Section 11.4

Empirical and Molecular Formulas

Objectives

- **Explain** what is meant by the percent composition of a compound.
- **Determine** the empirical and molecular formulas for a compound from mass percent and actual mass data.

Vocabulary

percent composition
empirical formula
molecular formula

Chemists, such as those shown in **Figure 11-9**, are often involved in developing new compounds for industrial, pharmaceutical, and home uses. After a synthetic chemist (one who makes new compounds) has produced a new compound, an analytical chemist analyzes the compound to provide experimental proof of its composition and its chemical formula. You can learn more about the work of chemists by reading **Chemistry and Technology** at the end of this chapter.

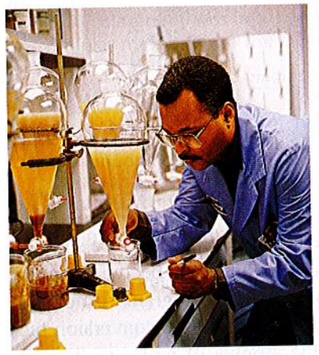

Figure 11-9
New compounds are first made on a small scale by a synthetic chemist like the one on the left. Then, an analytical chemist, like the one on the right, analyzes the compound to verify its structure and percent composition.

Percent Composition

It's the analytical chemist's job to identify the elements a compound contains and determine their percent by mass. Gravimetric and volumetric analyses are experimental procedures based on the measurement of mass for solids and liquids, respectively. For example, a 100-g sample of a new compound contains 55 g of element X and 45 g of element Y. The percent by mass of any element in a compound can be found by dividing the mass of the element by the mass of the compound and multiplying by 100.

$$\frac{\text{mass of element}}{\text{mass of compound}} \times 100 = \text{percent by mass}$$

$$\frac{55 \text{ g element X}}{100 \text{ g compound}} \times 100 = 55\% \text{ element X}$$

$$\frac{45 \text{ g element Y}}{100 \text{ g compound}} \times 100 = 45\% \text{ element Y}$$

Because percent means parts per 100, the percents by mass of all the elements of a compound must always add up to 100. The percent composition of the compound is 55% X and 45% Y. The percent by mass of each element in a compound is called the **percent composition** of a compound.

Percent composition from the chemical formula If you already know the chemical formula for a compound such as water (H_2O), can you calculate its percent composition? The answer is yes. You can use the chemical formula to calculate the molar mass of water (18.02 g/mol) and assume you have an 18.02-g sample. Because the percent composition of a compound is always the same, no matter the size of the sample, you can assume that the sample size is one mole. To find the mass of each element in a mole of water, multiply the molar mass of the element by its subscript in the chemical formula. Because one mole of water contains two moles of hydrogen atoms, the mass of hydrogen in a mole of water is (2 mol)(1.01 g/mol) = 2.02 g. To find the percent by mass of hydrogen in water, divide the mass of hydrogen by the molar mass of water (18.02 g/mol) and multiply by 100.

$$\frac{2.02 \text{ g H}}{18.02 \text{ g } H_2O} \times 100 = 11.2\% \text{ H}$$

One mole of water contains one mole of oxygen. Thus, the mass of oxygen in one mole of water is 16.00 g. The percent by mass of oxygen is

$$\frac{16.00 \text{ g O}}{18.02 \text{ g } H_2O} \times 100 = 88.80\% \text{ O}$$

The percent composition of water is 11.2% hydrogen and 88.80% oxygen.

The general equation for calculating the percent by mass of any element in a compound is

$$\frac{\text{mass of element in 1 mol compound}}{\text{molar mass of compound}} \times 100 = \% \text{ by mass element}$$

The **miniLAB** provides an opportunity to practice calculating percents.

Careers Using Chemistry

Analytical Chemist

Would you like to work in a laboratory, solving problems and making precise measurements with state-of-the-art equipment? If so, consider a career as an analytical chemist.

Analytical chemists identify and measure the elements and compounds found in substances. They might determine the composition of the raw materials used in manufacturing or help physicians diagnose diseases. They might identify air or water pollutants or determine which nutrients are in certain foods. Analytical chemists work in fields as varied as archeology, crime, and space science.

miniLAB

Percent Composition and Gum

Interpreting Data Water soluble sweeteners and flavorings are added to chewing gum. Are these chemicals added as an outside coating or are they mixed throughout the gum?

Materials balance, weighing paper, 250-mL beakers (2), pieces of chewing gum (2), stirring rod, paper towels, window screen (10 cm × 10 cm), scissors, clock or timer

Procedure

CAUTION: *Do not taste or eat any items used in the lab.*

1. Unwrap two pieces of chewing gum. Measure the mass of each separately on a piece of weighing paper. Label the weighing papers with the masses to avoid mixing up your data. Record the masses.
2. Add 150 mL of cold tap water to a 250-mL beaker. Place one piece of chewing gum in the water and stir for two minutes.
3. Remove the gum from the water and pat dry using paper towels. Measure and record the mass of the dried gum.
4. Use scissors to cut the second piece of gum into small pieces, each about the width of a pea. Repeat step 2 using fresh water. Use the stirring rod to keep the pieces of gum from clumping together.
5. Use the window screen to strain the water from the gum. Pat the gum dry using paper towels. Measure and record the mass of the dried gum.
6. Discard the gum in a waste container.

Analysis

1. For the uncut piece of gum, calculate the mass of sweeteners and flavorings that dissolved in the water. The mass of sweeteners and flavorings is the difference between the original mass of the gum and the mass of the dried gum.
2. For the gum that was in small pieces, calculate the mass of dissolved sweeteners and flavorings.
3. For both pieces of gum, calculate the percent of the original mass that was soluble sweeteners and flavorings. For help, refer to *Percents* in the **Math Handbook** on page 909 of this text.
4. What can you infer from the two percentages? Is the gum sugar-coated or are the sweeteners and flavorings mixed throughout?

Try at Home LAB

See page 957 in Appendix E for **Calculating Carbon Percentages**

Antacids often contain carbonates, for example, sodium hydrogen carbonate, calcium carbonate, and magnesium carbonate. A carbonate-containing antacid neutralizes excess stomach acid by reacting with acid to produce carbon dioxide.

EXAMPLE PROBLEM 11-10

Calculating Percent Composition

Sodium hydrogen carbonate, also called baking soda, is an active ingredient in some antacids used for the relief of indigestion. Determine the percent composition of sodium hydrogen carbonate ($NaHCO_3$).

1. Analyze the Problem

You are given only the chemical formula. Assume you have one mole of $NaHCO_3$. Calculate the molar mass and the mass of each element in one mole to determine the percent by mass of each element in the compound. The sum of all percents should be 100%.

Known

formula = $NaHCO_3$

Unknown

percent Na = ? % Na
percent H = ? % H
percent C = ? % C
percent O = ? % O

2. Solve for the Unknown

Determine the mass of each element present and the molar mass of $NaHCO_3$.

$$1 \text{ mol Na} \times \frac{22.99 \text{ g Na}}{1 \text{ mol Na}} = 22.99 \text{ g Na}$$

$$1 \text{ mol H} \times \frac{1.008 \text{ g H}}{1 \text{ mol H}} = 1.008 \text{ g H}$$

$$1 \text{ mol C} \times \frac{12.01 \text{ g C}}{1 \text{ mol C}} = 12.01 \text{ g C}$$

$$3 \text{ mol O} \times \frac{16.00 \text{ g O}}{1 \text{ mol O}} = 48.00 \text{ g O}$$

molar mass $NaHCO_3$ = 84.008 g/mol $NaHCO_3$ = 84.01g/mol $NaHCO_3$

Determine the percent by mass of each element by dividing the mass of the element by the molar mass of the compound and multiplying by 100.

$$\% \text{ mass element} = \frac{\text{mass of element in 1 mol compound}}{\text{molar mass of compound}} \times 100$$

$$\text{percent Na} = \frac{22.99 \text{ g Na}}{84.01 \text{ g } NaHCO_3} \times 100 = 27.37\% \text{ Na}$$

$$\text{percent H} = \frac{1.008 \text{ g H}}{84.01 \text{ g } NaHCO_3} \times 100 = 1.200\% \text{ H}$$

$$\text{percent C} = \frac{12.01 \text{ g C}}{84.01 \text{ g } NaHCO_3} \times 100 = 14.30\% \text{ C}$$

$$\text{percent O} = \frac{48.00 \text{ g O}}{84.01 \text{ g } NaHCO_3} \times 100 = 57.14\% \text{ O}$$

The percent composition of $NaHCO_3$ is 27.37% Na, 1.200% H, 14.30% C, and 57.14% O.

3. Evaluate the Answer

All masses and molar masses contain four significant figures. Therefore, the percents are correctly stated to four signigicant figures. The sum of the mass percents is 100.00% as required.

PRACTICE PROBLEMS

42. Determine the percent by mass of each element in calcium chloride.

43. Calculate the percent composition of sodium sulfate.

44. Which has the larger percent by mass of sulfur, H_2SO_3 or $H_2S_2O_8$?

45. What is the percent composition of phosphoric acid (H_3PO_4)?

Practice!

For more practice calculating percent composition, go to **Supplemental Practice Problems** in Appendix A.