in Chapter 3.

9.1 Chemical Equations

As was discussed in Chapter 3, during a chemical reaction, atoms rearrange to form one or more new compounds. This process is neatly summed up in written form as a **chemical equation**. A chemical equation shows the reacting substances, called **reactants**, before an arrow that points to the newly formed substances, called **products**:

$$\text{reactants} \longrightarrow \text{products}$$

Typically, reactants and products are represented by their elemental or chemical formulas. Sometimes molecular models or, simply, names may be used instead. Phases are also often shown: (*s*) for solid, (*l*) for liquid, and (*g*) for gas. Compounds dissolved in water are designated (*aq*) for aqueous solution. Finally, numbers are placed in front of the reactants or products to show the ratio in which they either combine or form. These numbers are called *coefficients*, and they represent numbers of individual atoms and molecules. For instance, to represent the chemical reaction in which carbon burns in the presence of oxygen to form gaseous carbon dioxide, we write the chemical equation using coefficients of 1:

$$1\,C\,(s) + 1\,O_2\,(g) \longrightarrow 1\,CO_2\,(g)$$

Reactants Products

One of the most important principles of chemistry is the **law of mass conservation**, which we discussed in Sections 1.4 and 2.2. The law of mass conservation states that matter is neither created nor destroyed during a chemical reaction. The atoms present at the beginning of a reaction are merely rearranged. This means that no atoms are lost or gained during any reaction. The chemical equation must therefore be *balanced*. In a balanced equation, each atom must appear on both sides of the arrow the same number of times. The equation for the formation of carbon dioxide is balanced because each side shows one carbon atom and two oxygen atoms. You can count the number of each type of atom in the models to see this for yourself.

In another chemical reaction, two hydrogen gas molecules, H_2, react with one oxygen gas molecule, O_2, to produce two molecules of water, H_2O, in the gaseous phase:

$$2\,H_2\,(g) + 1\,O_2\,(g) \longrightarrow 2\,H_2O\,(g)$$

This equation for the formation of water is also balanced—there are four hydrogen and two oxygen atoms before and after the arrow.

A coefficient in front of a chemical formula tells us the number of times that element or compound must be counted. For example, 2 H_2O indicates two water molecules, which contain a total of four hydrogen atoms and two oxygen atoms.

By convention, the coefficient 1 is omitted; so, the preceding chemical equations are typically written

$$C\,(s) + O_2\,(g) \longrightarrow CO_2\,(g) \quad \text{(balanced)}$$

$$2\,H_2\,(g) + O_2\,(g) \longrightarrow 2\,H_2O\,(g) \quad \text{(balanced)}$$

CONCEPT **CHECK**

How many oxygen atoms are indicated by the following balanced equation?

$3\,O_2\,(g) \rightarrow 2\,O_3\,(g)$

CHECK YOUR ANSWER

There are six oxygen atoms. Before the reaction, these six oxygen atoms are found in three O_2 molecules. After the reaction, these same six atoms are found in two O_3 molecules.

An unbalanced chemical equation shows the reactants and products without the correct coefficients. For example, the equation

$$NO\ (g) \longrightarrow N_2O\ (g) + NO_2\ (g) \quad \text{(unbalanced)}$$

is not balanced because there are one nitrogen atom and one oxygen atom before the arrow but three nitrogen atoms and three oxygen atoms after the arrow.

You can balance unbalanced equations by adding or changing coefficients to produce correct ratios. It's important not to change subscripts, however, because to do so changes the compound's identity—H_2O is water, but H_2O_2 is hydrogen peroxide. For example, to balance the preceding equation, place a 3 before the NO:

$$3\ NO\ (g) \longrightarrow N_2O\ (g) + NO_2\ (g) \quad \text{(balanced)}$$

Now there are three nitrogen atoms and three oxygen atoms on each side of the arrow, and the law of mass conservation is not violated.

Practicing chemists develop a skill for balancing equations. This skill involves creative energy and, like other skills, improves with experience. More important than being an expert at balancing equations is knowing why they need to be balanced. And the reason is the law of mass conservation, which tells us that atoms are neither created nor destroyed in a chemical reaction—they are simply rearranged. So, every atom present before the reaction must be present after the reaction, even though the groupings of atoms are different.

READING CHECK

Why must the chemical equation be balanced?

Many students enjoy learning how to balance chemical equations. Perhaps this is because balancing an equation is akin to solving a crossword or Sudoku puzzle. There are many different approaches one can take to balancing a chemical equation. There are also some crafty tricks one can perform to solve some difficult equations. Your instructor may share with you some of his or her favorite approaches and/or tricks to balancing equations. To get you started, we offer you the following guidelines, which you can follow as you work to balance the chemical equations appearing in the chapter review and elsewhere.

A Quick Guide to Balancing Chemical Equations

Unbalanced equations are balanced by changing the *coefficients*. Subscripts should **never** be changed, because this changes the chemical's identity—H_2O is water, but H_2O_2 is hydrogen peroxide. Also, a coefficient is a multiplier for all the atoms within a molecule. Writing 2 Fe_2O_3, for example, means four Fe atoms and six O atoms.

1. Focus on balancing only one element at a time. Start with the leftmost element and modify the coefficients so that this element appears on both sides of the arrow the same number of times.

2. Move to the next element and modify the coefficients so as to balance this element. Do not worry if you incidentally unbalance the previous element. You will come back to it in subsequent steps.

3. Continue from left to right focusing on only one element at a time. Change coefficients as needed for that one element and don't worry about messing up the other elements by doing so.

4. Repeat steps 1–3 until all the elements are balanced.

CONCEPT **CHECK**

Write a balanced equation for the reaction showing hydrogen gas, H_2, and nitrogen gas, N_2, forming ammonia gas, NH_3:

$$\_\_\_H_2(g) + \_\_\_N_2(g) \rightarrow \_\_\_NH_3(g)$$

CHECK YOUR ANSWER

Initially, we see two hydrogen atoms before the reaction arrow and three on the right. This can be remedied by placing a coefficient of 3 by the hydrogen, H_2, and a coefficient of 2 by the ammonia, NH_3. This makes for six hydrogen atoms both before and after the reaction arrow. Meanwhile, the coefficient of 2 by the ammonia also makes for two nitrogen atoms after the arrow, which balances out the two nitrogen atoms appearing before the arrow. The full balanced equation, therefore, is

$$3\,H_2(g) + N_2(g) \longrightarrow 2\,NH_3(g)$$

Types of Chemical Equations

Chemical equations can be classified based upon how the atoms of a reaction rearrange to become products. Five categories include: synthesis, decomposition, single replacement, double replacement, and combustion.

Synthesis

Within a synthesis reaction two or more reactants combine to make a product containing the atoms of the reactants in some combination. It follows the general formula A + B $\rightarrow$ AB. Some examples include the formation of ammonia, NH_3, and water, H_2O:

$$3\,H_2 + N_2 \rightarrow 2\,NH_3$$

$$2\,H_2 + O_2 \rightarrow 2\,H_2O$$

Decomposition

Within a decomposition reaction, a reactant consisting of a grouping of multiple atoms splits apart into multiple products. A decomposition reaction follows the general formula AB $\rightarrow$ A + B. Some examples include the decomposition of calcium carbonate, $CaCO_3$, and hydrogen peroxide, H_2O_2:

$$CaCO_3 \rightarrow CaO + CO_2$$

$$2\,H_2O_2 \rightarrow 2\,H_2O + O_2$$

Single Replacement

Within a single replacement reaction, an atom (or polyatomic ion) jumps from one reactant to another. A single replacement reaction follows the general formula AX + B $\rightarrow$ A + BX. Some examples include the zinc, Zn, plus copper chloride, $CuCl_2$, reaction and the potassium, K, plus water, H_2O, reaction:

$$Zn + CuCl_2 \rightarrow ZnCl_2 + Cu$$

$$2\,K + 2\,H_2O \rightarrow 2\,KOH + H_2$$

Double Replacement

Within the double replacement reaction, an atom (or polyatomic ion) jumps from each reactant—there is a double switch. A double replacement reaction follows the general formula AY + BX $\rightarrow$ BY + AX. Some examples include the silver nitrate, $AgNO_3$, plus sodium chloride, NaCl reaction and the hydrogen chloride, HCl, plus sodium hydroxide, NaOH, reaction:

$$AgNO_3 + NaCl \rightarrow AgCl + NaNO_3$$

$$HCl + NaOH \rightarrow HOH + NaCl$$

Combustion Reaction

Lastly, there's the combustion reaction, which we'll explore in more detail in Chapter 11. A combustion reaction is the burning that occurs when a carbon compound, such as is found within wood, is ignited to react with oxygen, O_2. The products of a combustion reaction include carbon dioxide, CO_2, and water, H_2O plus lots of energy. Some examples include the combustion of methane, CH_4, and glucose, $C_6H_{12}O_6$:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$$

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O$$

CONCEPT **CHECK**

Balance and then interpret the following chemical equations as representing *synthesis*, *decomposition*, *single replacement*, *double replacement*, or a *combustion reaction*:

a) ___ $KClO_3$ (*s*) → ___ KCl (*s*) + ___ O_2 (*g*)

b) ___ $BaCl_2$ (*aq*) + ___ Na_2SO_4 (*aq*) → ___ $BaSO_4$ (*s*) + ___ NaCl (*aq*)

c) ___ C_3H_8O (*l*) → ___ C_3H_6 (*l*) + ___ H_2O (*l*)

d) ___ C_2H_2 (*g*) + ___ O_2 (*g*) → ___ CO_2 (*g*) + ___ H_2O (*g*)

e) ___ H_2 (*g*) + ___ Cl_2 (*g*) → ___ HCl (*g*)

f) ___ NH_3 (*g*) → ___ N_2 (*g*) + ___ H_2 (*g*)

g) ___ Cl_2 (*g*) + ___ NaBr (*aq*) → ___ NaCl (*aq*) + ___ Br_2 (*g*)

h) ___ N_2 (*g*) + ___ H_2 (*g*) → ___ NH_3 (*g*)

i) ___ Na (*l*) + ___ KCl (*l*) → ___ NaCl (*l*) + ___ K (*l*)

j) ___ $Pb(NO_3)_2$ (*aq*) + ___ KI (*aq*) → ___ KNO_3 (*aq*) + ___ PbI_2 (*s*)

CHECK YOUR ANSWERS

a) 2 $KClO_3$ (*s*) → 2 KCl (*s*) + 3 O_2 (*g*)	*decomposition*
b) $BaCl_2$ (*aq*) + Na_2SO_4 (*aq*) → $BaSO_4$ (*s*) + 2 NaCl (*aq*)	*double replacement*
c) C_3H_8O (*l*) → C_3H_6 (*l*) + H_2O (*l*)	*decomposition*
d) 2 C_2H_2 (*g*) + 5 O_2 (*g*) → 4 CO_2 (*g*) + 2 H_2O (*g*)	*combustion*
e) H_2 (*g*) + Cl_2 (*g*) → 2 HCl (*g*)	*synthesis*
f) 2 NH_3 (*g*) → N_2 (*g*) + 3 H_2 (*g*)	*decomposition*
g) Cl_2 (*g*) + 2 NaBr (*aq*) → 2 NaCl (*aq*) + Br_2 (*g*)	*single replacement*
h) N_2 (*g*) + 3 H_2 (*g*) → 2 NH_3 (*g*)	*synthesis*
i) Na (*l*) + KCl (*l*) → NaCl (*l*) + K (*l*)	*single replacement*
j) $Pb(NO_3)_2$ (*aq*) + 2 KI (*aq*) → 2 KNO_3 (*aq*) + PbI_2 (*s*)	*double replacement*