11.1 Describing Chemical Reactions

Connecting to Your World On May 6, 1937, the huge airship Hindenburg was heading for its landing site in Lakehurst, New Jersey, after an uneventful trans-Atlantic crossing. Suddenly, to the horror of observers on the ground, the airship erupted into a fireball. Within a short time, 210,000 cubic meters of the airship's lifting gas, hydrogen, had burned and the airship was destroyed. The chemical reaction that occurred can be described as "hydrogen combines with oxygen to produce water." In this section, you will learn to represent this chemical reaction by a chemical equation.

Guide for Reading

Key Concepts

- How do you write a word equation?
- How do you write a skeleton equation?
- What are the steps in writing a balanced chemical equation?

Vocabulary

chemical equation
skeleton equation
catalyst
coefficients
balanced equation

Reading Strategy

Relating Text and Visuals As you read this section, look at the illustrations of equations. In your notebook, explain how the illustrations demonstrate the difference between a balanced and unbalanced chemical equation.

Writing Chemical Equations

Every minute of the day chemical reactions take place—both inside you and around you. Not all are as dramatic as the explosion of the Hindenburg, but many are more complex. After a meal, a series of chemical reactions take place as your body digests food. Similarly, plants use sunlight to drive the photosynthetic processes needed to produce plant growth. Although the chemical reactions involved in photosynthesis and digestion are different, both chemical reactions are necessary to sustain life.

In a chemical reaction, one or more reactants change into one or more products. Figure 11.1a shows the ingredients for making leavened bread—flour, salt, yeast, and water. Chemical reactions take place when the ingredients are mixed together and heated in the oven. Figure 11.1b shows the product—a loaf of bread. Chemists use a chemical equation—a quick, shorthand notation—to convey as much information as possible about what happens in a chemical reaction.

Figure 11.1 Chemical changes occur when bread dough is mixed and baked. **a** Flour, salt, yeast, and water are the ingredients for making leavened bread.
b Reactants in the ingredients undergo chemical changes to form the product (baked bread).
Observing ***What evidence shows that chemical changes have occurred?***

Figure 11.2 Three common chemical reactions are shown. **a** When methane gas burns, it combines with oxygen to form carbon dioxide and water. **b** Iron turns to red-brown rust (iron(III) oxide) in the presence of oxygen in the air. **c** Hydrogen peroxide decomposes to water and oxygen when used as an antiseptic.

Word Equations How do you describe what happens in a chemical reaction? Recall from Chapter 2 the shorthand method for writing a description of a chemical reaction. In this method, the reactants were written on the left and the products on the right. An arrow separated them. You read the arrow as *yields, gives,* or *reacts to produce.*

Reactants ⟶ products

How could you describe the rusting of iron shown in Figure 11.2b? You could say: "Iron reacts with oxygen to produce iron(III) oxide (rust)." That's a perfectly good description, but it might be quicker and easier to identify the reactants and product by means of a word equation.

Iron + oxygen ⟶ iron(III) oxide

To write a word equation, write the names of the reactants to the left of the arrow separated by plus signs; write the names of the products to the right of the arrow, also separated by plus signs. Notice that no plus sign is needed on the product side of this equation because iron(III) oxide is the only product.

Have you ever poured the antiseptic hydrogen peroxide on an open cut? Bubbles of oxygen gas form rapidly, as shown in Figure 11.2c. The production of a new substance, a gas, is evidence of a chemical change. Two new substances are produced in this reaction, oxygen gas and liquid water. You could describe this reaction by saying, "Hydrogen peroxide decomposes to form water and oxygen gas." You could also write a word equation.

Hydrogen peroxide ⟶ water + oxygen

When you light a burner on your stove, methane gas bursts into flames and produces the energy needed to heat your soup. Methane is the major component of natural gas, a common fuel for heating homes and cooking food. The burning of methane, as shown in Figure 11.2a, is a chemical reaction. How would you write the word equation for this reaction? Burning a substance typically requires oxygen, so methane and oxygen are the reactants. The products are water and carbon dioxide. Thus the word equation is this:

Methane + oxygen ⟶ carbon dioxide + water

Checkpoint ***What does the arrow (⟶) in a word equation mean?***

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Chemical Equations Word equations adequately describe chemical reactions, but they are cumbersome. It's easier to use the formulas for the reactants and products to write chemical equations. A **chemical equation** is a representation of a chemical reaction; the formulas of the reactants (on the left) are connected by an arrow with the formulas of the products (on the right). Here is a chemical equation for rusting:

$$Fe + O_2 \longrightarrow Fe_2O_3$$

Equations that show just the formulas of the reactants and products are called skeleton equations. A **skeleton equation** is a chemical equation that does not indicate the relative amounts of the reactants and products. The first step in writing a complete chemical equation is to write the skeleton equation. **Write the formulas of the reactants to the left of the yields sign (arrow) and the formulas of the products to the right.**

To add more information to the equation, you can indicate the physical states of substances by putting a symbol after each formula. Use (*s*) for a solid, (*l*) for a liquid, (*g*) for a gas, and (*aq*) for a substance in aqueous solution (a substance dissolved in water). Here is the equation for rusting with symbols for the physical states added:

$$Fe(s) + O_2(g) \longrightarrow Fe_2O_3(s)$$

In many chemical reactions, a catalyst is added to the reaction mixture. A **catalyst** is a substance that speeds up the reaction but is not used up in the reaction. A catalyst is neither a reactant nor a product, so its formula is written above the arrow in a chemical equation. For example, Figure 11.3 shows that the compound manganese(IV) oxide ($MnO_2(s)$) catalyzes the decomposition of an aqueous solution of hydrogen peroxide ($H_2O_2(aq)$) to produce water and oxygen.

$$H_2O_2(aq) \xrightarrow{MnO_2} H_2O(l) + O_2(g)$$

Many of the symbols commonly used in writing chemical equations are listed in Table 11.1.

Table 11.1

Symbols Used in Chemical Equations

Symbol	Explanation
+	Used to separate two reactants or two products
$\longrightarrow$	"Yields," separates reactants from products
$\rightleftharpoons$	Used in place of $\longrightarrow$ for reversible reactions
(*s*)	Designates a reactant or product in the solid state; placed after the formula
(*l*)	Designates a reactant or product in the liquid state; placed after the formula
(*g*)	Designates a reactant or product in the gaseous state; placed after the formula
(*aq*)	Designates an aqueous solution; the substance is dissolved in water; placed after the formula
$\xrightarrow{\Delta}$ $\xrightarrow{heat}$	Indicates that heat is supplied to the reaction
$\xrightarrow{Pt}$	A formula written above or below the yield sign indicates its use as a catalyst (in this example, platinum).

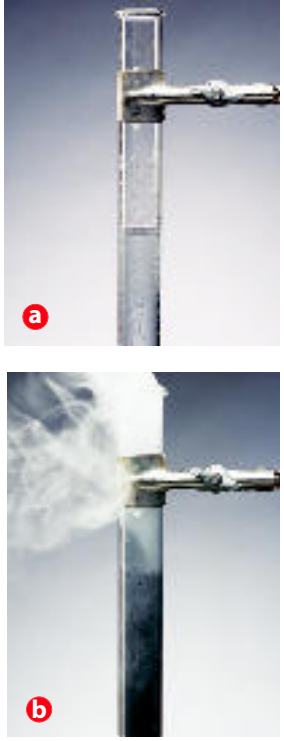

Figure 11.3 Hydrogen peroxide decomposes to form water and oxygen gas. **a** Bubbles of oxygen appear slowly as decomposition proceeds. **b** With the addition of the catalyst manganese(IV) oxide (MnO_2), decomposition speeds up. The white "smoke" is condensed water vapor.

Interactive Textbook

Animation 12 Relate chemical symbols and formulas to the information they communicate.

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CONCEPTUAL PROBLEM 11.1

Writing a Skeleton Equation

Hydrochloric acid and solid sodium hydrogen carbonate are shown before being placed in the beaker to react. The products formed are aqueous sodium chloride, water, and carbon dioxide gas. Write a skeleton equation for this chemical reaction.

1 Analyze ***Identify the relevant concepts.***
Write the correct formula for each substance in the reaction. Separate the reactants from the products by means of an arrow. Indicate the state of each substance.

2 Solve ***Apply concepts to this situation.***
solid sodium hydrogen carbonate: $NaHCO_3(s)$
hydrochloric acid: $HCl(aq)$
aqueous sodium chloride: $NaCl(aq)$
water: $H_2O(l)$
carbon dioxide gas: $CO_2(g)$
$NaHCO_3(s) + HCl(aq) \longrightarrow NaCl(aq) + H_2O(l) + CO_2(g)$

Practice Problems

1. Write a sentence that describes this chemical reaction.
$Na(s) + H_2O(l) \longrightarrow NaOH(aq) + H_2(g)$

2. Sulfur burns in oxygen to form sulfur dioxide. Write a skeleton equation for this chemical reaction. Include appropriate symbols from Table 11.1.

Interactive Textbook
Problem-Solving 11.2
Solve Problem 2 with the help of an interactive guided tutorial.
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Balancing Chemical Equations

How would you write a word equation for the manufacture of bicycles? Simplify your task by limiting yourself to four major components: frames, wheels, handlebars, and pedals. Your word equation for making a bicycle could read like this.

$$\underset{\text{(reactants)}}{\text{Frame + wheel + handlebar + pedal}} \longrightarrow \underset{\text{(product)}}{\text{bicycle}}$$

Your word equation shows the reactants (the kinds of parts) and the product (a bicycle). But if you were responsible for ordering parts to make a bicycle, this word equation would be inadequate because it does not indicate the quantity of each part needed to make one bicycle.

A standard bicycle is composed of one frame (F), two wheels (W), one handlebar (H), and two pedals (P). Using these symbols, the formula for a bicycle would be FW_2HP_2. The skeleton equation for bicycle assembly would be this:

$$F + W + H + P \longrightarrow FW_2HP_2$$

This is an unbalanced equation. An unbalanced equation does not indicate the quantity of the reactants needed to make the product. A complete description of the reaction must include not only the kinds of parts involved but also the quantities of parts required.

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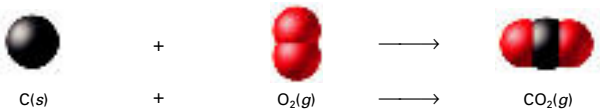
$$F + 2W + H + 2P \longrightarrow FW_2HP_2$$

This is a balanced equation for making a bicycle. It tells you that one frame, two wheels, one handlebar, and two pedals produce one bicycle. To balance the equation, the number 2 was placed before wheels and pedals. The number 1 is understood to be in front of frame, handlebar, and bicycle. These numbers are called **coefficients**—small whole numbers that are placed in front of the formulas in an equation in order to balance it. In this balanced equation, the number of each bicycle part on the reactant side is the same as the number of those parts on the product side. A chemical reaction is also described by a **balanced equation** in which each side of the equation has the same number of atoms of each element and mass is conserved. Real bicycles are being assembled in Figure 11.4.

Recall that John Dalton's atomic theory states that as reactants are converted to products, the bonds holding the atoms together are broken and new bonds are formed. The atoms themselves are neither created nor destroyed; they are merely rearranged. This part of Dalton's theory explains the law of conservation of mass: In any chemical change, mass is conserved. The atoms in the products are the same atoms that were in the reactants—they are just rearranged.

Representing a chemical reaction by a balanced chemical equation is a two-step process. **To write a balanced chemical equation, first write the skeleton equation. Then use coefficients to balance the equation so that it obeys the law of conservation of mass.** In every balanced equation, each side of the equation has the same number of atoms of each element.

Sometimes a skeleton equation may already be balanced. For example, carbon burns in the presence of oxygen to produce carbon dioxide.



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

Reactants
1 carbon atom, 2 oxygen atoms

Product
1 carbon atom, 2 oxygen atoms

This equation is balanced. One carbon atom and two oxygen atoms are on each side of the equation. You do not need to change the coefficients; they are all understood to be 1.

Checkpoint ***What is the law of conservation of mass?***

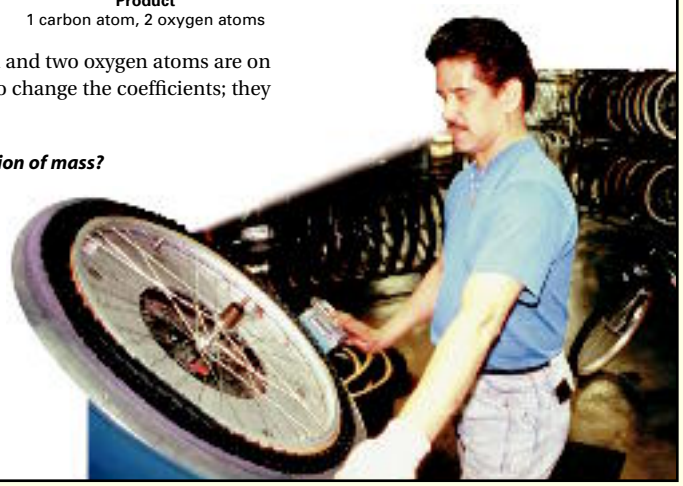


Figure 11.4 If a bicycle factory runs out of any part needed for a bicycle, production must stop.

Quick LAB

Removing Silver Tarnish

Materials

- aluminum foil, 20 cm × 20 cm
- large beaker or glass pan
- tarnished silver fork or spoon
- sodium hydrogen carbonate
- plastic tablespoon
- hot water

Procedure

1. Fill the beaker about three-quarters full of hot water and add 2 tablespoons of sodium hydrogen carbonate ($NaHCO_3$).
2. Crush the aluminum foil into a loose ball and place it in the beaker.
3. Write a brief description of the tarnished silver fork, then place it in the beaker so that it is touching the aluminum ball.
4. Allow the beaker to stand undisturbed for 30 minutes.
5. Remove the fork and aluminum ball and rinse them with water.

Analyze and Conclude

1. Compare the silver fork with your observations before placing the fork in the water. What changes do you observe?
2. Did a chemical reaction occur? How do you know?
3. The tarnish on the silver fork is silver sulfide (Ag_2S). Silver becomes tarnished when it is exposed to air, egg yolk, or rubber bands. Each of these substances contains sulfur. Look carefully for a pale yellow precipitate of aluminum sulfide on the bottom of the beaker. Write the formula for aluminum sulfide.
4. The unbalanced equation for the reaction is

$$Ag_2S(s) + Al(s) \longrightarrow Al_2S_3(s) + Ag(s)$$

Balance the equation.

What about the equation for the reaction of hydrogen gas and oxygen gas? This is the reaction that occurred in the Hindenburg disaster, which you read about in *Connecting to Your World.* When hydrogen and oxygen are mixed, a spark will initiate a rapid reaction. The product of the reaction is water. This is the equation for the burning of hydrogen:

$$H_2(g) + O_2(g) \longrightarrow H_2O(l)$$

Hydrogen + Oxygen ⟶ Water

Reactants
2 hydrogen atoms
2 oxygen atoms

Product
2 hydrogen atoms
1 oxygen atom

The formulas for all the reactants and product are correct, but this equation is not balanced. Count the atoms on both sides of the equation. Two oxygen atoms are on the reactant (left) side of the equation and only one oxygen atom is on the product (right) side. As written, the equation does not obey the law of conservation of mass and so it does not describe what really happens. What can you do to balance it? A few guidelines for writing and balancing equations will help.

Interactive Textbook

Simulation 11 Sharpen your skills by balancing chemical equations.

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Rules for Writing and Balancing Equations

1. Determine the correct formulas for all the reactants and products.
2. Write the skeleton equation by placing the formulas for the reactants on the left and the formulas for the products on the right with a yields sign (⟶) in between. If two or more reactants or products are involved, separate their formulas with plus signs.
3. Determine the number of atoms of each element in the reactants and products. Count a polyatomic ion as a single unit if it appears unchanged on both sides of the equation.
4. Balance the elements one at a time by using coefficients. When no coefficient is written, it is assumed to be 1. Begin by balancing elements that appear only once on each side of the equation. Never balance an equation by changing the subscripts in a chemical formula. Each substance has only one correct formula.
5. Check each atom or polyatomic ion to be sure they are equal on both sides of the equation.
6. Make sure all the coefficients are in the lowest possible ratio.

CONCEPTUAL PROBLEM 11.2

Writing a Balanced Chemical Equation

Hydrogen and oxygen react to form water. The reaction releases enough energy to launch a rocket. Write a balanced equation for the reaction.

1 Analyze ***Identify the relevant concepts.***
Apply the rules for balancing equations to the skeleton equation describing the reaction.

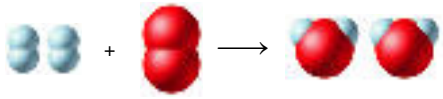
2 Solve ***Apply concepts to this situation.***
Write correct formulas to give the skeleton equation.

$$H_2(g) + O_2(g) \longrightarrow H_2O(l)$$

Count the number of each kind of atom. Hydrogen is balanced but oxygen is not. If you put the coefficient 2 in front of H_2O, the oxygen will be balanced.

$$H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

Now twice as many hydrogen atoms are in the product as are in the reactants. To correct this, put the coefficient 2 in front of H_2. Four hydrogen atoms and two oxygen atoms are on each side of the chemical equation. The equation is now balanced.



$2H_2(g)$ Hydrogen + $O_2(g)$ Oxygen ⟶ $2H_2O(l)$ Water

Reactants
4 hydrogen atoms
2 oxygen atoms

Products
4 hydrogen atoms
2 oxygen atoms

Practice Problems

3. Balance each equation.
   a. $AgNO_3 + H_2S \longrightarrow Ag_2S + HNO_3$
   b. $Zn(OH)_2 + H_3PO_4 \longrightarrow Zn_3(PO_4)_2 + H_2O$
4. Rewrite these word equations as balanced chemical equations.
   a. hydrogen + sulfur ⟶ hydrogen sulfide
   b. iron(III) chloride + calcium hydroxide ⟶ iron(III) hydroxide + calcium chloride

Interactive Textbook

Problem-Solving 11.4 Solve Problem 4 with the help of an interactive guided tutorial.

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The reaction of copper metal with an aqueous solution of silver nitrate is described by this skeleton equation. How can it be balanced?

$$Cu(s) + AgNO_3(aq) \longrightarrow Cu(NO_3)_2(aq) + Ag(s)$$

The nitrate ion appears unchanged on both sides of the equation, so this ion can be balanced as a unit. Do this by placing a 2 in front of $AgNO_3$.

$$Cu(s) + 2AgNO_3(aq) \longrightarrow Cu(NO_3)_2(aq) + Ag(s)$$

But now the atoms of silver are not balanced. You must add a 2 in front of Ag on the product side to balance the atoms of silver.

$$Cu(s) + 2AgNO_3(aq) \longrightarrow Cu(NO_3)_2(aq) + 2Ag(s)$$

The equation is now balanced because the same number of each kind of atom are on both sides of the equation.

CONCEPTUAL PROBLEM 11.3

Balancing a Chemical Equation

Aluminum is a good choice for outdoor furniture because it reacts with oxygen in the air to form a thin protective coat of aluminum oxide. Balance the equation for this reaction.

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

1 Analyze ***Identify the relevant concepts.***

Apply the rules for balancing equations.

2 Solve ***Apply concepts to this situation.***

First balance the aluminum by placing the coefficient 2 in front of Al(*s*).

$$2Al(s) + O_2(g) \longrightarrow Al_2O_3(s)$$

How can the odd number of oxygen atoms in the product (right side) balance the even number of oxygen atoms on the left? Any whole-number coefficient placed in front of the O_2 will give an even number of oxygen atoms on the left. This is because the coefficient is always being multiplied by the subscript 2. The solution is to multiply the formula with the odd number of oxygen atoms by 2.

$$2Al(s) + O_2(g) \longrightarrow 2Al_2O_3(s)$$

Now six oxygen atoms are on the right. Balance the oxygens on the left by placing a 3 in front of O_2. Then rebalance the aluminum by changing the coefficient of Al(*s*) from 2 to 4.

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

Suppose the equation for the formation of aluminum oxide was written this way.

$$8Al(s) + 6O_2(g) \longrightarrow 4Al_2O_3(s)$$

Because this equation obeys the law of conservation of mass, it is correct. However, equations are normally written with coefficients in their lowest possible ratio. Each of the coefficients can be divided by 2 to give the previous equation, which has the lowest whole-number ratio of coefficients.

Practice Problems

5. Balance each equation.

a. $FeCl_3 + NaOH \longrightarrow Fe(OH)_3 + NaCl$

b. $CS_2 + Cl_2 \longrightarrow CCl_4 + S_2Cl_2$

6. Write and balance this equation.

calcium hydroxide + sulfuric acid $\longrightarrow$ calcium sulfate + water

Interactive Textbook

Problem-Solving 11.6
Solve Problem 6 with the help of an interactive guided tutorial.

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Hazardous Materials Specialist

Hazardous materials specialists do the vital work of keeping the environment safe from harmful substances. Backed by regulations devised primarily by the Environmental Protection Agency (EPA), these specialists are responsible for the safe handling, treatment, storage, and transportation of hazardous materials. They work at all levels of government and are employed by industries and universities where dangerous materials are generated or used. Part of their jobs may be to educate those who need to know, including the public, about the rules and regulations applied to hazardous materials.

Hazardous materials specialists often work in the field inspecting, testing, overseeing cleanup work, and determining whether storage facilities are in compliance with regulations. First on the scene when a chemical spill occurs, these specialists must be able to identify the spilled chemical substance and know how to take emergency action to neutralize its effect and thus protect the public. Then they must devise a cleanup procedure and oversee its implementation.

Entry into the field usually requires a degree from a four-year college with a major in chemistry or other physical science. Other areas of concentration might be industrial hygiene, environmental health, or engineering.

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11.1 Section Assessment

7. **Key Concept** How do you write a word equation?

8. **Key Concept** How do you write a skeleton equation?

9. **Key Concept** Describe the steps in writing a balanced chemical equation.

10. Write skeleton equations for these reactions.
- **a.** Heating copper(II) sulfide in the presence of diatomic oxygen produces pure copper and sulfur dioxide gas.
- **b.** When heated, baking soda (sodium hydrogen carbonate) decomposes to form the products sodium carbonate, carbon dioxide, and water.

11. Write and balance equations for the following reactions.
- **a.** Iron metal and chlorine gas react to form solid iron(III) chloride.
- **b.** Solid aluminum carbonate decomposes to form solid aluminum oxide and carbon dioxide gas.
- **c.** Solid magnesium reacts with aqueous silver nitrate to form solid silver and aqueous magnesium nitrate.

12. Balance the following equations.
- **a.** $SO_2 + O_2 \longrightarrow SO_3$
- **b.** $Fe_2O_3 + H_2 \longrightarrow Fe + H_2O$
- **c.** $P + O_2 \longrightarrow P_4O_{10}$
- **d.** $Al + N_2 \longrightarrow AlN$

Writing Activity

Paragraph Some products are marketed as biodegradable. What does *biodegradable* mean? Identify three biodegradable products. How do these products benefit the environment?

Interactive Textbook

Assessment 11.1 Test yourself on the concepts in Section 11.1.

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