7.1 Mole Ratios in Chemical Equations

Figure 1 The combustion of hydrogen fuel was used to launch the space shuttle into orbit. Aboard the shuttle, hydrogen fuel cells used the same chemical reaction to provide astronauts with electricity and water.

The reaction of hydrogen and oxygen has been an important energy source for the space program (**Figure 1**). Hydrogen combines with oxygen in a synthesis reaction to form water and a great deal of energy:

$$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g) + \text{energy}$$

As you discovered in Investigation 4.4.1 Hydrogen Blast-Off in Unit 3, this reaction releases the most energy per mole of reactants when the volumes of hydrogen and oxygen are in a 2:1 ratio.

Ratios in Chemical Equations

A chemical equation is similar to a recipe, with the chemical formulas indicating the "ingredients" of the reaction. The coefficients in the equation give the ratio of one chemical to another chemical used in the reaction. However, these are ratios of numbers of entities rather than masses. For example, the equation

$$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g) + \text{energy}$$

states that hydrogen molecules and oxygen molecules combine in a 2:1 ratio. This implies that 2 molecules of hydrogen are required to completely react with 1 molecule of oxygen. But what if more hydrogen is present? The amount of oxygen required to use up this extra hydrogen is determined using the 2:1 ratio. The amount of water produced is also determined by this ratio (**Figure 2**).

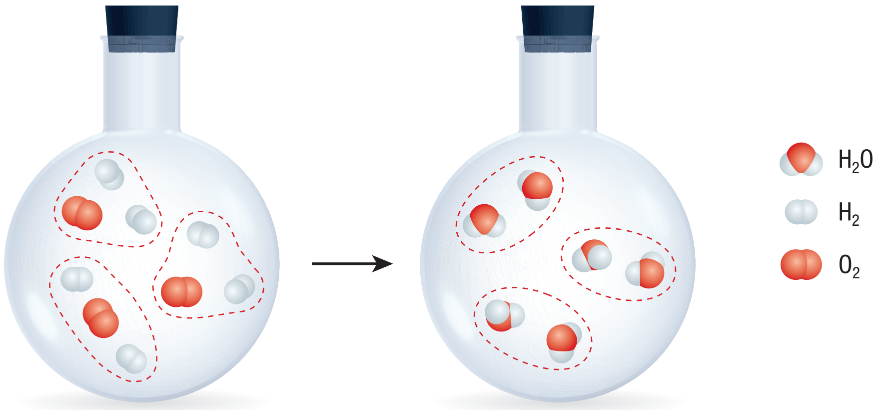


Figure 2 The synthesis of water from its elements. The coefficients in the chemical equation for the reaction give the ratio in which hydrogen and oxygen combine. In this case, 6 hydrogen molecules react with 3 oxygen molecules to form 6 water molecules.

Working with ratios is an essential skill in chemistry. The following analogy illustrates the reasoning used when working with ratios in chemical equations.

CAREER LINK

Chemical process engineers plan which reactants should be mixed, under which conditions, to give the optimum yield and produce the smallest quantity of unwanted by-products. To find out about this career,

GO TO NELSON SCIENCE

A Ratio Analogy

S'mores are sweet snacks that are fun to make over a campfire. They probably got their name from people asking, "Can I have some more?" Each one consists of two graham crackers sandwiching four chocolate chips and one marshmallow.

To make this recipe analogous to a chemical reaction, we will give each ingredient and product a chemical symbol:

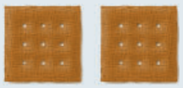
- graham cracker, Gc
- chocolate chip, Cc
- marshmallow, Mm
- s'more, Sm

Therefore, the "equation" that describes the synthesis of a s'more is

2 Gc + 4 Cc + Mm → Sm

According to the equation, the "reactants" combine in a 2:4:1 ratio to produce 1 entity of the product. You can make whatever quantity of s'mores you wish, provided the quantities of reactants are in this ratio (**Table 1**). For example, four times as many chocolate chips are required as marshmallows. Similarly, twice as many crackers are required as marshmallows. Any ingredient that is in excess of this ratio is left over after all the s'mores are made.

Table 1 Quantities in the Synthesis Reaction of S'mores

2 Gc +	4 Cc +	Mm →	Sm
Number of Gc entities 	Number of Cc entities 	Number of Mm entities	Number of Sm entities 
2	4	1	1
4	8	2	2
50	100	25	25
2000	4000	1000	1000
$2 \times 6.02 \times 10^{23} = 2$ mol	$4 \times 6.02 \times 10^{23} = 4$ mol	$1 \times 6.02 \times 10^{23} = 1$ mol	$1 \times 6.02 \times 10^{23} = 1$ mol

Note that, in our s'more synthesis analogy, the sum of the masses of "reactants" must equal the total mass of the "products," since all the ingredients were used to make s'mores. In other words, this analogy illustrates the law of conservation of mass. Notice, however, that the total number of entities on the left side is not the same as the number of entities on the right side.

The Synthesis of Water

We can apply our s'mores reasoning to the water synthesis reaction (**Table 2**).

Table 2 Quantities in the Synthesis Reaction of Water

$2\ H_2(g)$ +	$O_2(g)$ →	$2\ H_2O(g)$
Number of H_2 molecules	Number of O_2 molecules	Number of H_2O molecules
2	1	2
4	2	4
50	25	50
2000	1000	2000
$2 \times 6.02 \times 10^{23} = 2$ mol	$1 \times 6.02 \times 10^{23} = 1$ mol	$2 \times 6.02 \times 10^{23} = 2$ mol
10 mol	5 mol	10 mol

Note that each set of quantities is in the ratio 2:1:2, as given by the coefficients in the chemical equation. In fact, each set is a whole-number multiple of the coefficients 2, 1, and 2. This ratio is valid whether you are considering a few or a huge number of entities.

mole ratio the ratio of the amounts of the entities in a chemical reaction

The ratio of the amount (in moles) of one chemical to another in a chemical equation is called the **mole ratio**. The mole ratio can describe the ratio of reactants required to react. It can also describe the amount of product expected from a given amount of reactants. The mole ratio is related to the coefficients in the chemical equation.

Mini **Investigation**

One Plus One Does Not Always Equal Two

Skills: Predicting, Performing, Observing, Analyzing, Communicating SKILLS HANDBOOK A2.4

In this investigation, you will use a molecular model kit to help visualize the proportions of reactants and products in a chemical reaction.

Equipment and Materials: molecular model kit

1. Build models of 1 molecule of hydrogen, H_2, and 1 molecule of fluorine, F_2. Predict the product(s) of the synthesis reaction involving these molecules. Use your models to evaluate your prediction. Record your observations.
2. Build models of 2 molecules of water, H_2O. Predict the products of the decomposition reaction involving these molecules. Use your molecules to evaluate your prediction.
3. Build models of 1 ethyne molecule, C_2H_2, and 2 fluorine molecules, F_2. Predict the molecular formula of the product of the synthesis reaction involving these molecules.

A. Write a balanced chemical equation for each reaction. K/U C

B. For each reaction, compare the total number of molecules on either side of the arrow. T/I

C. Do these reactions illustrate the law of conservation of mass? Explain your answer. K/U T/I

Determining Mole Ratios in Chemical Equations

You have seen how the amounts of reactants and products in a chemical reaction are multiples of the coefficients in the balanced chemical equation. Whole-number multiples are easy to predict, as Tables 1 and 2 illustrate, but what about fractional multiples?

Tutorial **1** Using Mole Ratios to Determine Amounts

In this Tutorial, you will learn a general process you can use to predict the amount of one chemical from a given amount of another.

Sample Problem 1: Determining Amounts Using Mole Ratios

What amount of hydrogen is produced when 5.2 mol of ammonia decomposes (**Figure 3**)?

Given: amount of ammonia, $n_{NH_3} = 5.2$ mol

Required: amount of hydrogen, n_{H_2}

Solution:

Step 1. Write a balanced equation for the reaction, listing the given value(s) and required value(s) below the substances being considered in the problem. Use the symbol of the required value since its value is unknown.

$$2\ NH_3(g) \rightarrow N_2(g) + 3\ H_2(g)$$

5.2 mol $\qquad\qquad n_{H_2}$

Step 2. Convert amount of the given substance to amount of the required substance. To do this, multiply the amount of the given substance by a suitable conversion factor derived from the mole ratio in the balanced equation.

Figure 3 Ammonia fertilizes the soil by adding nitrogen—an important plant nutrient.

The mole ratio between NH_3 and H_2 may be expressed as

$$\frac{2\ \text{mol}_{NH_3}}{3\ \text{mol}_{H_2}} \text{ or } \frac{3\ \text{mol}_{H_2}}{2\ \text{mol}_{NH_3}}$$

Since we want to convert amount of ammonia to amount of hydrogen, we use the factor $\frac{3\ \text{mol}_{H_2}}{2\ \text{mol}_{NH_3}}$ as follows:

$$n_{H_2} = 5.2\ \cancel{\text{mol}_{NH_3}} \times \frac{3\ \text{mol}_{H_2}}{2\ \cancel{\text{mol}_{NH_3}}}$$

$$n_{H_2} = 7.8\ \text{mol}_{H_2}$$

Statement: The decomposition of 5.2 mol of ammonia produces 7.8 mol of hydrogen.

Sample Problem 2: Determining Amounts Using Mole Ratios

A freshly exposed surface of aluminum quickly reacts with oxygen to form a layer of aluminum oxide. What amount of oxygen is required to react completely with 6.4×10^{-2} mol of aluminum?

Given: $n_{Al} = 6.4 \times 10^{-2}$ mol

Required: amount of oxygen, n_{O_2}

Solution:

Step 1. Write a balanced equation for the reaction, listing the given value(s) and required value(s).

$$\begin{array}{lll} 4\ Al(s) & + & 3\ O_2(g) \rightarrow 2\ Al_2O_3(s) \\ 6.4 \times 10^{-2}\ \text{mol} & & n_{O_2} \end{array}$$

Step 2. Convert amount of the given substance to amount of the required substance.

$$n_{O_2} = 6.4 \times 10^{-2}\ \cancel{\text{mol}_{Al}} \times \frac{3\ \text{mol}_{O_2}}{4\ \cancel{\text{mol}_{Al}}}$$

$$n_{O_2} = 4.8 \times 10^{-2}\ \text{mol}$$

Statement: 4.8×10^{-2} mol of oxygen is required to react completely with 6.4×10^{-2} mol of aluminum.

Practice

SKILLS HANDBOOK A6.5

1. Phosphorus, P_4, burns in oxygen to produce diphosphorus pentoxide, P_2O_5:

   $P_4(s) + 5\ O_2(g) \rightarrow 2\ P_2O_5(g)$

   What amount of oxygen is required to produce 0.25 mol of the product? T/I [ans: 0.63 mol]

2. Iron can be produced from the reaction of iron(III) oxide, found in iron ore, with carbon monoxide, CO. The other product is carbon dioxide:

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

   What amount of carbon monoxide is required to produce 1.4×10^3 mol of iron? T/I [ans: 2.1×10^3 mol]

3. What amount of potassium is produced when 0.15 mol of potassium oxide decomposes?

   $2\ K_2O(s) \rightarrow 4\ K(s) + O_2(g)$ T/I [ans: 0.30 mol]

7.1 Summary

- A mole ratio is the ratio of the amounts of reactants and/or products in a chemical reaction.
- Coefficients in a chemical equation are used to determine mole ratios.
- A mole ratio is used to predict the amount of reactant required or product produced in a chemical reaction.

7.1 Questions

1. Why is it necessary to balance a chemical equation before determining the amount of product that can be made from a given amount of reactant? T/I
2. What is conserved during a chemical reaction: mass or the number of moles? Justify your choice. K/U T/I
3. Write the mole ratio of potassium chlorate, $KClO_3$, to oxygen, O_2, in the chemical equation

   $2\ KClO_3(s) \rightarrow 2\ KCl(s) + 3\ O_2(g)$ K/U
4. Aluminum metal reacts with chlorine gas to form aluminum chloride, $AlCl_3$:

   $2\ Al(s) + 3\ Cl_2(g) \rightarrow 2\ AlCl_3(s)$

   Copy **Table 3** into your notebook. Complete the table, predicting the amounts of other chemicals that correspond to the given amount. K/U T/I

Table 3 Amounts Involved in the Synthesis of Aluminum Chloride

Amount of Al(s) (mol)	Amount of Cl_2(g) (mol)	Amount of $AlCl_3$(s) (mol)
		2
	1.5	
0.80		
		1.6
	0.45	

5. Explain what is meant by the term "relative" in the statement "chemical equations give the relative amounts of one chemical to another but not the actual amounts." T/I
6. The chemical equation for the reaction of ammonia, NH_3, with oxygen is

   $4\ NH_3(g) + 5\ O_2(g) \rightarrow 4\ NO(g) + 6\ H_2O(g)$

   Predict the amounts of ammonia and oxygen required to produce the following amounts of products:
   (a) 2 mol NO
   (b) 1.8 mol H_2O
   (c) 5.2×10^{-3} mol NO T/I
7. In Unit 2 you learned that one of the hazards of the incomplete combustion of a hydrocarbon is the production of carbon monoxide. Methane is a hydrocarbon that is commonly used as a heating fuel. A possible chemical equation for the incomplete combustion of methane, CH_4, is

   $2\ CH_4(g) + 3\ O_2(g) \rightarrow 2\ CO(g) + 4\ H_2O(g) + \text{energy}$

   Copy **Table 4** into your notebook. Complete the table, predicting the amounts of other chemicals that correspond to the given amount. K/U T/I

Table 4 Amounts Involved in the Combustion of Methane

Amount of CH_4(g) (mol)	Amount of O_2(g) (mol)	Amount of CO(g) (mol)	Amount of H_2O (mol)
3			
	9		
		0.2	
			1

8. The chemical equation for the decomposition of ammonia, NH_3, into its elements is

   $2\ NH_3(g) \rightarrow 3\ H_2(g) + N_2(g)$ K/U T/I C
   (a) Sketch a diagram of four ammonia molecules inside a sealed container and another diagram of the same container after the reaction is complete, similar to Figure 2.
   (b) How many molecules of each product are there?
   (c) What is the simplest ratio of molecules of reactants and products? Relate your answer to the chemical equation.
9. Magnesium nitride is a green ionic solid that reacts with water:

   $Mg_3N_2(s) + 6\ H_2O(l) \rightarrow 3\ Mg(OH)_2(s) + 2\ NH_3(g)$
   (a) Predict the amount of magnesium nitride required to produce 1.5 mol of ammonia.
   (b) Predict the amount of water required to produce 1.5 mol of ammonia.
   (c) What amount of magnesium nitride is required to react completely with 0.25 mol of water? What amounts of the products are expected? T/I