Third Edition

CHEMISTRY

The Central Science

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3 Stoichiometry

Antoine Lavoisier (Section 1.1) was among the first to draw conclusions about chemical processes from careful, quantitative observations. His work laid the basis for the law of conservation of mass, one of the most fundamental laws of chemistry. In this chapter, we will consider many practical problems based on the law of conservation of mass. These problems involve the quantitative relationships between substances undergoing chemical changes. The study of these quantitative relationships is known as **stoichiometry** (pronounced stoy-key-AHM-uh-tree), a word derived from the Greek words *stoicheion* ("element") and *metron* ("measure").

3.1 LAW OF CONSERVATION OF MASS

Studies of countless chemical reactions have shown that the total mass of all substances present after a chemical reaction is the same as the total mass before the reaction. This observation is embodied in the **law of conservation of mass:** There are no *detectable* changes in mass in any chemical reaction.* More precisely, *atoms are neither created nor destroyed during a chemical reaction;* instead, they merely exchange partners or become otherwise rearranged. The simplicity with which this law can be stated should not mask its significance. As with many other scientific laws, this law has implications far beyond the walls of the scientific laboratory.

The law of conservation of mass reminds us that we really can't throw anything away. If we discharge wastes into a lake to get rid of them, they are diluted and seem to disappear. However, they are part of the envi-

*In Chapter 19, we will discuss the relationship between mass and energy summarized by the equation $E = mc^2$ (E is energy, m is mass, and c is the speed of light). We will find that whenever an object loses energy it loses mass, and whenever it gains energy it gains mass. These changes in mass are too small to detect in chemical reactions. However, for nuclear reactions, such as those involved in a nuclear reactor or in a hydrogen bomb, the energy changes are enormously larger; in these reactions there are detectable changes in mass.

ronment. They may undergo chemical changes or remain inactive; they may reappear as toxic contaminants in fish or in water supplies or lie on the bottom unnoticed. Whatever their fates, the atoms are not destroyed.

The law of conservation of mass suggests that we are converters, not consumers. In drawing upon nature's storehouse of iron ore to build the myriad iron-containing objects used in modern society, we are not reducing the number of iron atoms on the planet. We may, however, be converting the iron to less useful, less available forms from which it will not be practical to recover it later. For example, consider the millions of old washing machines that lie buried in dumps. Of course, if we expend enough energy, we can bring off almost any chemical conversions we choose. We have learned in recent years, however, that energy itself is a limited resource. Whether we like it or not, we must learn to conserve all our energy and material resources.

3.2 CHEMICAL EQUATIONS

We have seen (in Sections 2.2 and 2.6) that chemical substances can be represented by symbols and formulas. These chemical symbols and formulas can be combined to form a kind of statement, called a **chemical equation,** that represents or describes a chemical reaction. For example, the combustion of carbon involves a reaction with oxygen (O_2) in the air to form gaseous carbon dioxide (CO_2). This reaction is represented as

$$C + O_2 \longrightarrow CO_2 \qquad [3.1]$$

We read the + sign to mean "reacts with" and the arrow as "produces." Carbon and oxygen are referred to as **reactants** and carbon dioxide as the **product** of the reaction.

It is important to keep in mind that a chemical equation is a description of a chemical process. Before you can write a complete equation you must know what happens in the reaction or be prepared to predict the products. In this sense, a chemical equation has qualitative significance; it identifies the reactants and products in a chemical process. In addition, a chemical equation is a quantitative statement; it must be consistent with the law of conservation of mass. This means that the equation must contain equal numbers of each type of atom on each side of the equation. When this condition is met the equation is said to be **balanced.** For example, Equation 3.1 is balanced because there are equal numbers of carbon and oxygen atoms on each side.

A slightly more complicated situation is encountered when methane (CH_4), the principal component of natural gas, burns and produces carbon dioxide (CO_2) and water (H_2O). The combustion is "supported by" oxygen (O_2), meaning that oxygen is involved as a reactant. The unbalanced equation is

$$CH_4 + O_2 \longrightarrow CO_2 + H_2O \qquad [3.2]$$

The reactants are shown to the left of the arrow, the products to the right. Notice that the reactants and products both contain one carbon atom. However, the reactants contain more hydrogen atoms (four) than the products (two). If we place a coefficient 2 in front of H_2O, indicating formation of two molecules of water, there will be four hydrogens on each side of the equation:

$$CH_4 + O_2 \longrightarrow CO_2 + 2H_2O \qquad [3.3]$$

Before we continue to balance this equation, let's make sure that we clearly understand the distinction between a coefficient in front of a formula and a subscript in a formula. Refer to Figure 3.1. Notice that changing a subscript in a formula, such as from H_2O to H_2O_2, changes the identity of the chemical involved. The substance H_2O_2, hydrogen peroxide, is quite different from water. *The subscripts in the chemical formulas should never be changed in balancing an equation.* On the other hand, placing a coefficient in front of a formula merely changes the amount and not the identity of the substance; $2H_2O$ means two molecules of water, $3H_2O$ means three molecules of water, and so forth. Now let's continue balancing Equation 3.3. There are equal numbers of carbon and hydrogen atoms on both sides of this equation; however, there are more oxygen atoms among the products (four) than among the reactants (two). If we place a coefficient 2 in front of O_2 there will be equal numbers of oxygen atoms on both sides of the equation:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O \qquad [3.4]$$

The equation is now balanced. There are four oxygen atoms, four hydrogen atoms, and one carbon atom on each side of the equation. The balanced equation is shown schematically in Figure 3.2.

Now, let's look at a slightly more complicated example, analyzing stepwise what we are doing as we balance the equation. Combustion of octane (C_8H_{18}), a component of gasoline, produces CO_2 and H_2O. The balanced chemical equation for this reaction can be determined by using the following four steps.

First, the reactants and products are written in the unbalanced equation

$$C_8H_{18} + O_2 \longrightarrow CO_2 + H_2O \qquad [3.5]$$

Before a chemical equation can be written the identities of the reactants and products must be determined. In the present example this information was given to us in the verbal description of the reaction.

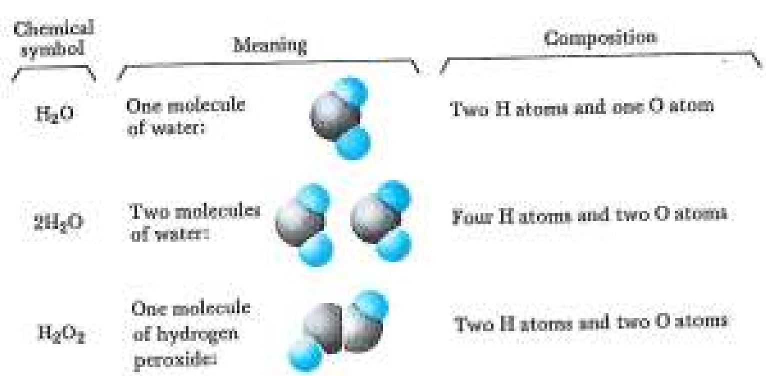

FIGURE 3.1 Illustration of the difference in meaning between a subscript in a chemical formula and a coefficient in front of the formula. Notice that the number of atoms of each type (listed under composition) is obtained by multiplying the coefficient and the subscript associated with each element in the formula.

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