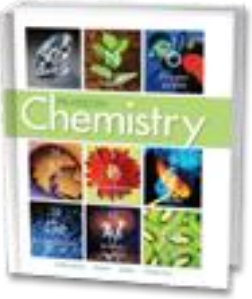


Chapter 12
Stoichiometry

12.1 The Arithmetic of Equations

12.2 Chemical Calculations

12.3 Limiting Reagent and Percent Yield

PEARSON

How do manufacturers know how to make enough of their desired product?

If chemical plants produce too much ammonia, then it might be wasted. But if too little is produced, then there might not be enough for all their customers.

Writing and Using Mole Ratios

How are mole ratios used in chemical calculations?

A **mole ratio** is a conversion factor derived from the coefficients of a balanced chemical equation interpreted in terms of moles.

In chemical calculations, mole ratios are used to convert between a given number of moles of a reactant or product to moles of a different reactant or product.

Look again at the balanced equation for the production of ammonia.

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

The three mole ratios derived from the balanced equation above are:

$$\frac{1 \text{ mol } N_2}{3 \text{ mol } H_2} \qquad \frac{2 \text{ mol } NH_3}{1 \text{ mol } N_2} \qquad \frac{3 \text{ mol } H_2}{2 \text{ mol } NH_3}$$

Mole-Mole Calculations

- In the mole ratio below, *W* is the unknown, wanted quantity and *G* is the given quantity. The values of *a* and *b* are the coefficients from the balanced equation.
- The general solution for a mole-mole problem is given by

$$x \text{ mol } G \times \frac{b \text{ mol } W}{a \text{ mol } G} = \frac{xb}{a} \text{ mol } W$$

Calculating Moles of a Product

How many moles of NH_3 are produced when 0.60 mol of nitrogen reacts with hydrogen?

1 Analyze List the known and the unknown.

$$N_2 + 3H_2 \rightarrow 2NH_3$$

- The conversion is mol $N_2 \rightarrow$ mol NH_3.
- 1 mol N_2 combines with 3 mol H_2 to produce 2 mol NH_3.
- To determine the number of moles of NH_3, the given quantity of N_2 is multiplied by the form of the mole ratio from the balanced equation that allows the given unit to cancel.

KNOWN

moles of nitrogen = 0.60 mol N_2

UNKNOWN

moles of ammonia = ? mol NH_3

2 Calculate Solve for the unknown.

Write the mole ratio that will allow you to convert from moles N_2 to moles NH_3.

$$\frac{2 \text{ mol } NH_3}{1 \text{ mol } N_2}$$

2 Calculate Solve for the unknown.

Multiply the given quantity of N_2 by the mole ratio in order to find the moles of NH_3.

$$0.60 \text{ mol } N_2 \times \frac{2 \text{ mol } NH_3}{1 \text{ mol } N_2} = 1.2 \text{ mol } NH_3$$

Remember that the mole ratio must have N_2 on the bottom so that the mol N_2 in the mole ratio will cancel with mol N_2 in the known.

3 Evaluate Does the result make sense?

The ratio of 1.2 mol NH_3 to 0.60 mol N_2 is 2:1, as predicted by the balanced equation.

Mass-Mass Calculations

In the laboratory, the amount of a substance is usually determined by measuring its mass in grams.

- If a given sample is measured in grams, then the mass can be converted to moles by using the molar mass.
- Then the mole ratio from the balanced equation can be used to calculate the number of moles of the unknown.
- If it is the mass of the unknown that needs to be determined, the number of moles of the unknown can be multiplied by the molar mass.

Steps for Solving a Mass-Mass Problem

1. Change the mass of *G* to moles of *G* (mass *G* $\rightarrow$ mol *G*) by using the molar mass of *G*.

$$\text{mass } G \times \frac{1 \text{ mol } G}{\text{molar mass } G} = \text{mol } G$$

Steps for Solving a Mass-Mass Problem

1. Change the mass of *G* to moles of *G* (mass *G* $\rightarrow$ mol *G*) by using the molar mass of *G*.

$$\text{mass } G \times \frac{1 \text{ mol } G}{\text{molar mass } G} = \text{mol } G$$

2. Change the moles of *G* to moles of *W* (mol *G* $\rightarrow$ mol *W*) by using the mole ratio from the balanced equation.

$$\text{mol } G \times \frac{b \text{ mol } W}{a \text{ mol } G} = \text{mol } W$$

Steps for Solving a Mass-Mass Problem

1. Change the mass of *G* to moles of *G* (mass *G* $\rightarrow$ mol *G*) by using the molar mass of *G*.

$$\text{mass } G \times \frac{1 \text{ mol } G}{\text{molar mass } G} = \text{mol } G$$

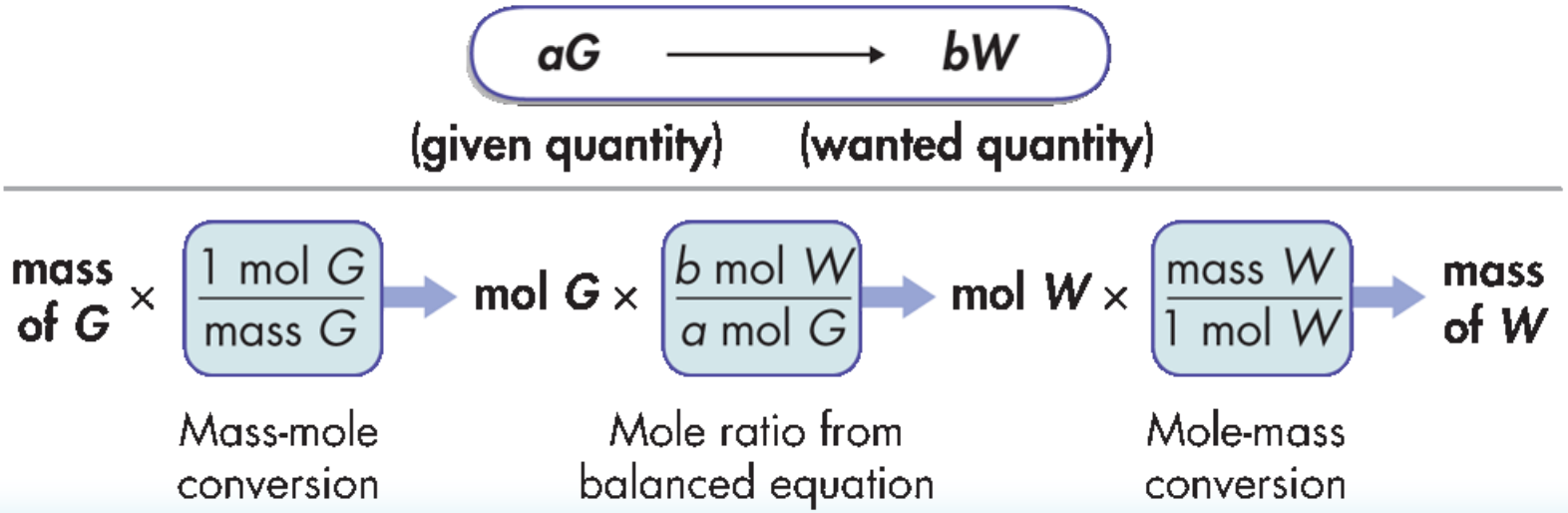
2. Change the moles of *G* to moles of *W* (mol *G* $\rightarrow$ mol *W*) by using the mole ratio from the balanced equation.

$$\text{mol } G \times \frac{b \text{ mol } W}{a \text{ mol } G} = \text{mol } W$$

3. Change the moles of *W* to grams of *W* (mol *W* $\rightarrow$ mass *W*) by using the molar mass of *W*.

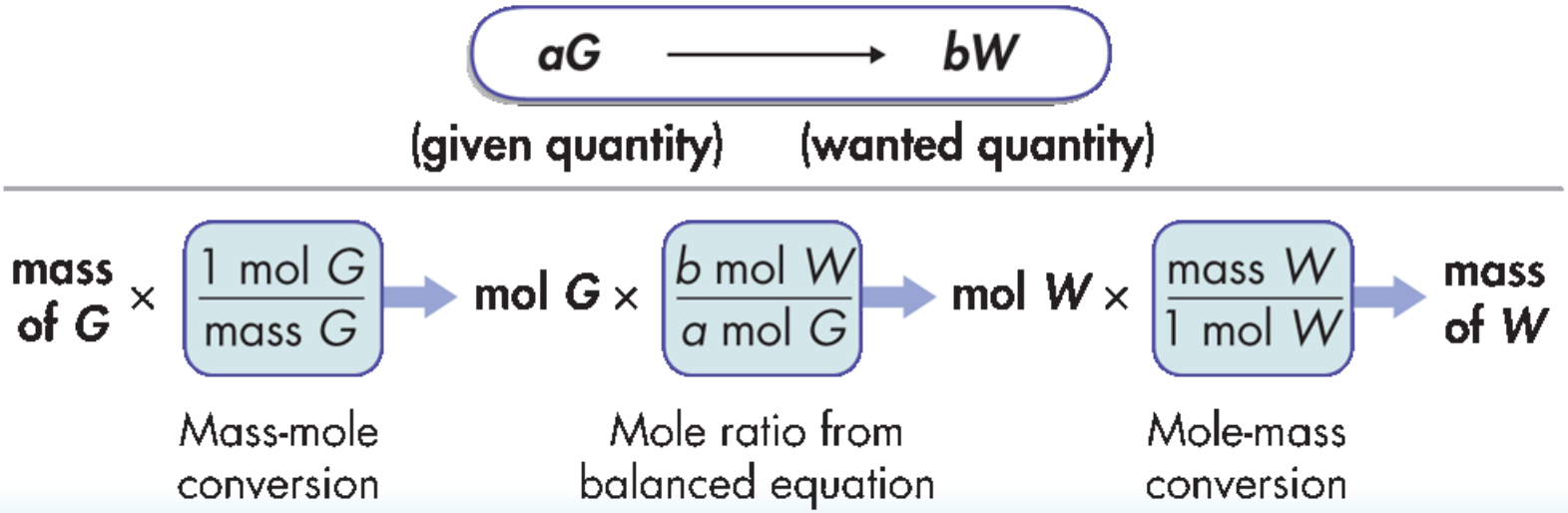
$$\text{mol } W \times \frac{\text{molar mass } W}{1 \text{ mol } W} = \text{mass } W$$

The figure below shows another way to represent the steps for doing mole-mass and mass-mole stoichiometric calculations.



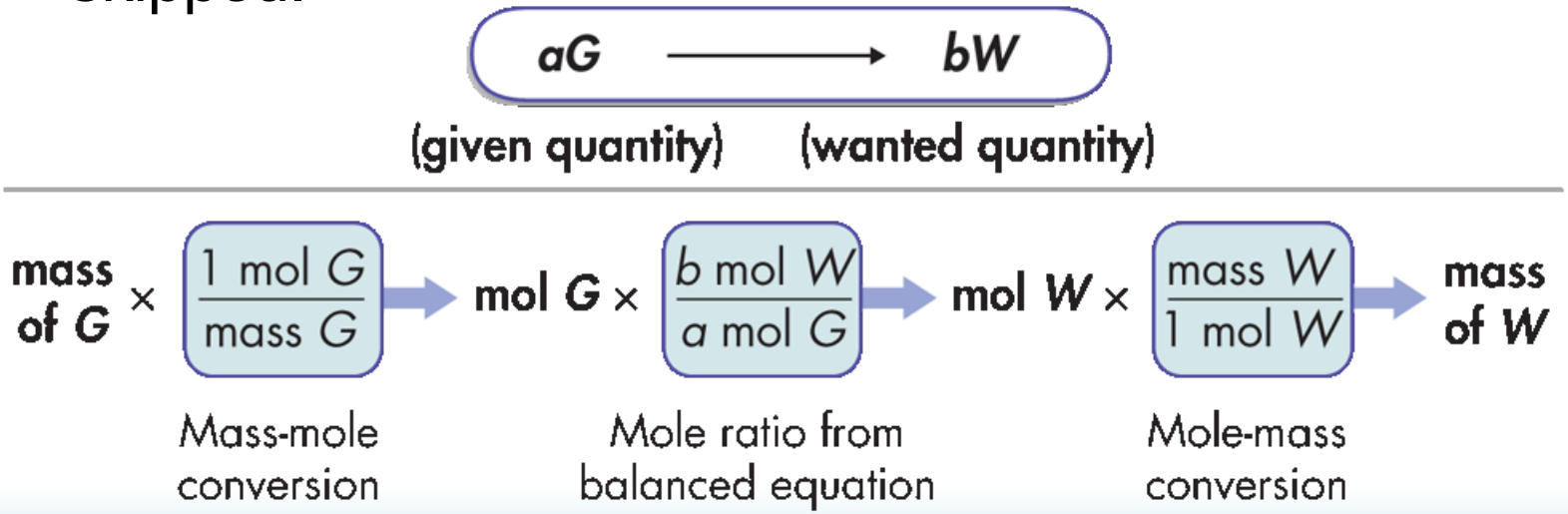
The figure below shows another way to represent the steps for doing mole-mass and mass-mole stoichiometric calculations.

- For a mole-mass problem, the first conversion is skipped.



The figure below shows another way to represent the steps for doing mole-mass and mass-mole stoichiometric calculations.

- For a mole-mass problem, the first conversion is skipped.
- For a mass-mole problem, the last conversion is skipped.



Calculating the Mass of a Product

Calculate the number of grams of NH_3 produced by the reaction of 5.40 g of hydrogen with an excess of nitrogen. The balanced equation is:

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

1 Analyze List the knowns and the unknown.

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

KNOWNS

mass of hydrogen = 5.40 g H_2

3 mol H_2 = 2 mol NH_3 (from balanced equation)

1 mol H_2 = 2.0 g H_2 (molar mass)

1 mol NH_3 = 17.0 g NH_3 (molar mass)

UNKNOWN

mass of ammonia = ? g NH_3

1 Analyze List the knowns and the unknown.

- The mass of hydrogen will be used to find the mass of ammonia: g $H_2 \rightarrow$ g NH_3.
- The coefficients of the balanced equation show that 3 mol H_2 reacts with 1 mol N_2 to produce 2 mol NH_3.
- The following steps are necessary to determine the mass of the ammonia:

$$\text{g } H_2 \rightarrow \text{mol } H_2 \rightarrow \text{mol } NH_3 \rightarrow \text{g } NH_3$$

Sample Problem 12.4

2 Calculate Solve for the unknown.

Start with the given quantity, and convert from mass to moles.

$$5.40\ \text{g}\ \cancel{\text{H}_2} \times \frac{1\ \text{mol}\ \text{H}_2}{2.0\ \cancel{\text{g}}\ \cancel{\text{H}_2}}$$

Given quantity

Change given unit to moles

Don't forget to cancel the units at each step.

2 Calculate Solve for the unknown.

Then convert from moles of reactant to moles of product by using the correct mole ratio.

$$5.40\ \text{g}\ H_2 \times \frac{1\ \text{mol}\ H_2}{2.0\ \text{g}\ H_2} \times \frac{2\ \text{mol}\ NH_3}{3\ \text{mol}\ H_2}$$

Given quantity

Change given unit to moles

Mole ratio

2 Calculate Solve for the unknown.

Finish by converting from moles to grams. Use the molar mass of NH_3.

$$5.40\ \text{g}\ H_2 \times \frac{1\ \text{mol}\ H_2}{2.0\ \text{g}\ H_2} \times \frac{2\ \text{mol}\ NH_3}{3\ \text{mol}\ H_2} \times \frac{17.0\ \text{g}\ NH_3}{1\ \text{mol}\ NH_3}$$

Given quantity	Change given unit to moles	Mole ratio	Change moles to grams

$$= 31\ \text{g}\ NH_3$$

3 Evaluate Does the result make sense?

- Because there are three conversion factors involved in this solution, it is more difficult to estimate an answer.
- Because the molar mass of NH_3 is substantially greater than the molar mass of H_2, the answer should have a larger mass than the given mass.
- The answer should have two significant figures.

Phosphorus burns in air to produce a phosphorus oxide in the following reaction:

$$4P(s) + 5O_2(g) \rightarrow P_4O_{10}(s)$$

What mass of phosphorus will be needed to produce 3.25 mol of P_4O_{10}?

Checkpoint

Phosphorus burns in air to produce a phosphorus oxide in the following reaction:

$$4P(s) + 5O_2(g) \rightarrow P_4O_{10}(s)$$

What mass of phosphorus will be needed to produce 3.25 mol of P_4O_{10}?

$$3.25 \text{ mol } P_4O_{10} \times \frac{4 \text{ mol P}}{1 \text{ mol } P_4O_{10}} \times \frac{31.0 \text{ g P}}{1 \text{ mol P}} = 403 \text{ g P}$$

Other Stoichiometric Calculations

What is the general procedure for solving a stoichiometric problem?

In a typical stoichiometric problem:

- The given quantity is first converted to moles.
- Then, the mole ratio from the balanced equation is used to calculate the number of moles of the wanted substance.
- Finally, the moles are converted to any other unit of measurement related to the unit mole, as the problem requires.

The mole-mass relationship gives you two conversion factors.

$$\frac{1\ \text{mol}}{\text{molar mass}} \text{ and } \frac{\text{molar mass}}{1\ \text{mol}}$$

Recall that the mole can be related to other quantities:

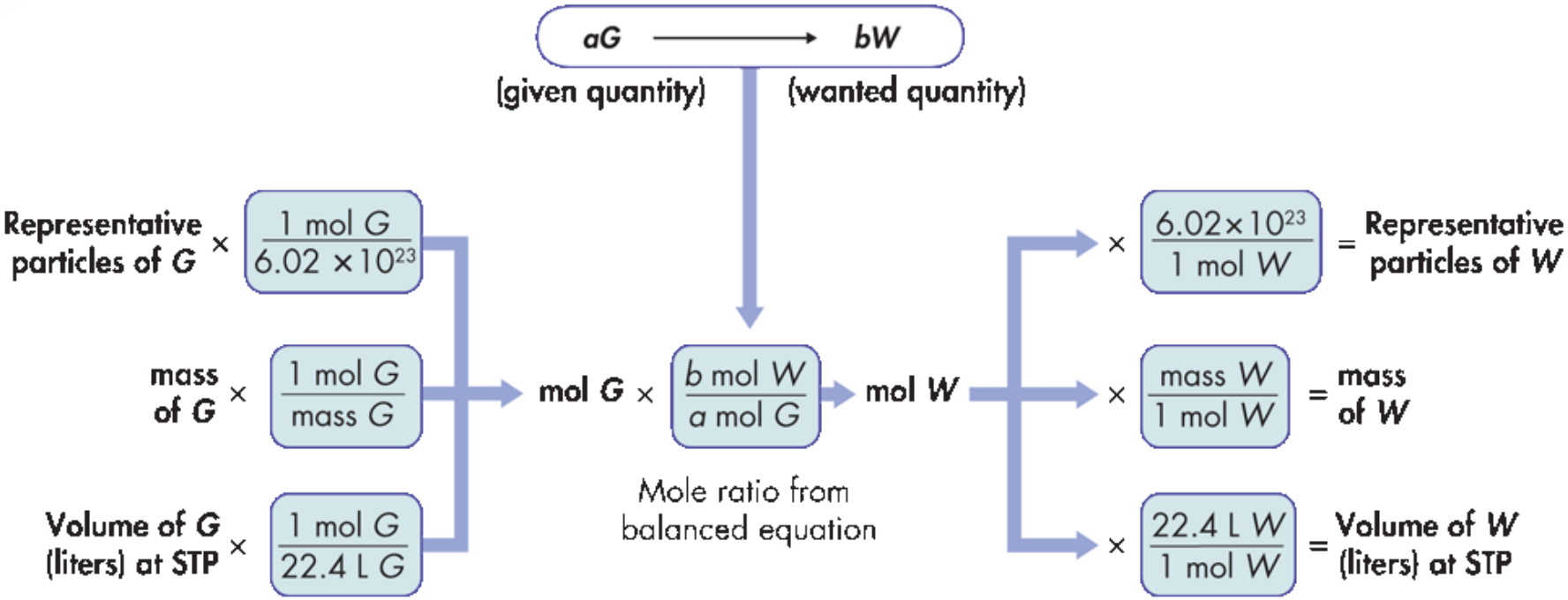
- 1 mol = 6.02×10^{23} particles
- 1 mol of a gas = 22.4 L at STP

These provide four more conversion factors:

$$\frac{1\text{ mol}}{6.02\times10^{23}\text{ particles}} \quad \text{and} \quad \frac{6.02\times10^{23}\text{ particles}}{1\text{ mol}}$$

$$\frac{1\text{ mol}}{22.4\text{ L}} \quad \text{and} \quad \frac{22.4\text{ L}}{1\text{ mol}}$$

The figure below summarizes the steps for a typical stoichiometric problem.



CHEMISTRY & YOU

How do you think air bag manufacturers know how to get the right amount of air in an inflated air bag?

How do you think air bag manufacturers know how to get the right amount of air in an inflated air bag?

They take the volume of air needed to inflate the bag and convert it to number of moles (assuming STP). Then, they use the mole ratio from a balanced chemical equation to calculate the number of moles of reactants needed. This could be converted to any other unit of measurement related to the unit mole.

Sample Problem 12.5

Calculating the Molecules of a Product

How many molecules of oxygen are produced when 29.2 g of water is decomposed by electrolysis according to this balanced equation?

$$2H_2O(l) \xrightarrow{\text{electricity}} 2H_2(g) + O_2(g)$$

Sample Problem 12.5

1 Analyze List the knowns and the unknown.

The following calculations need to be performed:

$$\text{g } H_2O \rightarrow \text{mol } H_2O \rightarrow \text{mol } O_2 \rightarrow \text{molecules } O_2$$

The appropriate mole ratio relating mol O_2 to mol H_2O from the balanced equation is:

$$\frac{1 \text{ mol } O_2}{2 \text{ mol } H_2O}$$

1 Analyze List the knowns and the unknown.

KNOWNS

mass of water = 29.2 g H_2O

2 mol H_2O = 1 mol O_2 (from balanced equation)

1 mol H_2O = 18.0 g H_2O (molar mass)

1 mol O_2 = 6.02×10^{23} molecules O_2

UNKNOWN

molecules of oxygen = ? molecules O_2

2 Calculate Solve for the unknown.

Start with the given quantity, and convert from mass to moles.

$$29.2 \text{ g } H_2O \times \frac{1 \text{ mol } H_2O}{18.0 \text{ g } H_2O}$$

Given quantity

Change to moles

Remember to also start your calculations with the given quantity, even if the given quantity is a product in the reaction.

2 Calculate Solve for the unknown.

Then, convert from moles of reactant to moles of product.

$$29.2\ \text{g}\ H_2O \times \frac{1\ \text{mol}\ H_2O}{18.0\ \text{g}\ H_2O} \times \frac{1\ \text{mol}\ O_2}{2\ \text{mol}\ H_2O}$$

Given quantity

Change to moles

Mole ratio

2 Calculate Solve for the unknown.

Finish by converting from moles to molecules.

$$29.2\ \text{g } H_2O \times \frac{1\ \text{mol } H_2O}{18.0\ \text{g } H_2O} \times \frac{1\ \text{mol } O_2}{2\ \text{mol } H_2O} \times \frac{6.02 \times 10^{23}\ \text{molecules } O_2}{1\ \text{mol } O_2}$$

Given quantity	Change to moles	Mole ratio	Change to molecules

2 Calculate Solve for the unknown.

Finish by converting from moles to molecules.

$$29.2\ \text{g } H_2O \times \frac{1\ \text{mol } H_2O}{18.0\ \text{g } H_2O} \times \frac{1\ \text{mol } O_2}{2\ \text{mol } H_2O} \times \frac{6.02 \times 10^{23}\ \text{molecules } O_2}{1\ \text{mol } O_2}$$

Given quantity | Change to moles | Mole ratio | Change to molecules

$$= 4.88 \times 10^{23}\ \text{molecules } O_2$$

3 Evaluate Does the result make sense?

- The given mass of water should produce a little less than 1 mol of oxygen, or a little less than Avogadro's number of molecules.
- The answer should have three significant figures.

Volume-Volume Stoichiometric Calculations

Nitrogen monoxide and oxygen gas combine to form the brown gas nitrogen dioxide, which contributes to photochemical smog. How many liters of nitrogen dioxide are produced when 34 L of oxygen react with an excess of nitrogen monoxide? Assume conditions are at STP.

$$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$$

1 Analyze List the knowns and the unknown.

For gaseous reactants and products at STP, 1 mol of a gas is equal to 22.4 L.

KNOWNS

volume of oxygen = 34 L O_2

2 mol NO_2/1 mol O_2 (mole ratio from balanced equation)

1 mol O_2 = 22.4 L O_2 (at STP)

1 mol NO_2 = 22.4 L NO_2 (at STP)

UNKNOWN

volume of nitrogen dioxide = ? L NO_2

Sample Problem 12.6

2 Calculate Solve for the unknown.

Start with the given quantity, and convert from volume to moles by using the volume ratio.

$$34\ \text{L}\ O_2 \times \frac{1\ \text{mol}\ O_2}{22.4\ \text{L}\ O_2}$$

Given quantity

Change to moles

Did you notice that the 22.4 L/mol factors canceled out? This will always be true in a volume-volume problem.

2 Calculate Solve for the unknown.

Then, convert from moles of reactant to moles of product by using the correct mole ratio.

$$34\ \text{L}\ \cancel{O_2} \times \frac{1\ \cancel{\text{mol}\ O_2}}{22.4\ \cancel{\text{L}\ O_2}} \times \frac{2\ \text{mol}\ NO_2}{1\ \cancel{\text{mol}\ O_2}}$$

Given quantity

Change to moles

Mole ratio

2 Calculate Solve for the unknown.

Finish by converting from moles to liters.
Use the volume ratio.

$$34\ \text{L}\ \cancel{O_2} \times \frac{1\ \text{mol}\ \cancel{O_2}}{22.4\ \text{L}\ \cancel{O_2}} \times \frac{2\ \text{mol}\ \cancel{NO_2}}{1\ \text{mol}\ \cancel{O_2}} \times \frac{22.4\ \text{L}\ NO_2}{1\ \text{mol}\ \cancel{NO_2}}$$

Given quantity | Change to moles | Mole ratio | Change to liters

$$= 68\ \text{L}\ NO_2$$

3 Evaluate Does the result make sense?

- Because 2 mol NO_2 are produced for each 1 mol O_2 that reacts, the volume of NO_2 should be twice the given volume of O_2.
- The answer should have two significant figures.

Finding the Volume of a Gas Needed for a Reaction

Assuming STP, how many milliliters of oxygen are needed to produce 20.4 mL SO_3 according to this balanced equation?

$$2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$$

1 Analyze List the knowns and the unknown.

- For a reaction involving gaseous reactants or products, the coefficients also indicate relative amounts of each gas.
- You can use the volume ratios in the same way you have used mole ratios.

KNOWNS

volume of sulfur trioxide = 20.4 mL

2 mL SO_3/1 mL O_2 (volume ratio from balanced equation)

UNKNOWN

volume of oxygen = ? mL O_2

2 Calculate Solve for the unknown.

Multiply the given volume by the appropriate volume ratio.

$$20.4 \text{ mL } \cancel{SO_3} \times \frac{1 \text{ mL } O_2}{2 \text{ mL } \cancel{SO_3}} = 10.2 \text{ mL } O_2$$

The volume ratio can be written using milliliters as the units instead of liters.

3 Evaluate Does the result make sense?

- Because the volume ratio is 2 volumes SO_3 to 1 volume O_2, the volume of O_2 should be half the volume of SO_3.
- The answer should have three significant figures.

Methane burns in air by the following reaction:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

What volume of water vapor is produced at STP by burning 501 g of methane?

Checkpoint

Methane burns in air by the following reaction:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

What volume of water vapor is produced at STP by burning 501 g of methane?

$$501\ \text{g}\ CH_4 \times \frac{1\ \text{mol}\ CH_4}{16.05\ \text{g}\ CH_4} \times \frac{2\ \text{mol}\ H_2O}{1\ \text{mol}\ CH_4} \times \frac{22.4\ \text{L}\ H_2O}{1\ \text{mol}\ H_2O}$$

$$= 1.40 \times 10^3\ \text{L}\ H_2O$$

- In chemical calculations, mole ratios are used to convert between moles of reactant and moles of product, between moles of reactants, or between moles of products.

- In a typical stoichiometric problem, the given quantity is first converted to moles. Then, the mole ratio from the balanced equation is used to calculate the moles of the wanted substance. Finally, the moles are converted to any other unit of measurement related to the unit mole.

Mole-mole relationship for $aG \rightarrow bW$:

$$x \text{ mol } G \times \frac{b \text{ mol } W}{a \text{ mol } G} = \frac{xb}{a} \text{ mol } W$$

mole ratio: a conversion factor derived from the coefficients of a balanced chemical equation interpreted in terms of moles

BIG IDEA

The Mole and Quantifying Matter

Mole ratios from the balanced equation are used to calculate the amount of a reactant or product in a chemical reaction from a given amount of one of the reactants or products.

END OF 12.2