6.1 Percentage Composition

Section Preview/ Specific Expectations

In this section, you will

- **explain** the law of definite proportions
- **calculate** the percentage composition of a compound using the formula and the relative atomic masses of the elements
- **communicate** your understanding of the following terms: *law of definite proportions, mass percent, percentage composition*

mind STRETCH

If a bicycle factory has 1000 wheels and 400 frames, how many bicycles can be made? How many wheels does each bicycle have? Is the number of wheels per bicycle affected by any extra wheels that the factory may have in stock? Relate these questions to the law of definite proportions.

When you calculate and use the molar mass of a compound, such as water, you are making an important assumption. You are assuming that every sample of water contains hydrogen and oxygen in the ratio of two hydrogen atoms to one oxygen atom. Thus you are also assuming that the masses of hydrogen and oxygen in pure water always exist in a ratio of 2 g:16 g. This may seem obvious to you, because you know that the molecular formula of water is always H_2O, regardless of whether it comes from any of the sources shown in Figure 6.1. When scientists first discovered that compounds contained elements in fixed mass proportions, they did not have the periodic table. In fact, the discovery of fixed mass proportions was an important step toward the development of atomic theory.

The Law of Definite Proportions

In the late eighteenth century, Joseph Louis Proust, a French chemist, analyzed many samples of copper(II) carbonate, $CuCO_3$. He found that the samples contained the same proportion of copper, carbon, and oxygen, regardless of the source of the copper(II) carbonate. This discovery led Proust to propose the **law of definite proportions**: *the elements in a chemical compound are always present in the same proportions by mass.*

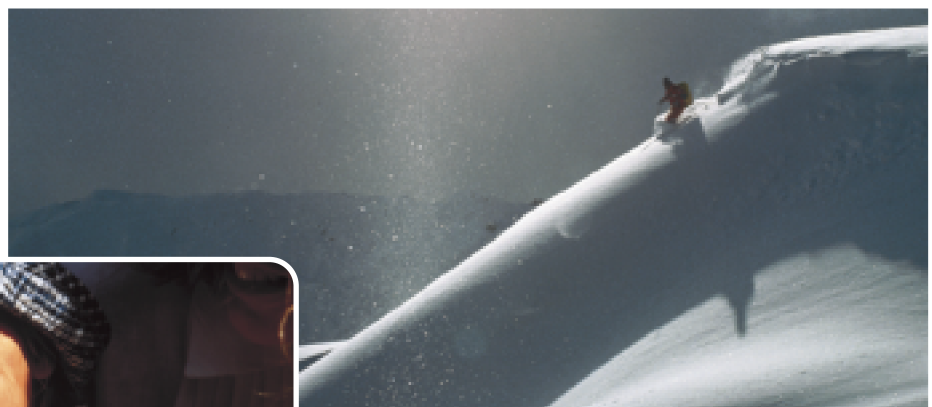

Figure 6.1 **Suppose that you distil pure water from each of these sources to purify it. Are the distilled water samples the same or different? What is the molar mass of the distilled water from each source?**

The mass of an element in a compound, expressed as a percent of the total mass of the compound, is the element's **mass percent.** The mass percent of hydrogen in water from any of the sources shown in Figure 6.1 is 11.2%. Similarly, the mass percent of oxygen in water is always 88.8%. Whether the water sample is distilled from a lake, an ice floe, or a drinking fountain, the hydrogen and oxygen in pure water are always present in these proportions.

Different Compounds from the Same Elements

The law of definite proportions does not imply that elements in compounds are always present in the same relative amounts. It is possible to have different compounds made up of different amounts of the same elements. For example, water, H_2O, and hydrogen peroxide, H_2O_2, are both made up of hydrogen and oxygen. Yet, as you can see in Figure 6.2, each compound has unique properties. Each compound has a different mass percent of oxygen and hydrogen. You may recognize hydrogen peroxide as a household chemical. It is an oxidizing agent that is used to bleach hair and treat minor cuts. It is also sold as an alternative to chlorine bleach.

Figure 6.3 shows a molecule of benzene, C_6H_6. Benzene contains 7.76% hydrogen and 92.2% carbon by mass. Octane, C_8H_{18}, is a major component of the fuel used for automobiles. It contains 84.1% carbon and 15.9% hydrogen.

CHEM FACT

Chemical formulas such as CO and CO_2 reflect an important law called the *law of multiple proportions*. This law applies when two elements (such as carbon and oxygen) combine to form two or more different compounds. In these cases, the masses of the element (such as O_2 in CO and CO_2) that combine with a fixed amount of the second element are in ratios of small whole numbers. For example, two moles of carbon can combine with one mole of oxygen to form carbon monoxide, or with two moles of oxygen to form carbon dioxide. The ratio of the two different amounts of oxygen that combine with the fixed amount of carbon is 1:2.

Figure 6.2 **Water contains hydrogen and oxygen, but it does not decompose in the presence of manganese dioxide. Hydrogen peroxide is also composed of hydrogen and oxygen. It is fairly unstable and decomposes vigorously in the presence of manganese dioxide.**

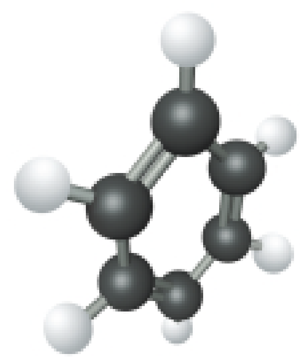

Figure 6.3 **Benzene C_6H_6, is made up of six carbon atoms and six hydrogen atoms. Why does benzene not contain 50% of each element by mass?**

Similarly, carbon monoxide, CO, and carbon dioxide, CO_2, are both made up of carbon and oxygen. Yet each compound is unique, with its own physical and chemical properties. Carbon dioxide is a product of cellular respiration and the complete combustion of fossil fuels. Carbon monoxide is a deadly gas formed when insufficient oxygen is present during the combustion of carbon-containing compounds. Carbon monoxide always contains 42.88% carbon by mass. Carbon dioxide always contains 27.29% carbon by mass.

Electronic Learning Partner

A video clip explaining the law of definite proportions can be found on the Chemistry 11 Electronic Learning Partner.

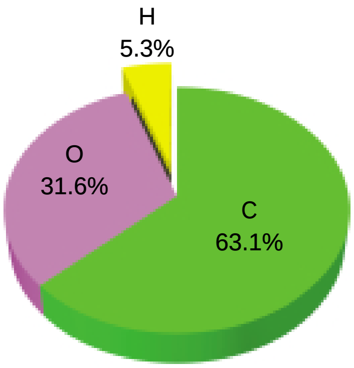

Figure 6.4 **This pie graph shows the percentage composition of vanillin.**

Percentage Composition

Carbon dioxide and carbon monoxide contain the same elements but have different proportions of these elements. In other words, they are composed differently. Chemists express the composition of compounds in various ways. One way is to describe how many moles of each element make up a mole of a compound. For example, one mole of carbon dioxide contains one mole of carbon and two moles of oxygen. Another way is to describe the percent mass of each element in a compound.

The **percentage composition** of a compound refers to the relative mass of each element in the compound. In other words, percentage composition is a statement of the values for mass percent of every element in the compound. For example, the compound vanillin, $C_8H_8O_3$, has a percentage composition of 63.1% carbon, 5.3% hydrogen, and 31.6% oxygen, as shown in Figure 6.4.

A compound's percentage composition is an important piece of information. For example, percentage composition can be determined experimentally, and then used to help identify the compound.

Examine the following Sample Problem to learn how to calculate the percentage composition of a compound from the mass of the compound and the mass of the elements that make up the compound. Then do the Practice Problems to try expressing the composition of substances as mass percents.

Sample Problem

Percentage Composition from Mass Data

Problem

A compound with a mass of 48.72 g is found to contain 32.69 g of zinc and 16.03 g of sulfur. What is the percentage composition of the compound?

What Is Required?

You need to find the mass percents of zinc and sulfur in the compound.

What Is Given?

You know the mass of the compound. You also know the mass of each element in the compound.

Mass of compound = 48.72 g

Mass of Zn = 32.69 g

Mass of S = 16.03 g

Plan Your Strategy

To find the percentage composition of the compound, find the mass percent of each element. To do this, divide the mass of each element by the mass of the compound and multiply by 100%.

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Does the unknown compound in the Sample Problem contain any elements other than zinc and sulfur? How do you know? Use the periodic table to predict the formula of the compound. Does the percentage composition support your prediction?

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Act on Your Strategy

$$\text{Mass percent of Zn} = \frac{\text{Mass of Zn}}{\text{Mass of compound}} \times 100\%$$
$$= \frac{32.69\ \cancel{g}}{48.72\ \cancel{g}} \times 100\%$$
$$= 67.10\%$$

$$\text{Mass percent of S} = \frac{\text{Mass of S}}{\text{Mass of compound}} \times 100\%$$
$$= \frac{16.03\ \cancel{g}}{48.72\ \cancel{g}} \times 100\%$$
$$= 32.90\%$$

The percentage composition of the compound is 67.10% zinc and 32.90% sulfur.

Check Your Solution

The mass of zinc is about 32 g per 50 g of the compound. This is roughly 65%, which is close to the calculated value.

Practice Problems

1. A sample of a compound is analyzed and found to contain 0.90 g of calcium and 1.60 g of chlorine. The sample has a mass of 2.50 g. Find the percentage composition of the compound.
2. Find the percentage composition of a pure substance that contains 7.22 g nickel, 2.53 g phosphorus, and 5.25 g oxygen only.
3. A sample of a compound is analyzed and found to contain carbon, hydrogen, and oxygen. The mass of the sample is 650 mg, and the sample contains 257 mg of carbon and 50.4 mg of hydrogen. What is the percentage composition of the compound?
4. A scientist analyzes a 50.0 g sample and finds that it contains 13.3 g of potassium, 17.7 g of chromium, and another element. Later the scientist learns that the sample is potassium dichromate, $K_2Cr_2O_7$. Potassium dichromate is a bright orange compound that is used in the production of safety matches. What is the percentage composition of potassium dichromate?

It is important to understand clearly the difference between percent by mass and percent by number. In the Thought Lab that follows, you will investigate the distinction between these two ways of describing composition.

mind STRETCH

Iron is commonly found as two oxides, with the general formula Fe_xO_y. One oxide is 77.7% iron. The other oxide is 69.9% iron. Use the periodic table to predict the formula of each oxide. Match the given values for the mass percent of iron to each compound. How can you use the molar mass of iron and the molar masses of the two iron oxides to check the given values for mass percent?

Web LINK

www.school.mcgrawhill.ca/resources/
Vitamin C is the common name for ascorbic acid, $C_6H_8O_6$. To learn about this vitamin, go to the web site above. Go to **Science Resources**, then to **Chemistry 11** to find out where to go next. Do you think there is a difference between natural and synthetic vitamin C? Both are ascorbic acid. Natural vitamin C comes from foods we eat, especially citrus fruits. Synthetic vitamin C is made in a laboratory. Why do the prices of natural and synthetic products often differ? Make a list to show the pros and cons of vitamins from natural and synthetic sources.

ThoughtLab: Percent by Mass and Percent by Number

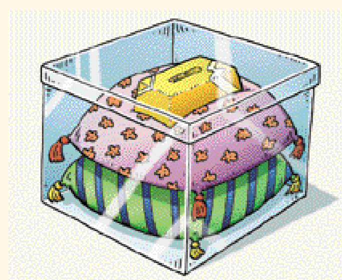
A company manufactures gift boxes that contain two pillows and one gold brick. The gold brick has a mass of 20 kg. Each pillow has a mass of 1.0 kg.

Procedure

1. You are a quality control specialist at the gift box factory. You need to know the following information:
   (a) What is the percent of pillows, in terms of the number of items, in the gift box?
   (b) What is the percent of pillows, by mass, in the gift box?
   (c) What is the percent of gold, by mass, in the gift box?
2. You have a truckload of gift boxes to inspect. You now need to know this information:
   (a) What is the percent of pillows, in terms of the number of items, in the truckload of gift boxes?
   (b) What is the percent of pillows, by mass, in the truckload of gift boxes?
   (c) What is the percent of gold, by mass, in the truckload of gift boxes?

Analysis

1. The truckload of gift boxes, each containing 2 light pillows and 1 heavy gold brick, can be used to represent a pure substance, water, containing 2 mol of a "light" element, such as hydrogen, and 1 mol of a "heavy" element, such as oxygen.
   (a) What is the percent of hydrogen, in terms of the number of atoms, in 1 mol of water?
   (b) What is the mass percent of hydrogen in 1 mol of water?
   (c) What is the mass percent of oxygen in 1 mol of water?
2. Would the mass percent of hydrogen or oxygen in question 1 change if you had 25 mol of water? Explain.
3. Why do you think chemists use mass percent rather than percent by number of atoms?



Calculating Percentage Composition from a Chemical Formula

In the previous Practice Problems, you used mass data to calculate percentage composition. This skill is useful for interpreting experimental data when the chemical formula is unknown. Often, however, the percentage composition is calculated from a known chemical formula. This is useful when you are interested in extracting a certain element from a compound. For example, many metals, such as iron and mercury, exist in mineral form. Mercury is most often found in nature as mercury(II) sulfide, HgS. Knowing the percentage composition of HgS helps a metallurgist predict the mass of mercury that can be extracted from a sample of HgS.

When determining the percentage composition by mass of a homogeneous sample, the size of the sample does not matter. According to the law of definite proportions, there is a fixed proportion of each element in the compound, no matter how much of the compound you have. This means that you can choose a convenient sample size when calculating percentage composition from a formula.

If you assume that you have one mole of a compound, you can use the molar mass of the compound, with its chemical formula, to calculate its percentage composition. For example, suppose that you want to find the percentage composition of HgS. You can assume that you have one mole of HgS and find the mass percents of mercury and sulfur in one mole of the compound.

$$\text{Mass percent of Hg in HgS} = \frac{\text{Mass of Hg in 1 mol of HgS}}{\text{Mass of 1 mol of HgS}} \times 100\%$$
$$= \frac{200.6\,\cancel{g}}{228.68\,\cancel{g}} \times 100\%$$
$$= 87.7\%$$

Mercury(II) sulfide is 87.7% mercury by mass. Since there are only two elements in HgS, you can subtract the mass percent of mercury from 100 percent to find the mass percent of sulfur.

$$\text{Mass percent of S in HgS} = 100\% - 87.7\% = 12.3\%$$

Therefore, the percentage composition of mercury(II) sulfide is 87.7% mercury and 12.3% sulfur.

Sometimes there are more than two elements in a compound, or more than one atom of each element. This makes determining percentage composition more complex than in the example above. Work through the Sample Problem below to learn how to calculate the percentage composition of a compound from its molecular formula.

History LINK

Before AD 1500, many alchemists thought that matter was composed of two "elements": mercury and sulfur. To impress their patrons, they performed an experiment with mercury sulfide, also called cinnabar, HgS. They heated the red cinnabar, which drove off the sulfur and left the shiny liquid mercury. On further heating, the mercury reacted to form a red compound again. Alchemists wrongly thought that the mercury had been converted back to cinnabar. What Hg(II) compound do you think was really formed when the mercury was heated in the air? What is the mass percent of mercury in this new compound? What is the mass percent of mercury in cinnabar?

Sample Problem

Finding Percentage Composition from a Chemical Formula

Problem

Cinnamaldehyde, C_9H_8O, is responsible for the characteristic odour of cinnamon. Determine the percentage composition of cinnamaldehyde by calculating the mass percents of carbon, hydrogen, and oxygen.

What Is Required?

You need to find the mass percents of carbon, hydrogen, and oxygen in cinnamaldehyde.

What Is Given?

The molecular formula of cinnamaldehyde is C_9H_8O.
Molar mass of C = 12.01 g/mol
Molar mass of H = 1.01 g/mol
Molar mass of O = 16.00 g/mol

Plan Your Strategy

From the molar masses of carbon, hydrogen, and oxygen, calculate the molar mass of cinnamaldehyde.

Then find the mass percent of each element. To do this, divide the mass of each element in 1 mol of cinnamaldehyde by the molar mass of cinnamaldehyde, and multiply by 100%. Remember that

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there are 9 mol carbon, 8 mol hydrogen, and 1 mol oxygen in each mole of cinnamaldehyde.

Act on Your Strategy

$$M_{C_9H_8O}$$
$$= (9 \times M_c) + (8 \times M_H) + (M_O)$$
$$= (9 \times 12.01\,g) + (8 \times 1.01\,g) + 16.00\,g$$
$$= 132\,g$$

$$\text{Mass percent of C} = \frac{9 \times M_C}{M_{C_9H_8O}} \times 100\%$$
$$= \frac{9 \times 12.01\,\cancel{g/mol}}{132\,\cancel{g/mol}} \times 100\%$$
$$= 81.9\%$$

$$\text{Mass percent of H} = \frac{8 \times M_H}{M_{C_9H_8O}} \times 100\%$$
$$= \frac{8 \times 1.01\,\cancel{g/mol}}{132\,\cancel{g/mol}} \times 100\%$$
$$= 6.12\%$$

$$\text{Mass percent of O} = \frac{1 \times M_O}{M_{C_9H_8O}} \times 100\%$$
$$= \frac{1 \times 16.00\,\cancel{g/mol}}{132\,\cancel{g/mol}} \times 100\%$$
$$= 12.1\%$$

The percentage composition of cinnamaldehyde is 81.9% carbon, 6.12% hydrogen, and 12.1% oxygen.

Check Your Solution

The mass percents add up to 100%.

Practice Problems

5. Calculate the mass percent of nitrogen in each compound.

(a) N_2O **(c)** NH_4NO_3

(b) $Sr(NO_3)_2$ **(d)** HNO_3

6. Sulfuric acid, H_2SO_4, is an important acid in laboratories and industries. Determine the percentage composition of sulfuric acid.

7. Potassium nitrate, KNO_3, is used to make fireworks. What is the mass percent of oxygen in potassium nitrate?

8. A mining company wishes to extract manganese metal from pyrolusite ore, MnO_2.

(a) What is the percentage composition of pyrolusite ore?

(b) Use your answer from part (a) to calculate the mass of pure manganese that can be extracted from 250 kg of pyrolusite ore.

CHECKPOINT

When it is heated, solid potassium nitrate reacts to form solid potassium oxide, gaseous nitrogen, and gaseous oxygen. Write a balanced chemical equation for this reaction. What type of reaction is it?

Section Wrap-up

In this section, you learned that you can calculate percentage composition using a chemical formula. Often, however, chemists do not know the chemical formula of the compound they are analyzing, as in Figure 6.5. Through experiment, they can determine the masses of the elements that make up the compound. Then they can use the masses to calculate the percentage composition. (You will learn about one example of this kind of experimental technique in section 6.4.) From the percentage composition, chemists can work backward to determine the formula of the unknown compound. In section 6.2, you will learn about the first step in using the percentage composition of a compound to determine its chemical formula.

mind STRETCH

You know that both elements and compounds are pure substances. Write a statement, using the term "percentage composition," to distinguish between elements and compounds.

Figure 6.5 **One of these compounds is vanillin, $C_8H_8O_3$, and one is glucose, $C_6H_{12}O_6$. How could a chemist use percentage composition to find out which is which?**

Section Review

1. C Acetylene, C_2H_2, is the fuel in a welder's torch. It contains an equal number of carbon and hydrogen atoms. Explain why acetylene is not 50% carbon by mass.
2. K/U When determining percentage composition, why is it acceptable to work with either molar quantities, expressed in grams, or average molecular (or atomic or formula unit) quantities, expressed in atomic mass units?
3. I Indigo, $C_{16}H_{10}N_2O_2$, is the common name of the dye that gives blue jeans their characteristic colour. Calculate the mass of oxygen in 25.0 g of indigo.

Unit Investigation Prep

Before you design your experiment to find the composition of a mixture, think about using mass percents in analysis. If you wanted to determine the percent by mass of each component in a mixture, what would you need to do first? Compare this situation to finding percentage composition of a pure substance.

4. I Potassium perchlorate, , is used extensively in explosives. Calculate the mass of oxygen in a 24.5 g sample of potassium perchlorate.

5. I 18.4 g of silver oxide, , is decomposed into silver and oxygen by heating. What mass of silver will be produced?

6. MC The label on a box of baking soda (sodium hydrogen carbonate,) claims that there are 137 mg of sodium per 0.500 g of baking soda. Comment on the validity of this claim.

7. I A typical soap molecule consists of a polyatomic anion associated with a cation. The polyatomic anion contains hydrogen, carbon, and oxygen. One particular soap molecule has 18 carbon atoms. It contains 70.5% carbon, 11.5% hydrogen, and 10.4% oxygen by mass. It also contains one alkali metal cation. Identify the cation.

8. I Examine the photographs below. When concentrated sulfuric acid is added to sucrose, , a column of pure carbon is formed, as well as some water vapour and other gases. How would you find the mass percent of carbon in sucrose using this reaction? You may assume that all the carbon in the sucrose is converted to carbon. Design an experiment to determine the mass percent of carbon in sucrose, based on this reaction. Do not try to perform this experiment. What difficulties might you encounter?