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12 Stoichiometry

Big idea

THE MOLE AND QUANTIFYING MATTER, REACTIONS

12.1 The Arithmetic of Equations

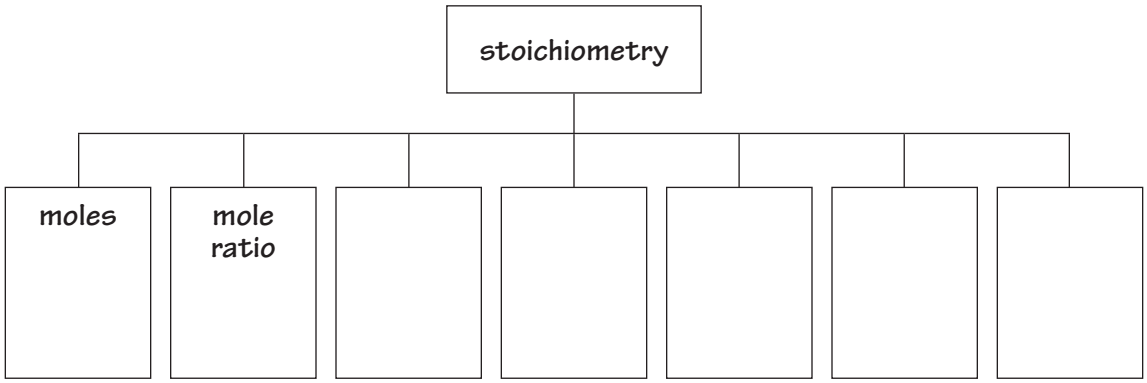
For students using the Foundation edition, assign problems 2–4, 7, 10–12.

Essential Understanding The law of conservation of mass applies to all chemical equations.

Reading Strategy

Vocabulary Word Map A vocabulary word map will help you learn vocabulary by associating the word with related words and images. Begin by writing the word *stoichiometry* in the top box.

As you read Lesson 12.1, use the word map below to help you get a better understanding of the meaning of the word *stoichiometry*. As you read, fill in the other boxes with terms, phrases, or images that are associated with the word.



Lesson Summary

Using Equations Stoichiometric calculations tell us the amounts of reactants and products under ideal conditions.

- Knowing the quantity of one substance in an equation allows you to calculate the amount of any other substance consumed or created in the reaction.

Chemical Equations The solution to every stoichiometric problem requires a balanced chemical equation.

- In a balanced chemical equation, the total number of atoms of each element in the reactants must equal the total number of atoms of that element in the products.
- In a balanced chemical equation, the total mass of the reactants must equal the total mass of the products.

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After reading Lesson 12.1, answer the following questions.

Using Equations

1. How can you determine the quantities of reactants and products in a chemical reaction?

   You can use the balanced equation.

2. Quantity usually means the *amount* of a substance expressed in grams or moles.

3. A bookcase is to be built from 3 shelves (Sh), 2 side boards (Sb), 1 top (T), 1 base (B), and 4 legs (L). Write a "balanced equation" for the construction of this bookcase.

   $3Sh + 2Sb + T + B + 4L = Sh_3Sb_2TBL_4$

4. Is the following sentence true or false? Stoichiometry is the calculation of quantities in chemical reactions. *true*

5. Calculations using balanced equations are called *stoichiometric calculations*.

Chemical Equations

6. From what elements is ammonia produced? How is it used?

   Ammonia molecules are composed of nitrogen and hydrogen; it is used as a fertilizer.

7. Circle the letter of the term that tells what kind of information you CANNOT get from a chemical equation.

   a. moles

   b. mass

   c. size of particles

   d. volume

   e. number of particles

8. The coefficients of a balanced chemical equation tell you the relative number of moles of *reactants* and *products* in a chemical reaction.

9. Why is the relative number of moles of reactants and products the most important information that a balanced chemical equation provides?

   Knowing the relative number of moles allows you to calculate the amounts of reactants and products.

10. Is the following sentence true or false? A balanced chemical equation must obey the law of conservation of mass. *true*

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11. Use Figure 12.2 on page 389. Complete the table about the reaction of nitrogen and hydrogen.

$N_2(g)$	+ $3H_2(g)$	→ $2NH_3(g)$
2 atoms N	+ 6 atoms H	→ **2** atoms N and **6** atoms H
1 molecule N_2	+ **3** molecules H_2	→ **2** molecules NH_3
1 × (6.02×10^{23} molecules N_2)	+ 3 × (6.02×10^{23} molecules H_2)	→ **2** × (6.02×10^{23} molecules NH_3)
1 mol N_2	+ **3** mol H_2	→ 2 mol NH_3
28 g N_2	+ 3 × **2** g H_2	→ 2 × **17** g NH_3
	34 g reactants	→ 34 g products
Assume STP 22.4 L N_2	+ 67.2 L H_2	→ **44.8** L NH_3

12. Circle the letter(s) of the items that are ALWAYS conserved in every chemical reaction.

a. volume of gases
b. mass
c. formula units
d. moles
e. molecules
f. atoms

13. What reactant combines with oxygen to form sulfur dioxide? Where can this reactant be found in nature?

Hydrogen sulfide gas combines with oxygen to form sulfur dioxide. It can be found in volcanic gases.

12.2 Chemical Calculations

For students using the Foundation edition, assign problems 4–6, 9–12.

Essential Understanding Amounts of reactants and products are always related by mole ratios.

Lesson Summary

Writing and Using Mole Ratios A mole ratio is a conversion factor derived from the coefficients of a balanced chemical equation.

- Mole ratios are used to convert between mass and moles in stoichiometric problems.
- The coefficients indicate the number of moles in a balanced equation.

Other Stoichiometric Calculations The first step in solving stoichiometric problems is writing the balanced chemical equation.

- Moles are always involved when solving stoichiometric problems.
- Several mole ratios can be created from a balanced equation.

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Steps to solving a stoichiometric problem

Step 1	Step 2	Step 3
Change the given quantity to moles.	Use the mole ratio to calculate moles of the wanted substance.	Convert moles of the wanted substance into the unit required by the problem.

BUILD Math Skills

Ratios You use ratios every day, whether you realize it or not. A ratio is a term used to compare two numbers or quantities. For example, \$3.00 per gallon of gas can be expressed as 3:1 or as $\frac{3}{1}$. Or suppose you see 35 people, and 15 of these people are men. Then the *ratio of men to women* is 15:20. Remember that order is very important. If the expression had been *the ratio of women to men*, then the numbers would have been 20:15.

The way you set up a ratio is very important. Consider a recipe for pink paint.

If you write the ratio of white paint to red paint incorrectly, you'll get a different shade of pink.

These are not the same.

$\frac{1 \text{ white}}{3 \text{ red}}$ = dark pink $\frac{3 \text{ white}}{1 \text{ red}}$ = light pink

Sample Problem Set up a ratio for a recipe using 2 parts white paint to 5 parts blue paint.

Pull out the information you need. two white to five blue

Express it as a ratio. $\frac{2}{5}$

Hint: You simply write the numbers as they are stated.

Now you try to set up the following ratios.

1. Make two cups of coffee for every one cup of tea. *2/1*
2. Candle A is 9 cm tall. Candle B is 30 mm tall. What is the ratio of their heights? (Hint: 10 mm = 1 cm) *Candle A is 9 cm; Candle B is 3 cm; so the ratio is 9:3 or 3:1.*
3. Miguel and Ellen have to share a prize of \$50 at a ratio of $\frac{2}{3}$. How much does each get? (Hint: 1 share = \$10) *Miguel gets 2 shares or \$20, and Ellen gets 3 shares or \$30.*

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After reading Lesson 12.2, answer the following questions.

Writing and Using Mole Ratios

4. What is essential for all calculations involving amounts of reactants and products?

A balanced chemical equation is essential.

5. Is the following sentence true or false? If you know the number of moles of one substance in a reaction, you need more information than the balanced chemical equation to determine the number of moles of all the other substances in the reaction.
false

6. The coefficients from a balanced chemical equation are used to write conversion factors called *mole ratios*.

7. What are mole ratios used for?

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.

8. The equation for the formation of potassium chloride is given by the equation

$$2K(s) + Cl_2(g) \rightarrow 2KCl(s)$$

Write the six possible mole ratios for this equation.

$\frac{2\ K}{1\ Cl_2}$ $\frac{1\ Cl_2}{2\ K}$

$\frac{2\ K}{2\ KCl}$ $\frac{2\ KCl}{2\ K}$

$\frac{1\ Cl_2}{2\ KCl}$ $\frac{2\ KCl}{1\ Cl_2}$

9. Is the following sentence true or false? Laboratory balances are used to measure substances directly in moles. *false*

10. The amount of a substance is usually determined by measuring its mass in *grams*.

11. Is the following sentence true or false? If a sample is measured in grams, molar mass can be used to convert the mass to moles. *true*

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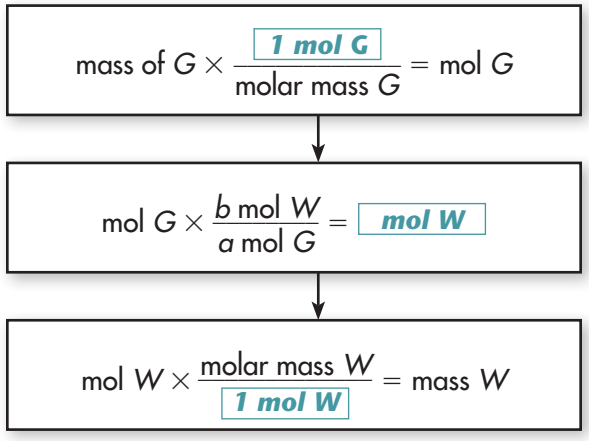
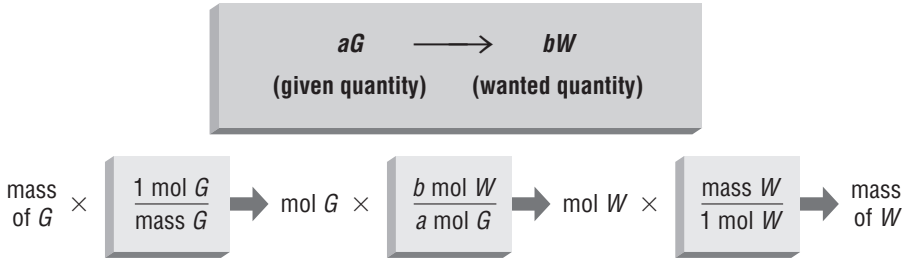
12. Complete the flow chart to show the steps for the mass–mass conversion of any given mass of *G* to any wanted mass of *W*. In the chemical equation, *a* moles of *G* react with *b* moles of *W*.



13. Use the diagram below. Describe the steps needed to solve a mass–mass stoichiometry problem.

First convert mass of G to moles of G. Then use the mole ratio to find moles of W.

Finally convert moles of W to mass of W.



Other Stoichiometric Calculations

14. Is the following sentence true or false? From the mole ratios, you can calculate any measurement unit that is related to the mole, such as representative particles, units of mass, or volumes of gases at STP. ***true***

15. List two or three types of problems that can be solved with stoichiometric calculations.

The problems can include mass–volume, volume–volume, and particle–mass calculations.

16. In any problem relating to stoichiometric calculations, the given quantity is first converted to ***moles***.

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17. The combustion of methane produces carbon dioxide and water. The chemical equation for this reaction is $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$

Write the three conversion factors you would use to find the volume of carbon dioxide obtained from 1.5 L of oxygen.

$\frac{1\ mol\ O_2}{22.4\ L\ O_2}$ $\frac{1\ mol\ CO_2}{2\ mol\ O_2}$ $\frac{22.4\ L\ CO_2}{1\ mol\ CO_2}$

12.3 Limiting Reagent and Percent Yield

For students using the Foundation edition, assign problems 2–5, 8, 9.

Essential Understanding A limiting reagent limits the amount of product.

Lesson Summary

Limiting and Excess Reagents All stoichiometric calculations must be based on the limiting reagent.

- The limiting reagent is the reactant that determines the amount of product that can be formed by a reaction.
- The reaction will stop when the limiting reagent has been used up.
- An excess reagent is any reactant that is not completely used up in a reaction.

Percent Yield The percent yield is the ratio of the actual yield to the theoretical yield expressed as a percent.

- The theoretical yield is the maximum amount of product that could be formed from given amounts of reactants. Actual yield is the amount of product that actually forms when the reaction is carried out in the laboratory.
- Actual yield can be influenced by the purity of the reactants, competing side reactions, or a loss of product during collection or transfer.

After reading Lesson 12.3, answer the following questions.

Limiting Reagent and Percent Yield

1. What is a limiting reagent?

A limiting reagent limits or determines the amount of product that can be formed by a reaction.

2. Is the following sentence true or false? A chemical reaction stops before the limiting reagent is used up. *false*

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3. Circle the letter of the term that correctly completes the sentence. The reactant that is not completely used up in a chemical reaction is called the _____.

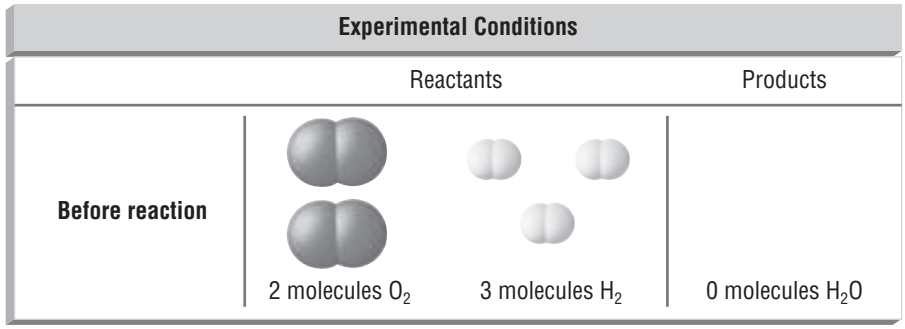
   a. spectator reagent
   c. excess reagent
   b. limiting reagent
   d. catalyst

4. If the quantities of reactants are given in units other than moles, what is the first step for determining the amount of product?

   a. Determine the amount of product from the given amount of limiting reagent.
   b. Convert each given quantity of reactant to moles.
   c. Identify the limiting reagent.

5. In the diagram below, which reactant is the limiting reagent and why? The chemical equation for the formation of water is $2H_2 + O_2 \rightarrow 2H_2O$

   Hydrogen is the limiting reagent because three hydrogen molecules will combine with only three oxygen atoms.



Percent Yield

6. What is the theoretical yield?

   The theoretical yield is the maximum amount of product that could be formed from given amounts of reactants.

7. The amount of product that actually forms when a chemical reaction is carried out in a laboratory is called the ***actual*** yield.

8. Is the following sentence true or false? The actual yield is usually greater than the theoretical yield. ***false***

9. Complete the equation for the percent yield of a chemical reaction.

$$\text{percent yield} = \frac{\text{***actual***\ yield}}{\text{***theoretical***\ yield}} \times 100\%$$

10. Describe four factors that may cause percent yields to be less than 100%.

    impure reactants, competing side reactions, loss of product during filtration or in transferring between containers, carelessly measuring reactants or products

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Guided Practice Problems

Answer the following questions about Practice Problem 12.

This equation shows the formation of aluminum oxide.

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

a. How many moles of oxygen are required to react completely with 14.8 moles of aluminum?

Analyze

1. What is the given information? *14.8 mol Al*

2. What is the unknown? *moles of O_2*

3. What conversion factor will you need to use? $\frac{\textit{3 mol } O_2}{\textit{4 mol Al}}$

Calculate

4. Complete the solution. 14.8 *mol Al* $\times \frac{3 \text{ mol } O_2}{\textit{4 mol Al}} =$ *11.1* mol O_2

Evaluate

5. Why does the answer have three significant figures?

The answer has three significant figures because the number of moles of aluminum is given to three significant figures, and because defined numbers such as mole ratios have an infinite number of significant figures.

b. How many moles of aluminum oxide are formed when 0.78 moles of oxygen react with an excess of aluminum?

Analyze

6. What information is given? *0.78 mol O_2*

7. What information is unknown? *moles of Al_2O_3*

Calculate

8. Complete the solution. *0.78* mol $O_2 \times \frac{\textit{2} \text{ mol } Al_2O_3}{\textit{3 mol } O_2} =$ *0.52* mol Al_2O_3

Evaluate

9. Why does the answer have two significant figures?

The answer has two significant figures because the number of moles of oxygen has two significant figures.

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Answer the following questions about Practice Problem 26.

The equation for the complete combustion of ethene (C_2H_4) is

$$C_2H_4(g) + 3O_2(g) \rightarrow 2CO_2(g) + 2H_2O(g)$$

If 2.70 moles of ethene reacted with 6.30 moles of oxygen, identify the limiting reagent.

Step 1. Calculate the number of moles of oxygen needed to react with 2.70 moles of ethene. Multiply by the mole ratio.

2.70 *mol C_2H_4* $\times \frac{\boxed{3}\ \text{mol } O_2}{1\ \text{mol } C_2H_4}$
$= \underline{8.10}$ mol O_2

Step 2. Compare the number of moles of oxygen needed to the number given.

6.30 mol O_2 given is less than
8.10 mol O_2 needed

Step 3. Identify the limiting reagent.

Because *8.10* mol O_2 are needed to react with the 2.70 mol C_2H_4 and only *6.30* mol O_2 are available, *oxygen* is the limiting reagent.

Answer the following questions about Practice Problem 30.

When 84.8 g of iron(III) oxide reacts with an excess of carbon monoxide, iron is produced.

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

What is the theoretical yield of iron?

Step 1. Begin by finding the molar mass of Fe_2O_3.

2 mol Fe × (*55.8* g Fe/mol Fe)
+ 3 mol O × (*16.0* g O/mol O)
= *111.6* g + 48.0 g = *159.6* g

Step 2. Calculate the number of moles of iron(III) oxide. Multiply by the mole/mass conversion factor.

84.8 g Fe_2O_3 $\times \frac{1\ \text{mol } Fe_2O_3}{159.6\ \text{g } Fe_2O_3}$
$= \underline{0.531}$ mol

Step 3. Find the number of moles of Fe expected. Multiply by the mole ratio.

0.531 *mol Fe_2O_3* $\times \frac{\boxed{2}\ \text{mol Fe}}{1\ \text{mol } Fe_2O_3}$
$= \underline{1.062}$ mol Fe

Step 4. Find the mass of iron that should be produced. Multiply by the mole/mass conversion factor.

1.062 *mol Fe* $\times \frac{\boxed{55.8}\ \text{g Fe}}{1\ \text{mol Fe}} = 59.26$ g Fe

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Extra Practice

How many molecules of oxygen are produced by the decomposition of 1225 grams of potassium chlorate ($KClO_3$)?

$$2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$$

$$1225\ g\ KClO_3 \times \frac{1\ mol\ KClO_3}{122.5\ g\ KClO_3} \times \frac{3\ mol\ O_2}{2\ mol\ KClO_3} \times \frac{6.02 \times 10^{23}\ molecules\ O_2}{1\ mol\ O_2}$$
$$= 15 \times 6.02 \times 10^{23}\ molecules\ O_2 = 9.03 \times 10^{24}\ molecules\ O_2$$

The equation for the combustion of carbon monoxide is

$$2CO(g) + O_2(g) \rightarrow 2CO_2(g)$$

How many liters of oxygen are needed to burn 10 liters of carbon monoxide?

$$10\ L\ CO \times \frac{1\ mol\ CO}{22.4\ L\ CO} \times \frac{1\ mol\ O_2}{2\ mol\ CO} \times \frac{22.4\ L\ O_2}{1\ mol\ O_2} = 5\ L\ O_2$$

Apply the Big idea

1a. How many moles of chlorine gas (Cl_2) would react with 5 moles of sodium (Na) according to the following chemical equation? (Balance the equation first.)

$$2Na + Cl_2 \rightarrow 2NaCl$$

ratio of Na to Cl_2 is 2:1 so 5 mol Na : 2.5 mol Cl_2

1b. What mass of Na must be used to produce 29.2 g of NaCl?

1. $29.2\ g\ NaCl \times \frac{1\ mol\ NaCl}{58.5\ g\ NaCl} = 0.5\ mol\ NaCl$

2. According to the equation, the mole ratio is 2 mol Na : 2 mol NaCl, so 0.5 mol Na : 0.5 mol NaCl

3. $0.5\ mol\ Na \times \frac{23\ g\ Na}{1\ mol\ Na} = 11.5\ g\ Na$

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12 Self-Check Activity

For Questions 1–8, complete each statement by writing the correct word or words. If you need help, you can go online.

12.1 The Arithmetic of Equations

1. Chemists use balanced chemical equations as a basis to calculate how much ***reactant*** is needed or how much ***product*** will be formed in a reaction.

2. A balanced chemical equation can be interpreted in terms of different quantities, including numbers of atoms, molecules, or ***moles***; mass; and ***volume***.

12.2 Chemical Calculations

3. 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.

4. In a typical stoichiometric problem, the given quantity is first converted to ***moles***.

5. Then, the ***mole ratio*** from the balanced equation is used to calculate the number of moles of the wanted substance.

6. Finally, the moles are converted to any other unit of measurement related to the ***unit mole***, as the problem requires.

12.3 Limiting Reagent and Percent Yield

7. In a chemical reaction, an insufficient quantity of any of the ***reactants*** will limit the amount of product that forms.

8. The percent yield is a measure of the ***efficiency*** of a reaction carried out in the laboratory.

EXTENSION **Fill in the missing terms in the equations below.**

$$\text{Percent yield} = \frac{\textit{actual yield}}{\textit{theoretical yield}} \times \textit{100\%}$$

If You Have Trouble With...								
Question	1	2	3	4	5	6	7	8
See Page	386	386	390	394	394	394	400	405

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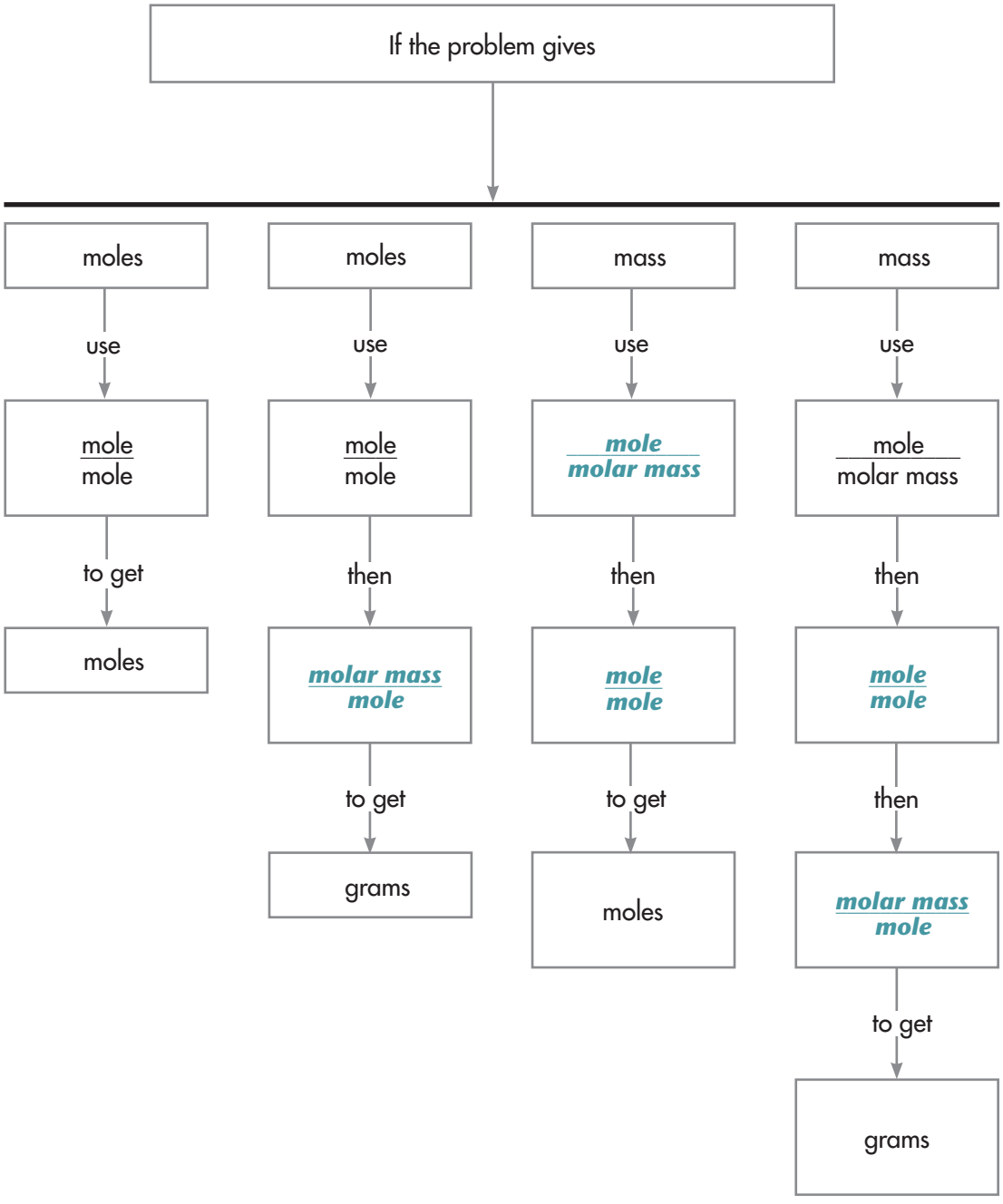
Review Conversion Factors

Use what you learned about stoichiometry and conversion factors to fill in the concept map.

Mole and mass stoichiometry must have a balanced equation.



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Review Vocabulary

Answer the questions by writing the correct vocabulary term in the blanks. Then arrange the circled letters to find the hidden term.

Clues	Vocabulary Terms
ideal amount of product	(t)h e o r e t i (c)a l y (i)e l d
involved in all stoichiometric calculations	(m)o l e r a t i (o)
quantitative relationship between reactants and products in a balanced chemical reaction	s (t)(o) i c h (i)(o)m (e) t (r) y
the amount of product that is measured	(a)(c) t (u)a (l) y i e (l) d
determines the amount of product formed	l (i)m i (t) i n g r e a g e (n) t
a measure of the efficiency of a chemical reaction	p e r (c)e n t y (i)e l d
leftover reactants	e x (c)e (s)(s) r e (a)g e n t

Hidden Term: s t o i c h i o m e t r i c c a l c u l a t i o n s

EXTENSION **Write a definition for the hidden term.**

The calculation of quantities in a chemical reaction using a balanced chemical equation.