4.1 Chemical Equations

Section Preview/ Specific Expectations

In this section, you will

- **use** word equations and skeleton equations to describe chemical reactions
- **balance** chemical equations
- **communicate** your understanding of the following terms: *chemical reactions, reactant, product, chemical equations, word equation, skeleton equation, law of conservation of mass, balanced chemical equation*

In Chapter 3, you learned how and why elements combine to form different compounds. In this section, you will learn how to describe what happens when elements and compounds interact with one another to form new substances. These interactions are called **chemical reactions**. A substance that undergoes a chemical reaction is called a **reactant**. A substance that is formed in a chemical reaction is called a **product**.

For example, when the glucose in a marshmallow reacts with oxygen in the air to form water and carbon dioxide, the glucose and oxygen are the reactants. The carbon dioxide and water are the products. Chemists use **chemical equations** to communicate what is occurring in a chemical reaction. Chemical equations come in several forms. All of these forms condense a great deal of chemical information into a short statement.

Word Equations

A **word equation** identifies the reactants and products of a chemical reaction by name. In Chapter 3, you learned that chlorine and sodium combine to form the ionic compound sodium chloride. This reaction can be represented by the following word equation:

$$\text{sodium} + \text{chlorine} \rightarrow \text{sodium chloride}$$

In this equation, "+" means "reacts with" and "→" means "to form." Try writing some word equations in the following Practice Problems.

CHECKPOINT

Write the chemical formulas of the products in the reactions described in Practice Problem 1.

Practice Problems

1. Describe each reaction using a word equation. Label the reactant(s) and product(s).
   - **(a)** Calcium and fluorine react to form calcium fluoride.
   - **(b)** Barium chloride and hydrogen sulfate react to form hydrogen chloride and barium sulfate.
   - **(c)** Calcium carbonate, carbon dioxide, and water react to form calcium hydrogen carbonate.
   - **(d)** Hydrogen peroxide reacts to form water and oxygen.
   - **(e)** Sulfur dioxide and oxygen react to form sulfur trioxide.
2. Yeast can facilitate a reaction in which the sugar in grapes reacts to form ethanol and carbon dioxide. Write a word equation to describe this reaction.

CHEM FACT

Caffeine is an ingredient in coffee, tea, chocolate, and cola drinks. Its chemical name is 1,3,7-trimethylxanthene. You can see how long names like this would become unwieldy in word equations.

Word equations are useful because they identify the products and reactants in a chemical reaction. They do not, however, provide any chemical information about the compounds and elements themselves. If you did not know the formula for sodium chloride, for example, this equation would not help you understand the reaction very well. Another shortcoming of a word equation is that the names for chemicals are often very long and cumbersome. Chemists have therefore devised a more convenient way of representing reactants and products.

Skeleton Equations

Using a chemical formula instead of a chemical name simplifies a chemical equation. It allows you to see at a glance what elements and compounds are involved in the reaction. A **skeleton equation** lists the chemical formula of each reactant on the left, separated by a + sign if more than one reactant is involved, followed by an arrow →. The chemical formula of each product is listed on the right, again separated by a + sign if more than one product is produced. A skeleton equation also shows the state of each reactant by using the appropriate subscript, as shown in Table 4.1.

The reaction of sodium metal with chlorine gas to form sodium chloride can be represented by the following skeleton equation:

$$Na_{(s)} + Cl_{2(g)} \rightarrow NaCl_{(s)}$$

A skeleton equation is more useful to a chemist than a word equation, because it shows the formulas of the compounds involved. It also shows the state of each substance.Try writing some skeleton equations in the following Practice Problems.

Table 4.1 Symbols Used in Chemical Equations

Symbol	Meaning
+	reacts with (reactant side)
+	and (product side)
→	to form
(s)	solid or precipitate
(ℓ)	liquid
(g)	gas
(aq)	in aqueous (water) solution

Practice Problems

3. Write a skeleton equation for each reaction.

(a) Solid zinc reacts with chlorine gas to form solid zinc chloride.

(b) Solid calcium and liquid water react to form solid calcium hydroxide and hydrogen gas.

(c) Solid barium reacts with solid sulfur to produce solid barium sulfide.

(d) Aqueous lead(II) nitrate and solid magnesium react to form aqueous magnesium nitrate and solid lead.

4. In each reaction below, a solid reacts with a gas to form a solid. Write a skeleton equation for each reaction.

(a) carbon dioxide + calcium oxide → calcium carbonate

(b) aluminum + oxygen → aluminum oxide

(c) magnesium + oxygen → magnesium oxide

Why Skeleton Equations Are Incomplete

Although skeleton equations are useful, they do not fully describe chemical reactions. To understand why, consider the skeleton equation showing the formation of sodium chloride (above). According to this equation, one sodium atom reacts with one chlorine molecule containing two chlorine atoms. The product is one formula unit of sodium chloride, containing one atom of sodium and one atom of chlorine. Where has the extra chlorine atom gone?

The Law of Conservation of Mass

All atoms must be accounted for, according to an important law. The **law of conservation of mass** states that *in any chemical reaction, the mass of the products is always equal to the mass of the reactants*. In other words, according to this law, matter can be neither created nor destroyed. Chemical reactions proceed according to the law of conservation of mass, which is based on experimental evidence.

CHEM FACT

Many chemical reactions can go in either direction, so an arrow pointing in the opposite direction is often added to the equation. This can look like $\rightleftarrows$ or $\rightleftharpoons$. To indicate which reaction is more likely to occur, one arrow can be drawn longer than the other: for example: $\overset{\longrightarrow}{\leftarrow}$ or $\overset{\rightarrow}{\longleftarrow}$.

Careers in Chemistry

Food Chemist

How do you make a better tasting sports drink? How can you make a gravy mix that can be ready to serve in 5 min, yet maintain its consistency under a heat lamp for 8 h? Food chemists use their knowledge of chemical reactions to improve food quality and develop new products.

A good example of food chemistry in action is the red pimento stuffing in olives. Chopped pimentos (sweet red peppers) and sodium alginate are mixed. This mixture is then added to a solution of calcium chloride. The sodium alginate reacts with the calcium chloride. Solid calcium alginate forms, which causes the stream of pimento mixture to form a gel instantly. The gelled strip is then sliced thinly and stuffed into the olives.

Food chemists work in universities, government laboratories, and major food companies. To become a food chemist, most undergraduates take a food science degree with courses in chemistry. It is also possible to become a food chemist with an undergraduate chemistry degree plus experience in the food industry. Students can specialize in food chemistry at the graduate level.

Make Career Connections

1. If you are interested in becoming a food chemist, you can look for a summer or part-time job in the food industry.
2. To find out more about food science, search for Agriculture and Agri-Food Canada's web site and the Food Web web site. You can also contact the Food Science department of a university.

History LINK

Jan Baptista van Helmont (1577–1644) was a Flemish physician who left medical practice to devote himself to the study of chemistry. He used the mass balance in an important experiment that laid the foundations for the law of conservation of mass. He showed that a definite quantity of sand could be fused with excess alkali to form a kind of glass. He also showed that when this product was treated with acid, it regenerated the original amount of sand (silica). As well, Van Helmont is famous for demonstrating the existence of gases, which he described as "aerial fluids." Investigate on the Internet or in the library to find out how he did this.

Balanced Chemical Equations

A **balanced chemical equation** reflects the law of conservation of mass. This type of equation shows that there is the same number of each kind of atom on both sides of the equation. Some skeleton equations are, by coincidence, already balanced. For example, examine the reaction of carbon with oxygen to form carbon dioxide, shown in Figure 4.1. In the skeleton equation, one carbon atom and two oxygen atoms are on the left side of the equation, and one carbon atom and two oxygen atoms are on the right side of the equation.

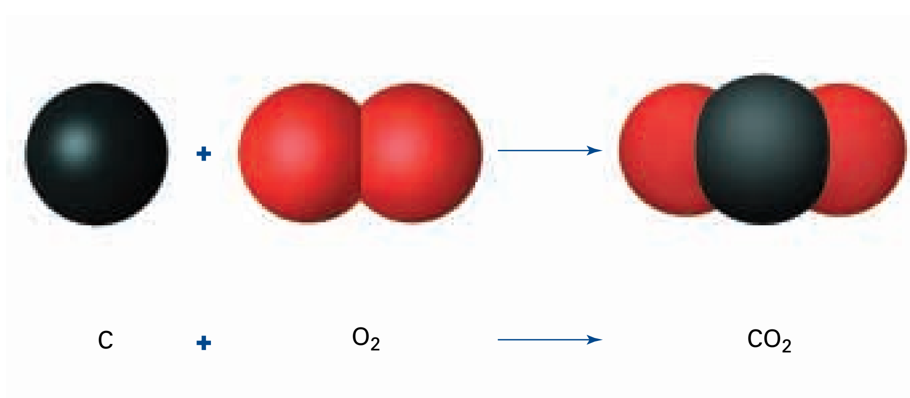

Figure 4.1 This skeleton equation is already balanced.

Most skeleton equations, however, are not balanced, such as the one showing the formation of sodium chloride. Examine Figure 4.2 to see why. There is one sodium atom on each side of the equation, but there are two chlorine atoms on the left side and only one chlorine atom on the right side.

To begin to balance an equation, you can add numbers in front of the appropriate formulas. The numbers that are placed in front of chemical formulas are called **coefficients**. They represent how many of each atom, molecule, or formula unit take part in each reaction. For example, if you add a coefficient of 2 to NaCl in the equation in Figure 4.2, you indicate that two formula units of NaCl are produced in the reaction. Is the equation balanced now? As you can see by examining Figure 4.3, it is not. The chlorine atoms are balanced, but now there is one sodium atom on the left side of the equation and two sodium atoms on the right side.

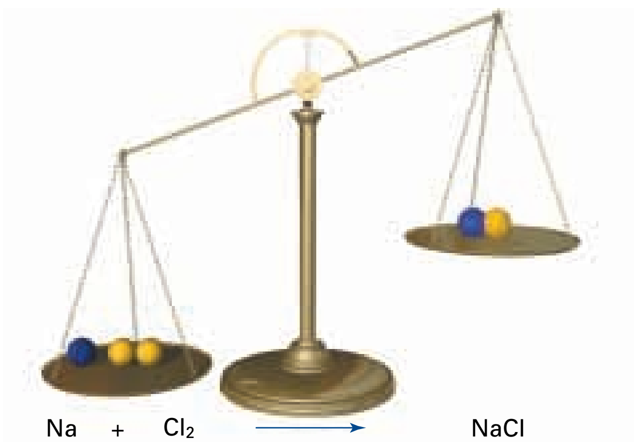

Figure 4.2 **This skeleton equation is unbalanced. The mass of the reactants is greater than the mass of the product.**

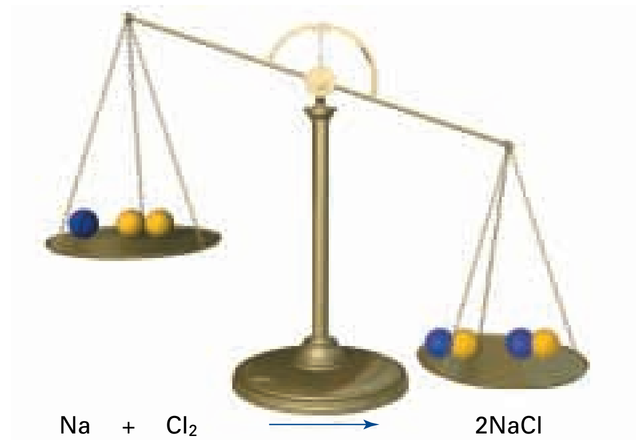

Figure 4.3 **The equation is still unbalanced. The mass of the product is now greater than the mass of the reactants.**

Add a coefficient of 2 to the sodium on the reactant side. As you can see in Figure 4.4, the equation is now balanced. The mass of the products is equal to the mass of the reactants. This balanced chemical equation satisfies the law of conservation of mass.

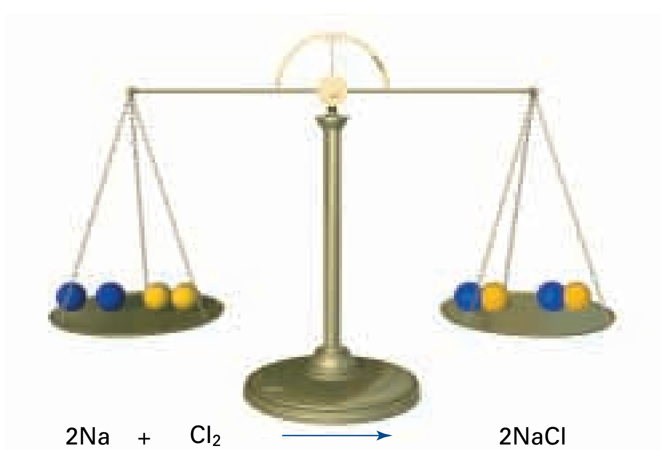

Figure 4.4 **The equation is now balanced according to the law of conservation of mass.**

mind STRETCH

Why is it *not* acceptable to balance the equation

$$Na + Cl_2 \rightarrow NaCl$$

by changing the formula of NaCl to $NaCl_2$? Would this not satisfy the law of conservation of mass? Write an explanation in your notebook.

You cannot balance an equation by changing any of the chemical formulas. The only way to balance a chemical equation is to put the appropriate numerical coefficient in front of each compound or element in the equation.

Many skeleton equations are simple enough to balance by a back-and-forth process of reasoning, as you just saw with the sodium chloride reaction. Try balancing the equations in the Practice Problems that follow.

Practice Problems

5. Copy each skeleton equation into your notebook, and balance it.

(a) $S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$

(b) $P_{4(s)} + O_{2(g)} \rightarrow P_4O_{10(s)}$

(c) $H_{2(g)} + Cl_{2(g)} \rightarrow HCl_{(g)}$

(d) $SO_{2(g)} + H_2O_{(\ell)} \rightarrow H_2SO_{3(aq)}$

6. Indicate whether these equations are balanced. If they are not, balance them.

(a) $4Fe_{(s)} + 3O_{2(g)} \rightarrow 2Fe_2O_{3(s)}$

(b) $HgO_{(s)} \rightarrow Hg_{(\ell)} + O_{2(g)}$

(c) $H_2O_{2(aq)} \rightarrow 2H_2O_{(\ell)} + O_{2(g)}$

(d) $2HCl_{(aq)} + Na_2SO_{3(aq)} \rightarrow 2NaCl_{(aq)} + H_2O_{(\ell)} + SO_{2(g)}$

Steps for Balancing Chemical Equations

More complex chemical equations than the ones you have already tried can be balanced by using a combination of inspection and trial and error. Here, however, are some steps to follow.

Step 1 Write out the skeleton equation. Ensure that you have copied all the chemical formulas correctly.

Step 2 Begin by balancing the atoms that occur in the largest number on either side of the equation. Leave hydrogen, oxygen, and other elements until later.

Step 3 Balance any polyatomic ions, such as sulfate, SO_4^{2-}, that occur on both sides of the chemical equation as an ion unit. That is, do not split a sulfate ion into 1 sulfur atom and 4 oxygen atoms. Balance this ion as one unit.

Step 4 Next, balance any hydrogen or oxygen atoms that occur in a combined and uncombined state. For example, combined oxygen might be in the form of CO_2, while uncombined oxygen occurs as O_2.

Step 5 Finally, balance any other element that occurs in its uncombined state: for example, Na or Cl_2.

Step 6 Check your answer. Count the number of each type of atom on each side of the equation. Make sure that the coefficients used are whole numbers in their lowest terms.

Examine the following Sample Problem to see how these steps work.

Electronic Learning Partner

Go to the Chemistry 11 Electronic Learning Partner for some extra practice balancing chemical equations.

Sample Problem

Balancing Chemical Equations

Problem

Copper(II) nitrate reacts with potassium hydroxide to form potassium nitrate and solid copper(II) hydroxide.
Balance the equation.

$$Cu(NO_3)_{2(aq)} + KOH_{(aq)} \rightarrow Cu(OH)_{2(s)} + KNO_{3(aq)}$$

What Is Required?

The atoms of each element on the left side of the equation should equal the atoms of each element on the right side of the equation.

Plan Your Strategy

Balance the polyatomic ions first (NO_3^-, then OH^-). Check to see whether the equation is balanced. If not, balance the potassium and copper ions. Check your equation again.

Act on Your Strategy

There are two NO_3^- ions on the left, so put a 2 in front of KNO_3.

$$Cu(NO_3)_{2(aq)} + KOH_{(aq)} \rightarrow Cu(OH)_{2(s)} + 2KNO_{3(aq)}$$

To balance the two OH^- ions on the right, put a 2 in front of the KOH.

$$Cu(NO_3)_{2(aq)} + 2KOH_{(aq)} \rightarrow Cu(OH)_{2(s)} + 2KNO_{3(aq)}$$

Check to see that the copper and potassium ions are balanced. They are, so the equation above is balanced.

Check Your Solution

Tally the number of each type of atom on each side of the equation.

$$Cu(NO_3)_{2(aq)} + 2KOH_{(aq)} \rightarrow Cu(OH)_{2(s)} + 2KNO_{3(aq)}$$

	Left Side	Right Side
Cu	1	1
NO_3^-	2	2
K	2	2
OH^-	2	2

Practice Problems

7. Copy each chemical equation into your notebook, and balance it.

(a) $SO_{2(g)} + O_{2(g)} \rightarrow SO_{3(g)}$

(b) $BaCl_{2(aq)} + Na_2SO_{4(aq)} \rightarrow NaCl_{(aq)} + BaSO_{4(s)}$

8. When solid white phosphorus, P_4, is burned in air, it reacts with oxygen to produce solid tetraphosphorus decoxide, P_4O_{10}. When water is added to the P_4O_{10}, it reacts to form aqueous phosphoric acid, H_3PO_4. Write and balance the chemical equations that represent these reactions.

Continued ...

Math LINK

What does it mean when a fraction is expressed in lowest terms? The fraction $\frac{5}{10}$, expressed in lowest terms, is $\frac{1}{2}$. Similarly, the equation

$4H_{2(g)} + 2O_{2(g)} \rightarrow 4H_2O_{(\ell)}$

is balanced, but it can be simplified by dividing all the coefficients by two.

$2H_{2(g)} + O_{2(g)} \rightarrow 2H_2O_{(\ell)}$

Write the balanced equation $6KClO_{3(s)} \rightarrow 6KCl_{(g)} + 9O_{2(s)}$ so that the coefficients are the lowest possible whole numbers. Check that the equation is still balanced.

Continued ...
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9. Copy each chemical equation into your notebook, and balance it.

(a) $As_4S_{6(s)} + O_{2(g)} \rightarrow As_4O_{6(s)} + SO_{2(g)}$

(b) $Sc_2O_{3(s)} + H_2O_{(\ell)} \rightarrow Sc(OH)_{3(s)}$

(c) $C_2H_5OH_{(\ell)} + O_{2(g)} \rightarrow CO_{2(g)} + H_2O_{(\ell)}$

(d) $C_4H_{10(g)} + O_{2(g)} \rightarrow CO_{(g)} + H_2O_{(g)}$

Section Wrap-up

In this section, you learned how to represent chemical reactions using balanced chemical equations. Because there are so many different chemical reactions, chemists have devised different classifications for these reactions. In section 4.2, you will learn about five different types of chemical reactions.

Section Review

1 MC In your own words, explain what a chemical reaction is. Write descriptions of four chemical reactions that you encounter every day.

2 C Write a word equation, skeleton equation, and balanced equation for each reaction.

(a) Sulfur dioxide gas reacts with oxygen gas to produce gaseous sulfur trioxide.

(b) Metallic sodium reacts with liquid water to produce hydrogen gas and aqueous sodium hydroxide.

(c) Copper metal reacts with an aqueous hydrogen nitrate solution to produce aqueous copper(II) nitrate, nitrogen dioxide gas, and liquid water.

3 K/U The equation for the decomposition of hydrogen peroxide, H_2O_2 is $H_2O_{2(aq)} \rightarrow H_2O_{(\ell)} + O_{2(g)}$. Explain why you cannot balance it by writing it as $H_2O_{2(aq)} \rightarrow H_2O_{(\ell)} + O_{(g)}$

4 K/U Balance the following chemical equations.

(a) $Al_{(s)} + O_{2(g)} \rightarrow Al_2O_{3(s)}$

(b) $Na_2S_2O_{3(aq)} + I_{2(aq)} \rightarrow NaI_{(aq)} + Na_2S_4O_{6(aq)}$

(c) $Al_{(s)} + Fe_2O_{3(s)} \rightarrow Al_2O_{3(s)} + Fe_{(s)}$

(d) $NH_{3(g)} + O_{2(g)} \rightarrow NO_{(g)} + H_2O_{(\ell)}$

(e) $Na_2O_{(s)} + (NH_4)_2SO_{4(aq)} \rightarrow Na_2SO_{4(aq)} + H_2O_{(\ell)} + NH_{3(aq)}$

(f) $C_5H_{12(\ell)} + O_{2(g)} \rightarrow CO_{2(g)} + H_2O_{(g)}$

5 I A student places 0.58 g of iron and 1.600 g of copper(II) sulfate in a reaction vessel. The reaction vessel has a mass of 40.32 g, and it contains 100.00 g of water. The aqueous copper sulfate and solid iron react to form solid copper and aqueous iron(II) sulfate. After the reaction, the reaction vessel plus the products have a mass of 142.5 g. Explain the results. Then write a balanced chemical equation to describe the reaction.