SECTION 7.1

What Is Stoichiometry?

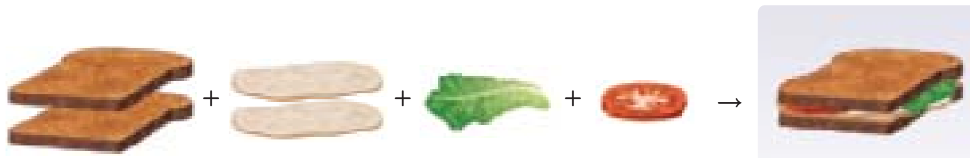
Key Terms

stoichiometry

mole ratio

stoichiometry the study of the quantitative relationships among the amounts of reactants used and the amounts of products formed in a chemical reaction

Stoichiometry is the study of the quantitative relationships among the amounts of reactants used and the amounts of products formed in a chemical reaction. The basic tool of stoichiometry is a balanced chemical equation. A balanced chemical equation is essential for making calculations and predictions related to quantities in a chemical reaction. A balanced chemical equation is much like a cooking recipe. The outcome of a chemical reaction or a cooking recipe depends on the quantities of reactants or starting ingredients. Suppose that you are making a turkey sandwich. **Figure 7.1** shows how you might express your sandwich recipe as an equation.



2 toast slices + 2 turkey slices + 1 lettuce leaf + 1 tomato slice → **1 sandwich**

Figure 7.1 A turkey sandwich might consist of two toast slices, two turkey slices, one lettuce leaf, and one tomato slice.

***Identify** how much of each ingredient you would need to make four turkey sandwiches.*

A balanced chemical equation gives the same kind of information as a recipe about the quantities of reactants that are needed to carry out a chemical reaction. Using the correct quantities of reactants prevents environmental problems, like the one shown in **Figure 7.2**, that are caused when excessive quantities of harmful chemicals enter ecosystems.

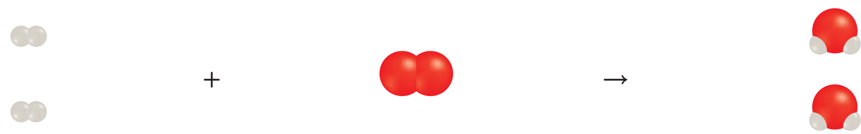
Aquatic wildlife are sensitive to changes in their environment. When chemicals are dumped into waterways, many changes occur that affect the wildlife. As shown below, chemicals that are toxic to wildlife can result in the death of large numbers of individuals. Some chemicals are directly toxic to organisms, while others act indirectly by changing the abiotic conditions of an aquatic ecosystem, such as the acidity and temperature of the water. When large numbers of organisms die, the decomposition of their bodies depletes the water of oxygen. Such oxygen depletion leads to the death of more aquatic organisms.

Go to **scienceontario** to find out more

Figure 7.2 Substances from chemical processes can be toxic to the environment. Quantitative accuracy in industrial chemical processes and responsible disposal of the wastes prevents environmental problems from occurring.

Particle Ratios in a Balanced Chemical Equation

The coefficients in front of the chemical formulas in a balanced chemical equation represent the relative numbers of particles involved in the chemical reaction, as shown in **Figure 7.3**. From the balanced chemical equation, you know that two molecules of hydrogen and one molecule of oxygen react to form two molecules of water.



$2H_2(g)$ + $O_2(g)$ → $2H_2O(g)$

Figure 7.3 The coefficients in a chemical equation represent the numbers of particles involved in the chemical reaction. In this reaction, four hydrogen atoms combine with two oxygen atoms to form two molecules of water.

Interpret *How many atoms of hydrogen and oxygen are needed to produce 10 molecules of water?*

At the molecular level, the ratio of the components in this reaction is

$$2 \text{ molecules of } H_2(g) : 1 \text{ molecule of } O_2(g) : 2 \text{ molecules of } H_2O(g)$$

Suppose that you want to produce twice as many molecules of water. You simply multiply the ratio of the reactants by 2 to get

$$4 \text{ molecules of } H_2(g) : 2 \text{ molecules of } O_2(g) : 4 \text{ molecules of } H_2O(g)$$

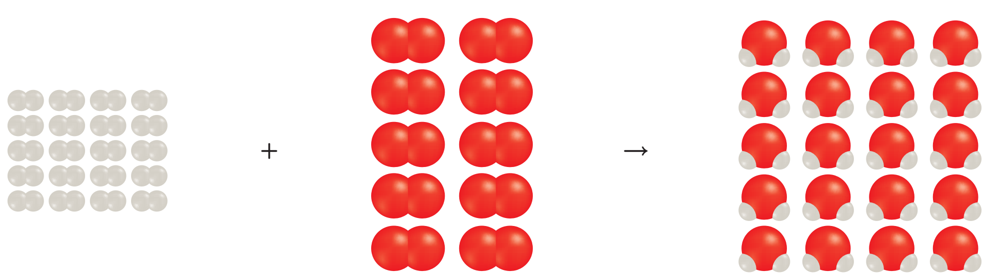
What if you want to produce 20 molecules of water? How many molecules of oxygen do you need? You know that you need one molecule of oxygen for every two molecules of water. In other words, the number of molecules of oxygen that you need is one half the number of molecules of water that you want to produce. This value can be determined mathematically by equating the known particle ratio for oxygen to water, as shown below.

$$\frac{x}{20 \text{ molecules of } H_2O} = \frac{1 \text{ molecule of } O_2}{2 \text{ molecules of } H_2O}$$

Solve for the unknown, x, to determine the number of oxygen molecules you need.

$$x = 20 \cancel{\text{ molecules of } H_2O} \times \frac{1 \text{ molecule of } O_2}{2 \cancel{\text{ molecules of } H_2O}} = 10 \text{ molecules of } O_2$$

Therefore, 10 oxygen molecules are needed to produce 20 water molecules, as shown in **Figure 7.4**.



$20H_2(g)$ + $10O_2(g)$ → $20H_2O(g)$

Figure 7.4 If you compare the chemical equation and molecules in this figure with the ones in **Figure 7.3**, you will see that each coefficient is multiplied by 10.

The Sample Problem on the next page shows you how to use ratios of coefficients to determine the number of particles that are produced in a chemical reaction. Notice that ratios of coefficients are used for individual elements, such as hydrogen and oxygen in the above example, and for large molecules, like octane in the Sample Problem on the next page.

Sample Problem

Using Ratios of Coefficients in a Balanced Chemical Equation

Problem

The combustion of octane, $C_8H_{18}(g)$, is represented by the following balanced equation:

$$2C_8H_{18}(g) + 25O_2(g) \longrightarrow 16CO_2(g) + 18H_2O(g)$$

If 450 molecules of water are produced, how many molecules of carbon dioxide, CO_2, are produced?

What Is Required?

You need to find the number of molecules of carbon dioxide that are produced when 450 molecules of water are produced.

What Is Given?

You know the balanced chemical equation:

$2C_8H_{18}(g) + 25O_2(g) \longrightarrow 16CO_2(g) + 18H_2O(g)$

You know the number of water molecules that are formed: 450

Plan Your Strategy	Act on Your Strategy
Use the balanced chemical equation to determine the ratio of coefficients for carbon dioxide molecules to water molecules.	The balanced chemical equation is $2C_8H_{18} + 25O_2(g) \longrightarrow 16CO_2(g) + 18H_2O(g)$ The ratio of coefficients is 16 molecules of CO_2 : 18 molecules of H_2O.
Equate the known ratio of coefficients for carbon dioxide to water to the unknown ratio. Then solve for the unknown.	$\frac{x}{450 \text{ molecules of } H_2O} = \frac{16 \text{ molecules of } CO_2}{18 \text{ molecules of } H_2O}$ $x = 450 \cancel{\text{ molecules of } H_2O} \times \frac{16 \text{ molecules of } CO_2}{18 \cancel{\text{ molecules of } H_2O}}$ $= 400 \text{ molecules of } CO_2$

Check Your Solution

The units are correct. The ratio 400 : 450 is equivalent to the ratio 16 : 18. The answer is reasonable.

Practice Problems

Write ratios of coefficients for the equations in questions 1–4 and answer the remaining questions.

1. $2Mg(s) + O_2(g) \longrightarrow 2MgO(s)$
2. $2NO(g) + O_2(g) \longrightarrow 2NO_2(g)$
3. $Ca(s) + 2H_2O(\ell) \longrightarrow Ca(OH)_2(s) + H_2(g)$
4. $2C_2H_6(g) + 7O_2(g) \longrightarrow 4CO_2(g) + 6H_2O(g)$
5. How many molecules of nitrogen, $N_2(g)$, produce 10 molecules of ammonia, $NH_3(g)$, in the following reaction?
$$N_2(g) + 3H_2(g) \longrightarrow 2NH_3(g)$$
6. Aluminum reacts with chlorine gas to form aluminum chloride:
$$2Al(s) + 3Cl_2(g) \longrightarrow 2AlCl_3(s)$$
How many molecules of aluminum chloride form when 155 atoms of aluminum react with an excess of chlorine gas?
7. How many formula units of calcium chloride are produced by 6.7×10^{23} molecules of hydrochloric acid in the following reaction?
$$Ca(OH)_2(aq) + 2HCl(aq) \longrightarrow CaCl_2(s) + 2H_2O(\ell)$$
8. How many formula units of magnesium chloride are produced by 7.7×10^{24} molecules of hydrochloric acid in this reaction?
$$Mg(OH)_2(aq) + 2HCl(aq) \longrightarrow MgCl_2(s) + 2H_2O(\ell)$$
9. The combustion of ethanol, $C_2H_5OH(\ell)$, is represented by the following equation:
$$C_2H_5OH(\ell) + 3O_2(g) \longrightarrow 2CO_2(g) + 3H_2O(\ell)$$
How many molecules of oxygen, $O_2(g)$, produce 1.81×10^{24} molecules of carbon dioxide, $CO_2(g)$, if an excess of ethanol is present?
10. Iron reacts with chlorine gas to form iron(III) chloride. How many atoms of iron react with three molecules of chlorine?

Mole Ratios in a Balanced Chemical Equation

Recall the reaction of hydrogen to produce water, $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$, from which you obtained the ratio of molecules:

$$2 \text{ molecules of } H_2(g) : 1 \text{ molecule of } O_2(g) : 2 \text{ molecules of } H_2O(g)$$

Previously, you multiplied each term in the ratio by 2 and by 10, and still had a correct ratio. It is more useful to multiply each term by 6.02×10^{23}, which is the numerical value of the Avogadro constant.

$$2(6.02 \times 10^{23}) \text{ molecules of } H_2(g) : 1(6.02 \times 10^{23}) \text{ molecule of } O_2(g) : 2(6.02 \times 10^{23}) \text{ molecules of } H_2O(g)$$

As you know, 6.02×10^{23} molecules is one mole. Therefore, the ratio becomes:

$$2 \text{ mol of } H_2(g) : 1 \text{ mol of } O_2(g) : 2 \text{ mol of } H_2O(g)$$

The ratio of the amounts in moles of any two substances in a balanced chemical equation is called the **mole ratio**.

mole ratio the ratio of the amounts (in moles) of any two substances in a balanced chemical equation

Learning Check

1. How much of each ingredient described in **Figure 7.1** is needed to make five turkey sandwiches?
2. Why are balanced chemical equations necessary for solving stoichiometric problems?
3. What do the coefficients in the following balanced chemical equation represent?
$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$
4. What relationships can be determined from a balanced chemical equation?
5. Why are coefficients, not subscripts, used in mole ratios?
6. Consider the following chemical equation:
$$2C_2H_6(g) + 7O_2(g) \rightarrow 4CO_2(g) + 6H_2O(g)$$
   a. Write the mole ratio for ethane, $C_2H_6(g)$, and carbon dioxide.
   b. Write the mole ratio for ethane and oxygen, $O_2(g)$.
   c. Write the mole ratio for carbon dioxide and water.

Using Mole Ratios

Mole ratios can be manipulated to solve problems. For example, consider the mole ratio below:

$$1 \text{ mol } O_2(g) : 2 \text{ mol } H_2O(g)$$

This mole ratio can be used to predict the amount of water, in moles, that will be produced if a certain amount of oxygen, $O_2(g)$, reacts according to the following chemical equation:

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

Suppose that you want to know the amount of water that is produced by 3.2 mol of oxygen. You know that you obtain 2 mol of water for every 1 mol of oxygen. Therefore, you can use this ratio in the following proportion:

$$\frac{n_{H_2O}}{3.2 \text{ mol } O_2} = \frac{2 \text{ mol } H_2O}{1 \text{ mol } O_2}$$

$$n_{H_2O} = 3.2 \cancel{\text{mol } O_2} \times \frac{2 \text{ mol } H_2O}{1 \cancel{\text{mol } O_2}} = 6.4 \text{ mol } H_2O$$

The Sample Problem on the next page illustrates how the mole ratios from a balanced chemical equation are used to solve problems.

Sample Problem

Using Mole Ratios in a Balanced Chemical Equation

Malachite

Problem

What amount in moles of copper(II) oxide, $CuO(s)$, forms when 0.0045 mol of malachite, $Cu_2(CO_3)(OH)_2(s)$, decomposes completely according to the following equation?

$$Cu_2(CO_3)(OH)_2(s) \rightarrow CO_2(g) + H_2O(g) + 2CuO(s)$$

What Is Required?

You need to determine the amount in moles of copper(II) oxide that is produced.

What Is Given?

You know the balanced chemical equation for the reaction:

$$Cu_2(CO_3)(OH)_2(s) \rightarrow CO_2(g) + H_2O(g) + 2CuO(s)$$

You know the amount of malachite: 0.0045 mol

Plan Your Strategy	Act on Your Strategy
Use the balanced chemical equation to write the mole ratio of copper(II) oxide to malachite.	$Cu_2(CO_3)(OH)_2(s) \rightarrow CO_2(g) + H_2O(g) + 2CuO(s)$ The ratio of copper(II) oxide to malachite is 2 mol CuO: 1 mol $Cu_2(CO_3)(OH)_2$
Equate the known mole ratio for copper(II) oxide to malachite with the unknown mole ratio. Then solve for the unknown to determine the amount of copper(II) oxide.	$\frac{n_{CuO}}{0.0045 \text{ mol } Cu_2(CO_3)(OH)_2} = \frac{2 \text{ mol CuO}}{1 \text{ mol } Cu_2(CO_3)(OH)_2}$ $n_{CuO} = 0.0045 \cancel{\text{mol } Cu_2(CO_3)(OH)_2} \times \frac{2 \text{ mol CuO}}{1 \cancel{\text{mol } Cu_2(CO_3)(OH)_2}}$ $= 0.0090$ mol CuO

Check Your Solution

The ratio of copper(II) oxide to malachite is 2:1. Accordingly, the amount of copper(II) oxide calculated is twice the amount of malachite.

Practice Problems

11. What amount in moles of silver chromate, $Ag_2CrO_4(s)$, is produced from 0.50 mol of silver nitrate, $AgNO_3(aq)$?

$$2AgNO_3(aq) + Na_2CrO_4(aq) \rightarrow Ag_2CrO_4(s) + 2NaNO_3(aq)$$

12. What amount in moles of water forms when 6.00 mol of carbon dioxide is consumed in the following reaction?

$$2NH_3(g) + CO_2(g) \rightarrow NH_2CONH_2(s) + H_2O(g)$$

13. Calculate the amount in moles of ammonia, $NH_3(g)$, that is needed to prepare 22 500 mol of the fertilizer ammonium sulfate, $(NH_4)_2SO_4(s)$.

$$2NH_3(g) + H_2SO_4(aq) \rightarrow (NH_4)_2SO_4(s)$$

14. Calculate the amount in moles of oxygen that is needed to react with 2.4 mol of ammonia to produce poisonous hydrogen cyanide, $HCN(g)$.

$$2NH_3(g) + 3O_2(g) + 2CH_4(g) \rightarrow 2HCN(g) + 6H_2O(g)$$

15. What amount in moles of fluorine, $F_2(g)$, yields 2.35 mol of xenon tetrafluoride, $XeF_4(s)$?

$$Xe(g) + 2F_2(g) \rightarrow XeFe_4(s)$$

16. These equations show two possible reactions:

$$2N_2(g) + O_2(g) \rightarrow 2N_2O(g)$$
$$N_2(g) + 2O_2(g) \rightarrow 2NO_2(g)$$

a. What amount in moles of oxygen reacts with 93.5 mol of nitrogen to form dinitrogen monoxide, $N_2O(g)$?

b. What amount in moles of nitrogen dioxide, $NO_2(g)$ forms in the other reaction?

17. What amount in moles of oxygen reacts with 11.3 mol of propane gas, $C_3H_8(g)$, during the combustion of propane?

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

18. What amount in moles of phosphorus produces 6.45 mol of tetraphosphorus hexoxide, $P_4O_6(s)$?

$$P_4(s) + 3O_2(g) \rightarrow P_4O_6(s)$$

19. Silver tarnishes when it is exposed to small amounts of hydrogen sulfide, $H_2S(g)$, in the air.

$4Ag(s) + 2H_2S(g) + O_2(g) \rightarrow 2Ag_2S(s) + 2H_2O(\ell)$

How many molecules of hydrogen sulfide react with 1.7 mol of silver?

20. When heated, magnesium hydrogen carbonate, $Mg(HCO_3)_2(s)$, decomposes and forms magnesium carbonate, $MgCO_3(s)$, carbon dioxide and water, vapour. What amount in moles of water is produced from 7.24×10^5 mol of magnesium hydrogen carbonate?

Activity 7.1 Chalk It Up to Molar Relationships

Common chalk (calcium carbonate), $CaCO_3(s)$, reacts with hydrochloric acid according to the following balanced equation:

$$CaCO_3(s) + 2HCl(aq) \rightarrow CO_2(g) + H_2O(\ell) + CaCl_2(aq)$$

In this activity, you will carry out the reaction between chalk and hydrochloric acid and then determine the molar relationships.

Safety Precautions

- Wear safety eyewear throughout this activity.
- Wear gloves throughout this activity.
- Do not inhale vapour from hydrochloric acid.
- Be careful when using hydrochloric acid.
- If acid gets on skin, flush with plenty of water.

Materials

- 1.0 g piece of chalk, $CaCO_3(s)$
- 40 mL of 1 mol/L hydrochloric acid, HCl(aq)
- balance (with precision to 0.01 g)
- 2 beakers (100 mL)
- graduated cylinder

Procedure

1. Measure and record the mass of an empty 100 mL beaker.
2. Your teacher will give you a piece of chalk, with a mass of approximately 1.0 g. Place the chalk in the beaker. Measure and record the mass of the beaker and the chalk.
3. Fill another 100 mL beaker with 40 mL of 1 mol/L hydrochloric acid. Place this beaker on the balance, next to the beaker containing the chalk. Measure and record the total mass of both beakers and their contents.
4. Remove the beakers from the balance. Slowly add hydrochloric acid from the second beaker to the beaker containing the chalk, a bit at a time, until all the chalk has disappeared and the solution produces no more bubbles.
5. Measure and record the total mass of both beakers and their contents. Dispose of the reacted chemicals and clean up your workarea as directed by your teacher.

Questions

1. Calculate the amount in moles of calcium carbonate used and the amount in moles of carbon dioxide produced. (**Hint:** Find the difference between the total mass of both beakers and their contents before and after the reaction. This difference represents the mass of carbon dioxide gas produced.)
2. According to the balanced chemical equation, how many formula units of calcium carbonate react to form one molecule of carbon dioxide? What amount in moles of each compound is involved in the reaction?
3. Based on the balanced chemical equation and the amount of chalk you used, what amount in moles of carbon dioxide was expected to form?
4. How does the amount of carbon dioxide you calculated in question 3 relate to the amount of carbon dioxide that was actually produced? Explain your results.

Mass Relationships in Chemical Equations

The mole ratio of any two substances in any balanced chemical equation consists of simple whole numbers. However, the mass ratio of any two substances in an actual chemical reaction rarely consists of whole numbers. Consider the reaction of hydrogen gas with oxygen: $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$

In this reaction, the mole ratio of hydrogen to oxygen is 2 mol $H_2(g)$: 1 mol $O_2(g)$.

Recall, from Chapter 5, that you can find the molar mass (M) of an element in the periodic table. The equation $m = n \times M$ can be used to find the mass of each compound in a reaction, as follows:

$$m_{H_2} = n_{H_2} \times M_{H_2} = 2\cancel{\text{mol}} \times \frac{2.02\text{ g}}{\cancel{\text{mol}}} = 4.04\text{ g} \qquad m_{O_2} = n_{O_2} \times M_{O_2} = 1\cancel{\text{mol}} \times \frac{32.00\text{ g}}{\cancel{\text{mol}}} = 32.00\text{ g}$$

Therefore, the mass ratio of hydrogen to oxygen is 4.04 g $H_2(g)$: 32.00 g $O_2(g)$.

Stoichiometric Mass Calculations

Go to **scienceontario** to find out more

If you know the amount in moles, number of particles, or mass in grams of any substance in a chemical reaction, you can calculate the amount, number of particles, or mass of any other substance in the reaction. This allows you to calculate the quantities of reactants required for a specific chemical reaction or to predict how much product will form in terms of moles, molecules, or grams. The following Sample Problems show how to use stoichiometry to determine these values.

Sample Problem

Mass Stoichiometry: Reactant to Product

Problem

Some scientists propose generating oxygen by photosynthesis during a mission to Mars. Photosynthesis is a process that uses energy from sunlight to drive a long series of reactions in which carbon dioxide and water are combined to form glucose and oxygen.

$$6CO_2(g) + 6H_2O(\ell) \rightarrow C_6H_{12}O_6(s) + 6O_2(g)$$

This reaction could help to eliminate carbon dioxide from the spacecraft, while producing breathable oxygen. An astronaut produces an average of 1.00×10^3 g of carbon dioxide each day. What mass of oxygen, per astronaut, would need to be produced by photosynthesis each day?

What Is Required?

You need to find the mass of oxygen produced from 1.00×10^3 g of carbon dioxide.

What Is Given?

You know the balanced chemical equation: $6CO_2(g) + 6H_2O(\ell) \rightarrow C_6H_{12}O_6(s) + 6O_2(g)$

You know the mass of carbon dioxide: 1.00×10^3 g

Plan Your Strategy	Act on Your Strategy
Write the balanced equation for the reaction and the mole ratio of oxygen to carbon dioxide.	$6CO_2(g) + 6H_2O(\ell) \rightarrow C_6H_{12}O_6(s) + 6O_2(g)$ The ratio of oxygen to carbon dioxide is 6 mol O_2: 6 mol CO_2.
Calculate the molar masses, M, of oxygen and carbon dioxide.	$M_{O_2} = 2M_O = 2(16.00\text{ g/mol}) = 32.00\text{ g/mol}$ $M_{CO_2} = 1M_C + 2M_O$ $= 1(12.01\text{ g/mol}) + 2(16.00\text{ g/mol}) = 44.01\text{ g/mol}$
Convert the mass of carbon dioxide into an amount in moles using the molar mass of carbon dioxide and $n = \frac{m}{M}$.	$n = \frac{m}{M}$ $= \frac{1.00 \times 10^3 \cancel{g}}{44.01\ \cancel{g}/\text{mol}} = 22.722\text{ mol }CO_2$
To solve for the amount of oxygen in moles, use the mole ratio of oxygen to carbon dioxide from the balanced equation, as well as the amount of carbon dioxide in moles.	$\frac{n_{O_2}}{22.722\text{ mol }CO_2} = \frac{6\text{ mol }O_2}{6\text{ mol CO}}$ $n_{O_2} = 22.722\ \cancel{\text{mol}}\ CO_2 \times \frac{6\text{ mol }O_2}{6\ \cancel{\text{mol}}\ CO_2} = 22.722\text{ mol }O_2$
Convert the amount of oxygen in moles into the mass of oxygen using the molar mass of oxygen and the equation $m = n \times M$.	$m = n \times M$ $= 22.722\ \cancel{\text{mol}} \times 32.00\text{ g/}\cancel{\text{mol}} = 727\text{ g }O_2$ Therefore, 727 g of oxygen is theoretically produced.

Check Your Solution

An alternative method for solving stoichiometric problems, called the factor-label method, can be used to check the solution. To use this method, set up the equation so that all the terms cancel, except for the required term.

$$m_{O_2} = 1.00 \times 10^3\ \cancel{\text{g }CO_2} \times \frac{1\ \cancel{\text{mol }CO_2}}{44.01\ \cancel{\text{g }CO_2}} \times \frac{6\ \cancel{\text{mol }O_2}}{6\ \cancel{\text{mol }CO_2}} \times \frac{32.00\text{ g }O_2}{1\ \cancel{\text{mol }O_2}} = 727\text{ g }O_2$$

Sample Problem

Mass Stoichiometry: Reactant to Reactant

One disadvantage of using photosynthesis to produce oxygen for a mission to Mars is that photosynthesis requires water, which is not readily available in space. What mass of water is required to remove the carbon dioxide from one astronaut's exhaled breath each day, using photosynthesis? Recall that an astronaut produces an average of 1.00×10^3 g of carbon dioxide each day and the reaction for photosynthesis is

$$6CO_2(g) + 6H_2O(\ell) \rightarrow C_6H_{12}O_6(s) + 6O_2(g)$$

Astronaut Working in Space

What Is Required?

You need to find the mass of water that is required to react with 1.00×10^3 g of carbon dioxide.

What Is Given?

You know the balanced chemical equation:

$6CO_2(g) + 6H_2O(\ell) \rightarrow C_6H_{12}O_6(s) + 6O_2(g)$

You know the mass of carbon dioxide: 1.00×10^3 g

Plan Your Strategy	Act on Your Strategy
Write the balanced equation for the reaction and the mole ratio of water to carbon dioxide.	$6CO_2(g) + 6H_2O(\ell) \rightarrow C_6H_{12}O_6(s) + 6O_2(g)$ The ratio of water to carbon dioxide is 6 mol H_2O: 6 mol CO_2.
Calculate the molar masses, M, of carbon dioxide and water.	$M_{CO_2} = M_C + 2M_O$ $= 1(12.01\text{ g/mol}) + 2(16.00\text{ g/mol})$ $= 44.01\text{ g/mol}$ $M_{H_2O} = 2M_H + 1M_O$ $= 2(1.01\text{ g/mol}) + 1(16.00\text{ g/mol})$ $= 18.02\text{ g/mol}$
Convert the mass of carbon dioxide into an amount in moles using the molar mass of carbon dioxide and $n = m/M$.	$n = \frac{m}{M} = \frac{1.00 \times 10^3 \cancel{\text{g}}}{44.01\ \cancel{\text{g}}/\text{mol}}$ $= 22.722\text{ mol } CO_2$
To determine the amount of water in moles, use the mole ratio of water to carbon dioxide from the balanced equation, as well as the amount of carbon dioxide in moles.	$\frac{n_{H_2O}}{22.722\text{ mol } CO_2} = \frac{6\text{ mol } H_2O}{6\text{ mol } CO_2}$ $n_{H_2O} = 22.722\ \cancel{\text{mol } CO_2} \times \frac{6\text{ mol } H_2O}{6\ \cancel{\text{mol } CO_2}}$ $= 22.722\text{ mol } H_2O$
Convert the amount of water into the mass of water using the molar mass of water and the equation $m = n \times M$.	$m = n \times M$ $= 22.722\text{ mol} \times 18.02\text{ g/mol}$ $= 409\text{ g } H_2O$ Therefore, 409 g of water is required each day to remove the carbon dioxide from one astronaut's exhaled breath.

Check Your Solution

The units are correct. Because carbon dioxide and water have a mole ratio of 6:6 or 1:1, and the molar mass of water is a little less than half of the molar mass of carbon dioxide, the mass of water should be less than 500 g. The answer is reasonable.

Using the factor-label method to check the answer,

$$m_{H_2O} = 1.00 \times 10^3\ \cancel{\text{g } CO_2} \times \frac{1\ \cancel{\text{mol } CO_2}}{44.01\ \cancel{\text{g } CO_2}} \times \frac{6\ \cancel{\text{mol } H_2O}}{6\ \cancel{\text{mol } CO_2}} \times \frac{18.02\text{ g } H_2O}{1\ \cancel{\text{mol } H_2O}} = 409\text{ g } H_2O$$

Practice Problems

21. The production of acetic acid, $CH_3COOH(\ell)$, is represented by the following chemical equation:

$$CH_3OH(\ell) + CO(g) \rightarrow CH_3COOH(\ell)$$

Calculate the mass of acetic acid that is produced by the reaction of 6.0×10^4 g of carbon monoxide with sufficient methanol, $CH_3OH(\ell)$.

22. Calculate the mass of silver nitrate, $AgNO_3(aq)$, that must react with solid copper to provide 475 kg of of copper nitrate, $Cu(NO_3)_2(aq)$.

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

23. What mass of oxygen is produced if 22.7 mol of carbon dioxide is consumed in a controlled photosynthesis reaction?

$$6CO_2(g) + 6H_2O(\ell) \rightarrow C_6H_{12}O_6(s) + 6O_2(g)$$

24. Sodium phosphate, $Na_3PO_4(aq)$, is an all-purpose cleaner that can be used to clean walls before painting. It is often referred to as trisodium phosphate, or TSP, and it must be handled with care because it is corrosive. It is prepared by the following reaction:

$$3NaOH(aq) + H_3PO_4(aq) \rightarrow Na_3PO_4(aq) + 3H_2O(\ell)$$

What amount in moles of TSP is produced if 14.7 g of sodium hydroxide reacts with phosphoric acid, $H_3PO_4(aq)$?

25. What mass of hydrogen is produced when 3.75 g of aluminum reacts with sulfuric acid, $H_2SO_4(aq)$?

$$2Al(s) + 3H_2SO_4(aq) \rightarrow 3H_2(g) + Al_2(SO_4)_3(aq)$$

26. Nitrogen monoxide, NO(g), reacts with oxygen gas to form nitrogen dioxide, $NO_2(g)$. What mass of nitrogen dioxide is produced from 2.84 g of nitrogen monoxide?

27. Iron(III) oxide, $Fe_2O_3(s)$, reacts with carbon monoxide to form solid iron and carbon dioxide in the following reaction:

$$Fe_2O_3(s) + 3CO(g) \rightarrow 2Fe(s) + 3CO_2(g)$$

What mass (in grams) of carbon dioxide is produced from 12.4 g of iron(III) oxide?

28. Methane, $CH_4(g)$, reacts with sulfur, $S_8(s)$, to produce carbon disulfide, $CS_2(\ell)$, and hydrogen sulfide, $H_2S(g)$. Carbon disulfide is often used in the production of cellophane.

$$2CH_4(g) + S_8(s) \rightarrow 2CS_2(\ell) + 4H_2S(g)$$

What mass of methane is required if 4.09 g of hydrogen sulfide is produced?

29. The addition of concentrated hydrochloric acid to manganese(IV) oxide, $MnO_2(s)$, produces chlorine gas, $Cl_2(g)$.

$$4HCl(aq) + MnO_2(s) \rightarrow MnCl_2(aq) + Cl_2(g) + 2H_2O(\ell)$$

What mass of manganese(IV) oxide is needed to react with 8.65×10^{-2} g of hydrochloric acid?

30. Aluminum carbide, $Al_4C_3(s)$, is a yellow powder that reacts with water, $H_2O(\ell)$, to produce aluminum hydroxide, $Al(OH)_3(s)$, and methane, $CH_4(g)$. Write a balanced chemical equation for the reaction and determine the mass of water required to react with 14.0 g of aluminum carbide.

Stoichiometry and Reactions in the Laboratory

In this section, you have learned how to do stoichiometric calculations using a balanced chemical equation. Stoichiometric calculations are based on the assumption that all the substances occur in an exact mole ratio, as shown in the chemical equation. However, reactants often are not present in the exact ratio. Furthermore, just as you might not always get exactly a dozen cookies from a chocolate-chip cookie recipe, as shown in **Figure 7.5**, the amount of final product that is predicted by stoichiometry is not always produced in a laboratory. In the next two sections, you will learn how to predict how much product will form in a given chemical equation.

Figure 7.5 The amount of final product is not always what is predicted when making cookies and when performing chemical reactions in the laboratory.

Section Summary

- The coefficients of a balanced chemical equation can be used to represent the relative amounts (in moles) of particles (atoms, ions, molecules, or formula units).
- Stoichiometric calculations are used to predict the amounts of reactants used or products formed in a chemical reaction.
- A mole ratio from a balanced chemical equation relates the amount in moles of one reactant or product to the amount in moles of another reactant or product.
- The amount in moles of any substance can be converted to number of particles or mass units, such as grams.

Review Questions

1. K/U What important chemical information about the reactants and products in a reaction is obtained from the coefficients of a balanced chemical equation?
2. K/U Why is a balanced chemical equation needed for stoichiometric calculations?
3. K/U Determine all the possible mole ratios for each balanced chemical equation.
   a. $4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(s)$
   b. $3Fe(s) + 4H_2O(\ell) \rightarrow Fe_3O_4(s) + 4H_2(g)$
   c. $2HgO(s) \rightarrow 2Hg(\ell) + O_2(g)$
   d. $2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$
   e. $CaO(s) + H_2O(\ell) \rightarrow Ca(OH)_2(s)$
4. T/I The oxidation of aluminum is represented by the following chemical equation:
   $$4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(aq)$$
   What mass of oxygen is required to oxidize 25 mol of aluminum?
5. T/I The reaction of nitrogen gas with hydrogen gas is represented by the following chemical equation:
   $$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$
   What mass (in grams) of nitrogen reacts with 6.0 g of hydrogen?
6. T/I A student says that 1.0 g of magnesium reacts with 1.0 g of chlorine, $Cl_2(g)$, according to this equation:
   $$Mg(s) + Cl_2(g) \rightarrow MgCl_2(s)$$
   Using mathematical calculations, explain why the student's reasoning is incorrect.
7. A Iron ore, $Fe_2O_3(s)$, is treated with carbon monoxide, $CO(g)$, to extract and purify the iron. This reaction is represented by the following unbalanced equation:
   $$\_\_\_Fe_2O_3(s) + \_\_\_CO(g) \rightarrow \_\_\_Fe(s) + \_\_\_CO_2(g)$$
   a. Balance the chemical equation.
   b. Calculate the minimum mass of carbon monoxide that must be ordered by a refining company for every metric tonne of iron ore that is processed.
8. C Complete a flowchart to show how you would use mole ratios to determine the unknown amount of a substance that reacts with a known amount of another substance.
9. T/I The neutralization reaction of hydrobromic acid, $HBr(aq)$, and calcium hydroxide, $Ca(OH)_2(aq)$, is represented by the following balanced chemical equation:
   $$2HBr(aq) + Ca(OH)_2(aq) \rightarrow CaBr_2(aq) + 2H_2O(\ell)$$
   Copy and complete this table to show all the quantity ratios that are implied by the balanced chemical equation.

Neutralization Reaction

	$2HBr(aq)$	$Ca(OH)_2(aq)$	$CaBr_2(aq)$	$2H_2O(\ell)$
Amount (mol)				
Number of Units				
Mass (g)				

10. T/I When heated, the orange crystals of ammonium dichromate, $(NH_4)_2Cr_2O_7(s)$, slowly decompose to form green chromium(III) oxide, $Cr_2O_3(s)$. Colourless nitrogen gas and water vapour are given off.
    $$(NH_4)_2Cr_2O_7(s) \rightarrow Cr_2O_3(s) + N_2(g) + 4H_2O(g)$$
    a. How many formula units of chromium(III) oxide are produced from the decomposition of 7.0 g of ammonium dichromate?
    b. How many formula units of ammonium dichromate are needed to produce 2.75 g of water vapour?
11. C A neighbour over-fertilizes his lawn. Fertilizer that cannot be absorbed by the plants runs into a nearby lake. The excess fertilizer causes algal bloom. Research algal bloom and write a letter to your neighbour explaining why using the correct chemical quantities is important for the environment.
12. C Gardening often involves the use of fertilizers, pesticides, and herbicides (organic and synthetic). Write a brief public service announcement explaining why it is important to use correct chemical quantities to grow a healthy garden and to protect the surrounding environment.