10.3 Percent Composition and Chemical Formulas

Connecting to Your World
Is your shirt made of 100 percent cotton or wool, or is the fabric a combination of two or more fibers? A tag sewed into the seam of the shirt usually tells you what fibers were used to make the cloth and the percent of each. It helps to know the percents of the components in the shirt because they affect how warm it is, whether it will need to be ironed, and how it should be cleaned. In this section you will learn how the percents of the elements in a compound are important in chemistry.

The Percent Composition of a Compound
If you have had experience with lawn care, you know that the relative amount, or the percent, of each nutrient in fertilizer is important. In spring, you may use a fertilizer that has a relatively high percent of nitrogen to “green” the grass. In fall, you may want to use a fertilizer with a higher percent of potassium to strengthen the root system. Knowing the relative amounts of the components of a mixture or compound is often useful.

The relative amounts of the elements in a compound are expressed as the percent composition or the percent by mass of each element in the compound. The percent composition of a compound consists of a percent value for each different element in the compound. As you can see in Figure 10.13, the percent composition of K₂CrO₄ is K = 40.3%, Cr = 26.8%, and O = 32.9%. These percents must total 100% (40.3% + 26.8% + 32.9% = 100%).

The percent by mass of an element in a compound is the number of grams of the element divided by the mass in grams of the compound, multiplied by 100%.

\[
\text{% mass of element} = \frac{\text{mass of element}}{\text{mass of compound}} \times 100\%
\]

Percent Composition from Mass Data Imagine you are a chemist who has just finished the synthesis of a new compound. You have purified your product and stored the crystalline solid in a vial. Now you must verify the composition of your new compound and determine its molecular formula. You use analytical procedures to determine the relative masses of each element in the compound and calculate the percent composition.

Figure 10.13 Potassium chromate (K₂CrO₄) is composed of 40.3% potassium, 26.8% chromium, and 32.9% oxygen. How does this percent composition differ from the percent composition of potassium dichromate (K₂Cr₂O₇), a compound composed of the same three elements?

Guide for Reading

Key Concepts
- How do you calculate the percent by mass of an element in a compound?
- What does the empirical formula of a compound show?
- How does the molecular formula of a compound compare with the empirical formula?

Vocabulary
percent composition
empirical formula

Reading Strategy
Comparing and Contrasting
When you compare and contrast things, you examine how they are alike and different. As you read, list the similarities and differences between empirical and molecular formulas.

The Percent Composition of a Compound

Objectives
10.3.1 Describe how to calculate the percent by mass of an element in a compound.
10.3.2 Interpret an empirical formula
10.3.3 Distinguish between empirical and molecular formulas.

Guide for Reading

Build Vocabulary

Paraphrase Have students read the definition of percent composition on this page. Then, have them define the term according to the definition in the dictionary. Their definitions should indicate that percent composition refers to the relative size of parts that make up 100 percent of something.

Reading Strategy

Relate Text and Visuals As they read the chapter, students should examine each visual as it is referenced in the text. Have them read each caption and answer any question.

INSTRUCT

Connecting to Your World

Ask, What should be the total of the percents listed on the label? (100%) If the shirt were 25% nylon, what percent would be cotton? (75%)

The Percent Composition of a Compound

Use Visuals

Figure 10.13 Have students study the figure and read the text on percent composition. Point out that the three numbers in each circle graph add up to a total of 100%. Ask, Which compound is a better source of potassium? (K₂CrO₄)

Answers to...

Figure 10.13 The percent composition of K₂Cr₂O₇ is 26.5% K, 35.4% Cr, and 38.1% O.

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Sample Problem 10.9

Answers

32. Mass of compound = 9.03 g + 3.48 g = 12.51 g; 9.03 g Mg/12.51 g compound × 100% = 72.2% Mg; 3.48 g N/12.51 g compound × 100% = 27.8% N

33. mass of O = 14.2 g − 13.2 g = 1.0 g; 1.0 g O/14.2 g × 100% = 7.0% O; 13.2 g Hg/14.2 g × 100% = 93.0% Hg

Practice Problems Plus

1. What is the percent composition of the compound formed when 2.70 g of aluminum combine with oxygen to form 5.10 g of aluminum oxide? (52.9% Al, 47.1% O)

2. Interactive Textbook with ChemASAP contains the following problem: Calculate the percent composition when 13.3 g Fe combine completely with 5.7 g O. (70% Fe, 30% O)

Math Handbook

For help with percents go to page R72.

Problem-Solving 10.33
Solve Problem 33 with the help of an interactive guided tutorial.

Math Handbook

For help with percents go to page R72.

Facts and Figures

Parts per Million and Parts per Billion

Percents are used to show relative parts of mixtures as well as the composition of a compound. But when an extremely small amount of a substance is present in a large amount of another substance, it might not be practical to use percents (parts per one hundred) to show the makeup of the mixture. Instead, concentrations of extremely dilute solutions are sometimes measured in units of parts per million (ppm) or parts per billion (ppb). For example, the composition of a mixture that consists of 1 gram of a substance per 10^6 grams of water (or 1 milligram of substance per liter of water) can be expressed as 1 ppm.

Figure 10.14
The percent composition of water is always the same regardless of the volume of the water sample. A sample of water is always 11.1% H and 88.9% O by mass.
Percent Composition from the Chemical Formula

You can also calculate the percent composition of a compound if you know only its chemical formula. The subscripts in the formula of the compound are used to calculate the mass of each element in one mole of that compound. The sum of these masses is the molar mass. Using the individual masses of the elements and the molar mass you can calculate the percent by mass of each element in one mole of the compound. Divide the mass of each element by the molar mass and multiply the result by 100%.

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

The percent composition of a compound is always the same, as Figure 10.14 on the preceding page indicates.

**SAMPLE PROBLEM 10.10**

Calculating the Percent Composition from a Formula

Propane (C\(_3\)H\(_8\)), the fuel commonly used in gas grills, is one of the lighter compounds obtained from petroleum. Calculate the percent composition of propane.

1. **Analyze** List the knowns and the unknowns.
   
   Knowns:
   
   - mass of C in 1 mol C\(_3\)H\(_8\) = 36.0 g
   - mass of H in 1 mol C\(_3\)H\(_8\) = 8.0 g
   - molar mass of C\(_3\)H\(_8\) = 44.0 g/mol
   
   Unknowns:
   
   - percent C
   - percent H

   Calculate the percent by mass of each element by dividing the mass of that element in one mole of the compound by the molar mass of the compound and multiplying by 100%.

2. **Calculate** Solve for the unknowns.

   \[
   \% \text{ C} = \frac{\text{mass of C}}{\text{mass of propane}} \times 100\% = \frac{36.0 \text{ g}}{44.0 \text{ g}} \times 100\% = 81.8\%
   \]

   \[
   \% \text{ H} = \frac{\text{mass of H}}{\text{mass of propane}} \times 100\% = \frac{8.0 \text{ g}}{44.0 \text{ g}} \times 100\% = 18\%
   \]

3. **Evaluate** Does the result make sense?

   The percents of the elements add up to 100% when the answers are expressed to two significant figures.

**Practice Problems**

34. Calculate the percent composition of these compounds.
   
   a. ethane (C\(_2\)H\(_6\))
   b. sodium bisulfate (NaHSO\(_4\))

35. Calculate the percent nitrogen in these common fertilizers.
   
   a. NH\(_3\)
   b. NH\(_4\)NO\(_3\)

**Answers**

34. a. 24.0 g C/30.0 g \times 100\% = 80.0\% C
   
   6.00 g H/30.0 g \times 100\% = 20.0\% H

   b. 23.0 g Na/120.1 g \times 100\% = 19.2\% Na
   
   1.0 g H/120.1 g \times 100\% = 0.83\% H

   32.1 g S/120.1 g \times 100\% = 26.7\% S
   
   64.0 g O/120.1 g \times 100\% = 53.3\% O

35. a. 14.0 g N/17.0 g \times 100\% = 82.4\% N
   
   b. 28.0 g N/80.0 g \times 100\% = 35.0\% N

**Practice Problems Plus**

1. Determine the percent composition of the following oxides:
   
   a. Fe\(_2\)O\(_3\) (69.9\% Fe, 30.1\% O)
   b. HgO (92.6\% Hg, 7.39\% O)
   c. Ag\(_2\)O (93.1\% Ag, 6.90\% O)
   d. Na\(_2\)O (74.2\% Na, 25.8\% O)

2. Calculate the grams of oxygen in 90.0 g of Cl\(_2\)O.
   
   (16.6 g)

**Differentiated Instruction**

**Gifted and Talented**

Have students research the formulas of the three different oxides of iron. Ask, **Which of the oxides contains a higher percent of iron?** (Of FeO (77.7\% Fe), Fe\(_2\)O\(_3\) (69.9\% Fe), and Fe\(_3\)O\(_4\) (72.3\% Fe), FeO has the highest percent of iron.)

**Answers to...**

Checkpoint: Divide the mass of the element in one mole of the compound by the molar mass and multiply by 100%.

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**Chemical Quantities**

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Percent Composition

Objective After completing this activity, students will be able to:
• determine the percent of water in a hydrate.

Skills Focus observing, calculating

Prep Time 20 minutes
Class Time 30 minutes

Safety Students should wear safety goggles and tie back loose hair. Caution students that while heating test tubes, they should not aim the opening of the tube toward anyone. Tell them to move the test tube in the flame and not to heat one spot excessively. CAUTION! Be sure that students allow the tubes to cool completely before they touch them. Hot glass looks exactly like cold glass!

Teaching Tips For best results, students should do a second heating and cooling of each sample to determine whether all of the water has been driven off.

Expected Outcome See data table at the bottom of the page.

Think About It

1–3. See data table.
4. The hydrated salt of sodium sulfate lost the greatest percent. The hydrated salt of calcium chloride lost the smallest percent.

For Enrichment

Have students design and conduct a similar experiment to determine the percent of oxygen in potassium chloride. Tell students that when potassium chloride is heated, potassium chloride and oxygen are produced, \(2\text{KClO}_3 \rightarrow 2\text{KCl} + 3\text{O}_2\). For classroom safety, no more than 5 g of potassium chloride should be used. Results should show that potassium chloride is approximately 39% oxygen.

Percent Composition as a Conversion Factor You can use percent composition to calculate the number of grams of any element in a specific mass of a compound. To do this, multiply the mass of the compound by a conversion factor based on the percent composition of the element in the compound. Suppose you want to know how much carbon and hydrogen are contained in 82.0 g of propane. In Sample Problem 10.10, you found that propane is 81.8% carbon and 18% hydrogen. That means that in a 100-g sample of propane, you would have 81.8 g of carbon and 18 g of hydrogen. You can use the ratio \(18 \text{ g H}/100 \text{ g C}_3\text{H}_8\) to calculate the mass of carbon contained in 82.0 g of propane (\(\text{C}_3\text{H}_8\)).

\[
\frac{82.0 \text{ g C}_3\text{H}_8}{100 \text{ g C}_3\text{H}_8} = \frac{81.8 \text{ g C}}{100 \text{ g C}_3\text{H}_8}
\]

Using the ratio \(18 \text{ g H}/100 \text{ g C}_3\text{H}_8\), you can calculate the mass of hydrogen.

\[
\frac{82.0 \text{ g C}_3\text{H}_8}{100 \text{ g C}_3\text{H}_8} = \frac{18 \text{ g H}}{100 \text{ g C}_3\text{H}_8}
\]

The sum of the two masses equals 82 g, the sample size, to two significant figures (67.1 g C + 15 g H = 82 g C\(_3\)H\(_8\)).

How many grams of hydrogen are contained in a 100-g sample of propane?
Empirical Formulas

A useful formula for cooking rice is to use one cup of rice and two cups of water. If a larger amount of rice is needed, you could double or triple the amounts, for example, two cups of rice and four cups of water. The formulas for some compounds also show a basic ratio of elements. Multiplying that ratio by any factor can produce the formulas for other compounds.

The percent composition of your newly synthesized compound is the data you need to calculate the basic ratio of the elements contained in the compound. The basic ratio, called the empirical formula, gives the lowest whole-number ratio of the atoms of the elements in a compound. For example, a compound may have the empirical formula CO2. The empirical formula shows the kinds and lowest relative count of atoms or moles of atoms in molecules or formula units of a compound. Figure 10.15 shows that empirical formulas may be interpreted at the microscopic (atomic) or macroscopic (molar) level.

An empirical formula may or may not be the same as a molecular formula. For example, the lowest ratio of hydrogen to oxygen in hydrogen peroxide is 1:1. Thus the empirical formula of hydrogen peroxide is HO. The actual molecular formula of hydrogen peroxide has twice the number of atoms as the empirical formula. The molecular formula is (HO)2, or H2O2. But notice that the ratio of hydrogen to oxygen is still the same, 1:1.

The empirical formula of a compound shows the smallest whole-number ratio of the atoms in the compound. The molecular formula tells the actual number of each kind of atom present in a molecule of the compound. For carbon dioxide, the empirical and molecular formulas are the same—CO2. Figure 10.16 shows two compounds of carbon having the same empirical formula (CH) but different molecular formulas.

### Empirical Formulas from Percent Composition

**Purpose** Students are provided with an analogy that helps clarify the concepts of percent composition and empirical formulas.

**Materials** 3 red marbles, 6 green marbles, 3 black marbles, and 12 blue marbles

**Procedure** Provide pairs of students with sets of marbles. Have students express the number of different colored marbles as fractions and percents of the whole collection.

**Expected Outcomes** Students express percent composition of the marbles and determine the "empirical formula" of a marble combination.

### Word Origins

**Empirical** comes from the Latin word empiricus meaning a doctor relying on experience alone. An empirical formula must be obtained from experimental data. Thus, an empirical formula relies on experience. **Is a molecular formula also based on experimental data?**

**Empirical Formulas from Mass Data**

A formula can be interpreted on a microscopic level in terms of atoms or on a macroscopic level in terms of moles of atoms.

### Differentiated Instruction

**Less Proficient Readers**

As students read about how to determine empirical and molecular formulas, have groups of students develop numbered lists of steps they would take to determine these formulas. They should have three lists: one for determining empirical formulas from percent composition; one for determining empirical formulas from mass data; and one for determining molecular formulas from the empirical formula and molar mass.
Sample Problem 10.11

Answers

36. a. 94.1 g O × 1 mol O/16.0 g O = 5.88 mol O
   5.9 g H × 1 mol H/1.0 g H = 5.9 mol H
   5.88 mol O/5.88 = 1.00 mol O
   5.9 mol H/5.88 = 1.0 mol H
   Empirical formula = HO

   b. 67.6 g Hg × 1 mol Hg/200.6 g Hg = 0.337 mol Hg
   10.8 g S × 1 mol S/32.1 g S = 0.336 mol S
   21.6 g O × 1 mol O/16.0 g O = 1.35 mol O
   0.337 mol Hg/0.336 = 1.00 mol Hg
   0.336 mol S/0.336 = 1.00 mol S
   1.35 mol O/0.336 = 4.02 mol O
   Empirical formula = HgSO4

37. a. 62.1 g C × 1 mol C/12.0 g C = 5.18 mol C
   13.8 g H × 1 mol H/1.00 g H = 13.8 mol H
   24.1 g N × 1 mol N/14.0 g N = 1.72 mol N
   5.18 mol C/1.72 = 3.01 mol C
   13.8 mol H/1.72 = 8.02 mol H
   1.72 mol N/1.72 = 1.00 mol N
   Empirical formula = C3H8N

Practice Problems Plus

What is the empirical formula of each of the following compounds?

- a. 36.1% Ca, 63.9% Cl (CaCl2)
- b. 40.0% C, 6.7% H, 53.3% O (CH2O)
- c. 3.7% H, 44.4% C, and 51.9% N (HCN)

Facts and Figures

Computing Formulas

In using percent composition to determine empirical formula, 100.0 g of compound is arbitrarily chosen because it is easy to use. If an element comprises 28.5% of the mass of a compound, for example, it makes up 28.5 g of a 100.0-g sample. Any other mass of compound can be used but computation will be more difficult.
Table 10.3

Comparison of Empirical and Molecular Formulas

<table>
<thead>
<tr>
<th>Formula (name)</th>
<th>Classification of formula</th>
<th>Molar mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>Empirical</td>
<td>13</td>
</tr>
<tr>
<td>C₂H₂ (ethyne)</td>
<td>Molecular</td>
<td>26 (2 × 13)</td>
</tr>
<tr>
<td>C₆H₆ (benzene)</td>
<td>Molecular</td>
<td>78 (6 × 13)</td>
</tr>
<tr>
<td>CH₃O (methanal)</td>
<td>Empirical and Molecular</td>
<td>30</td>
</tr>
<tr>
<td>C₅H₄O₂ (ethanoic acid)</td>
<td>Molecular</td>
<td>60 (2 × 30)</td>
</tr>
<tr>
<td>C₆H₁₂O₆ (glucose)</td>
<td>Molecular</td>
<td>180 (6 × 30)</td>
</tr>
</tbody>
</table>

Molecular Formulas

Look at the compounds listed in Table 10.3. Ethyne and benzene have the same empirical formula—CH. Methanal, ethanoic acid, and glucose, shown in Figure 10.17 have the same empirical formula—CH₂O. But the compounds in these two groups have different molar masses. Their molar masses are simple whole-number multiples of the molar masses of the empirical formulas, CH and CH₂O. The molecular formula of a compound is either the same as its experimentally determined empirical formula, or it is a simple whole-number multiple of its empirical formula.

Once you have determined the empirical formula of your newly synthesized compound, you can determine its molecular formula, but you must know the compound’s molar mass. A chemist often uses an instrument called a mass spectrometer to determine molar mass. The compound is broken into charged fragments (ions) that travel through a magnetic field. The magnetic field deflects the particles from their straight-line paths. The mass of the compound is determined from the amount of deflection experienced by the particles.

From the empirical formula, you can calculate the empirical formula mass (efm). This is simply the molar mass represented by the empirical formula. Then you can divide the experimentally determined molar mass by the empirical formula mass. This gives the number of empirical formula units in a molecule of the compound and is the multiplier to convert the empirical formula to the molecular formula. For example, recall that the empirical formula of hydrogen peroxide is H₂O. Its empirical formula mass is 17.0 g/mol. The molar mass of H₂O₂ is 34.0 g/mol.

\[
\frac{34.0 \text{ g/mol}}{17.0 \text{ g/mol}} = 2
\]

To obtain the molecular formula of hydrogen peroxide from its empirical formula, multiply the subscripts in the empirical formula by 2. (H₂O) × 2 = H₂O₂.

Check

How does the molecular formula of a compound relate to its empirical formula?

Chemical Quantities 311
Sample Problem 10.12

Answers
38. molar mass/efm = 62/31 = 2
   molecular formula = 2(CH₃O) = C₂H₆O₂
39. a. same empirical formula (CH₂O)
   b. different empirical formulas

Practice Problems Plus

1. What is the molecular formula of a compound with the empirical formula CCIN and a molar mass of 184.57? (C₂Cl₂N₂)
2. What is the molecular formula of a compound that is 56.6% K, 8.7% C, and 34.7% O? (K₂CO₃)

Evaluate Understanding

Have students list the steps they would take to calculate the molecular formula in each of the following situations:
• The empirical formula and molar mass are known.
• The percent composition and molar mass are known.

Reteach

Point out to students that when they know the percent composition and molar mass of a compound, they must first use the percent composition to calculate the empirical formula. They can then calculate the empirical formula mass and compare it to the molar mass of the molecular compound to determine the molecular formula.

Elements Handbook

CaO: 71.5%
CaCO₃: 40.1%
Ca(OH)₂: 54.1%
CaSO₄·2H₂O: 23.3%
Ca₃(PO₄)₂: 38.8%

10.3 Section Assessment

40. Key Concept How do you calculate the percent by mass of an element in a compound?
41. Key Concept What information can you obtain from an empirical formula?
42. Key Concept How is the molecular formula of a compound related to its empirical formula?
43. Calculate the percent composition of the compound that forms when 222.6 g N combines completely with 77.4 g O.
44. Calculate the percent composition of calcium acetate (Ca(C₂H₃O₂)₂).
45. The compound methyl butanoate smells like apples. Its percent composition is 58.8% C, 9.8% H, and 31.4% O and its molar mass is 102 g/mol. What is its empirical formula? What is its molecular formula?
46. What is an empirical formula? Which of the following molecular formulas are also empirical formulas?
   a. ribose (C₅H₁₀O₅)
   b. ethyl butyrate (C₆H₁₀O₂)
   c. chlorophyll (C₇₃H₉₀MgN₄O₅)
   d. DEET (C₁₄H₉NO)

Elements Handbook

Calcium Select three important compounds that contain calcium from among those discussed on page R11 of the Elements Handbook. Determine the percent of calcium in each.

Section 10.3 Assessment

40. Divide the mass of an element in the compound by the mass of the compound; then multiply by 100%.
41. The empirical formula gives the lowest whole-number ratio of atoms in the compound.
42. The molecular formula of a compound is a simple whole-number multiple of the empirical formula.
43. 74.2% N, 25.8% O
44. 25.4% Ca, 30.4% C, 3.8% H, 40.5% O
45. C₅H₁₀O₂ is both its empirical and molecular formula.
46. An empirical formula has the lowest whole-number ratio of elements.
   a. molecular
   b. molecular
   c. molecular and empirical
   d. molecular and empirical
Drug Testing

A test to identify an abused substance in the body must be extremely accurate. A false-positive result could ruin a career. A false-negative result could endanger lives. The best method currently available to test for drug abuse is the gas chromatography/mass spectrometer system, or GC/MS. Gas chromatography separates a chemical mixture and identifies its components. Mass spectrometry uses masses to verify the identification. Used together, the GC/MS testing is nearly 100% reliable.

**Interpreting Diagrams** What is the purpose of the separation column?

1. The sample to be tested, such as urine or blood serum, is vaporized and mixed with an unreactive carrier gas such as helium. The resulting gas mixture is forced through a separation column.

2. The separation column is packed with a material that interacts physically with the vaporized sample. Components of the mixture move at different rates along the column and then pass through a detector.

3. Each peak on a gas chromatogram shows the retention time for a component. Retention time is used to identify compounds.

4. The separated component enters a mass spectrometer where its identity is confirmed.

**Testing athletes** The results of a drug test could keep an athlete out of an upcoming event, and possibly off the team permanently.

**Facts and Figures**

**Drugs in the Blood**

Current drug tests can detect even small traces of drugs in the blood or urine. For example, THC (the metabolic product of marijuana use) remains detectable in the body for at least 18 hours for an occasional user and up to 30 days for a habitual user. It can be detected in concentrations as small as 50 ng/mL of solution.