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.

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

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 K_2CrO_4 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.

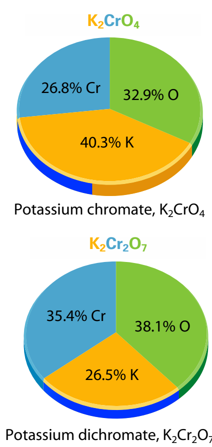


Figure 10.13 Potassium chromate (K_2CrO_4) is composed of 40.3% potassium, 26.8% chromium, and 32.9% oxygen. **Interpreting Diagrams** ***How does this percent composition differ from the percent composition of potassium dichromate ($K_2Cr_2O_7$), a compound composed of the same three elements?***

SAMPLE PROBLEM 10.9

Calculating Percent Composition from Mass Data

When a 13.60-g sample of a compound containing only magnesium and oxygen is decomposed, 5.40 g of oxygen is obtained. What is the percent composition of this compound?

1 Analyze ***List the knowns and the unknowns.***

Knowns
- mass of compound = 13.60 g
- mass of oxygen = 5.40 g O
- mass of magnesium = 13.60 g − 5.40 g = 8.20 g Mg

Unknowns
- percent Mg = ? % Mg
- percent O = ? % O

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

2 Calculate ***Solve for the unknown.***

$$\% \text{ Mg} = \frac{\text{mass of Mg}}{\text{mass of compound}} \times 100\% = \frac{8.20 \text{ g}}{13.60 \text{ g}} \times 100\%$$
$$= 60.3\%$$
$$\% \text{ O} = \frac{\text{mass of O}}{\text{mass of compound}} \times 100\% = \frac{5.40 \text{ g}}{13.60 \text{ g}} \times 100\%$$
$$= 39.7\%$$

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

The percents of the elements add up to 100%:

60.3% + 39.7% = 100%.

Practice Problems

32. A compound is formed when 9.03 g Mg combines completely with 3.48 g N. What is the percent composition of this compound?

33. When a 14.2-g sample of mercury(II) oxide is decomposed into its elements by heating, 13.2 g Hg is obtained. What is the percent composition of the compound?

Math Handbook

For help with percents go to page R72.

Interactive Textbook

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

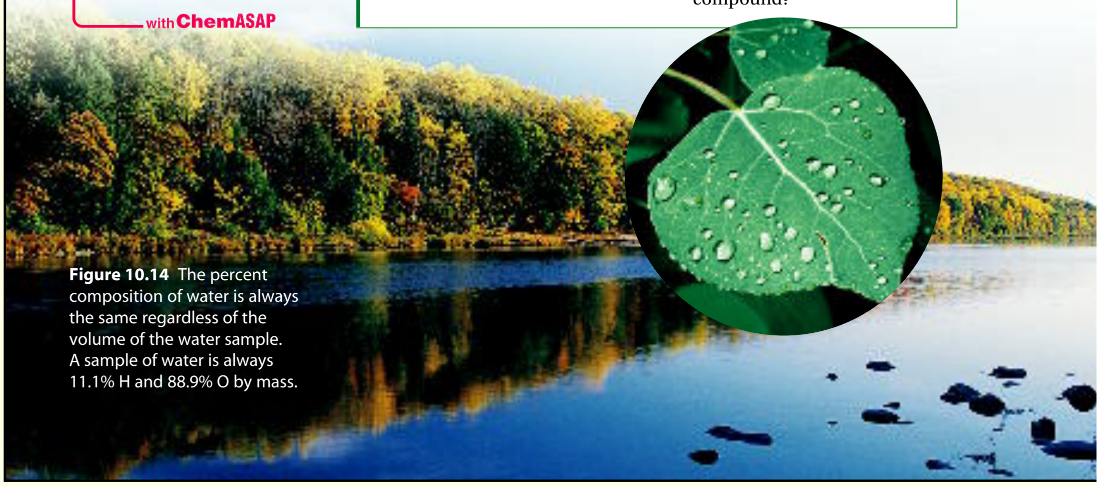


Figure 10.14 The percent composition of water is always the same regardless of the volume of the water sample. A sample of water is always 11.1% H and 88.9% O by mass.

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 a 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.

Checkpoint ***How can you determine the percent by mass of an element in a compound if you know only the compound's formula?***

SAMPLE PROBLEM 10.10

Calculating Percent Composition from a Formula

Propane (C_3H_8), the fuel commonly used in gas grills, is one of the 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_3H_8 = 36.0 g
- mass of H in 1 mol C_3H_8 = 8.0 g
- molar mass of C_3H_8 = 44.0 g/mol

Unknowns
- percent C = ? % C
- percent H = ? % 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_2H_6)
b. sodium hydrogen sulfate ($NaHSO_4$)

35. Calculate the percent nitrogen in these common fertilizers.
a. NH_3
b. NH_4NO_3

Go Online NSTA SCI LINKS
For: Links on Percent Composition
Visit: www.SciLinks.org
Web Code: cdn-1103

Math Handbook
For help with significant figures go to page R59.

Interactive Textbook
Problem-Solving 10.35
Solve Problem 35 with the help of an interactive guided tutorial.
with ChemASAP

Quick LAB

Percent Composition

Purpose

To measure the percent of water in a series of crystalline compounds called hydrates.

Materials

- centigram balance
- Bunsen burner
- 3 medium-sized test tubes
- test tube holder
- test tube rack
- spatula
- hydrated salts of copper(II) sulfate, calcium chloride, and sodium sulfate

Procedure

1. Label each test tube with the name of a salt. Measure and record the masses.
2. Add 2–3 g of salt (a good-sized spatula full) to the appropriately labeled test tube. Measure and record the mass of each test tube and salt.
3. Hold one of the tubes at a 45° angle and gently heat its contents over the burner, slowly passing it in and out of the flame. Note any change in the appearance of the solid salt.
4. As moisture begins to condense in the upper part of the test tube, gently heat the entire length of the tube. Continue heating until all of the moisture is driven from the tube. This may take 2–3 minutes. Repeat Steps 3 and 4 for the other two tubes.
5. Allow each tube to cool. Then measure and record the mass of each test tube and the heated salt.

Analyze and Conclude

1. Set up a data table so that you can subtract the mass of the empty tube from the mass of the salt and the test tube, both before and after heating.
2. Calculate the difference between the mass of each salt before and after heating. This difference represents the amount of water lost by the hydrate on heating.
3. Calculate the percent by mass of water lost by each compound.
4. Which compound lost the greatest percent by mass of water? The smallest?

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 81.8 g C/100 g C_3H_8 to calculate the mass of carbon contained in 82.0 g of propane (C_3H_8).

$$82.0\ \text{g}\ \cancel{C_3H_8} \times \frac{81.8\ \text{g C}}{100\ \text{g}\ \cancel{C_3H_8}} = 67.1\ \text{g C}$$

Using the ratio 18 g H/100 g C_3H_8, you can calculate the mass of hydrogen.

$$82.0\ \text{g}\ \cancel{C_3H_8} \times \frac{18\ \text{g H}}{100\ \text{g}\ \cancel{C_3H_8}} = 15\ \text{g H}$$

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_3H_8).

Checkpoint ***How many grams of hydrogen are contained in a 100-g sample of propane?***

308 Chapter 10

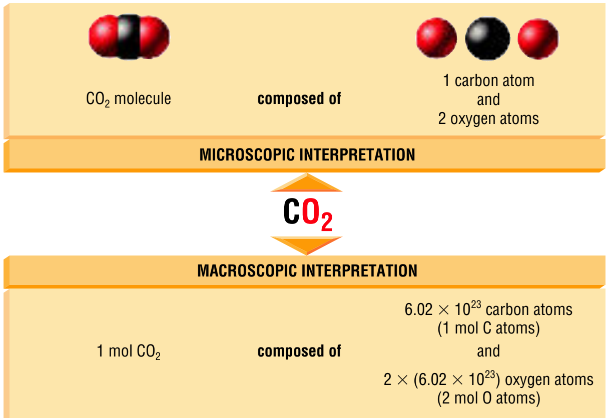


Figure 10.15 A formula can be interpreted on a microscopic level in terms of atoms or on a macroscopic level in terms of moles of atoms.

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

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 CO_2. 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 $(HO) \times 2$, or H_2O_2. 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—CO_2. Figure 10.16 shows two compounds of carbon having the same empirical formula (CH) but different molecular formulas.

Figure 10.16 Ethyne (C_2H_2), also called acetylene, is a gas used in welder's torches. Styrene (C_8H_8) is used in making polystyrene. These two compounds have the same empirical formula.
Calculating ***What is the empirical formula of ethyne and styrene?***

SAMPLE PROBLEM 10.11

Determining the Empirical Formula of a Compound

A compound is analyzed and found to contain 25.9% nitrogen and 74.1% oxygen. What is the empirical formula of the compound?

1 Analyze ***List the knowns and the unknown.***

Knowns
- percent of nitrogen = 25.9% N
- percent of oxygen = 74.1% O

Unknown
- Empirical formula = $N_?O_?$

The percent composition tells the ratio of the mass of nitrogen atoms to the mass of oxygen atoms in the compound. Change the ratio of masses to a ratio of moles by using conversion factors based on the molar mass of each element. Then reduce this ratio to the lowest whole-number ratio.

2 Calculate ***Solve for the unknown.***

Because percent means parts per 100, you can assume that 100.0 g of the compound contains 25.9 g N and 74.1 g O. Use these values to convert to moles.

$$25.9\ \cancel{\text{g N}} \times \frac{1\ \text{mol N}}{14.0\ \cancel{\text{g N}}} = 1.85\ \text{mol N}$$

$$74.1\ \cancel{\text{g O}} \times \frac{1\ \text{mol O}}{16.0\ \cancel{\text{g O}}} = 4.63\ \text{mol O}$$

The mole ratio of nitrogen to oxygen is $N_{1.85}O_{4.63}$. But formulas must have whole-number subscripts. Divide each molar quantity by the smaller number of moles. This gives 1 mol for the element with the smaller number of moles.

$$\frac{1.85\ \text{mol N}}{1.85} = 1\ \text{mol N}; \quad \frac{4.63\ \text{mol O}}{1.85} = 2.50\ \text{mol O}$$

The result, $N_1O_{2.5}$, still has a subscript that is not a whole number. To obtain the lowest whole-number ratio, multiply each part of the ratio by the smallest whole number (in this case 2) that will convert both subscripts to whole numbers.

$$1\ \text{mol N} \times 2 = 2\ \text{mol N}$$
$$2.5\ \text{mol O} \times 2 = 5\ \text{mol O}$$

The empirical formula is N_2O_5.

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

The subscripts are whole numbers, and the percent composition of this empirical formula equals the percents given in the original problem.

Practice Problems

36. Calculate the empirical formula of each compound.
a. 94.1% O, 5.9% H
b. 67.6% Hg, 10.8% S, 21.6% O

37. 1,6-diaminohexane is used to make nylon. What is the empirical formula of this compound if it is 62.1% C, 13.8% H, and 24.1% N?

Math Handbook

For help with dimensional analysis go to page R66.

Interactive Textbook

Problem-Solving 10.37
Solve Problem 37 with the help of an interactive guided tutorial.

with ChemASAP

310 Chapter 10

Table 10.3

Comparison of Empirical and Molecular Formulas

Formula (name)	Classification of formula	Molar mass
CH	Empirical	13
C_2H_2 (ethyne)	Molecular	26 (2 × 13)
C_6H_6 (benzene)	Molecular	78 (6 × 13)
CH_2O (methanal)	Empirical and Molecular	30
$C_2H_4O_2$ (ethanoic acid)	Molecular	60 (2 × 30)
$C_6H_{12}O_6$ (glucose)	Molecular	180 (6 × 30)

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—CH_2O. 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 CH_2O. **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 HO. Its empirical formula mass is 17.0 g/mol. The molar mass of H_2O_2 is 34.0 g/mol.

$$\frac{34.0\ \text{g}/\cancel{\text{mol}}}{17.0\ \text{g}/\cancel{\text{mol}}} = 2$$

To obtain the molecular formula of hydrogen peroxide from its empirical formula, multiply the subscripts in the empirical formula by 2. (HO) × 2 = H_2O_2.

Checkpoint ***How does the molecular formula for a compound relate to its empirical formula?***

Figure 10.17 Methanal (formaldehyde), ethanoic acid (acetic acid), and glucose have the same empirical formula. **Applying Concepts** ***How could you easily obtain the molar mass of glucose using the molar mass of methanal?***

SAMPLE PROBLEM 10.12

Finding the Molecular Formula of a Compound

Calculate the molecular formula of a compound whose molar mass is 60.0 g/mol and empirical formula is CH_4N.

1 Analyze ***List the knowns and the unknown.***

Knowns
- empirical formula = CH_4N
- molar mass = 60.0 g/mol

Unknown
- molecular formula = ?

2 Calculate ***Solve for the unknown.***

First calculate the empirical formula mass. Then divide the molar mass by the empirical formula mass to obtain a whole number. To get the molecular formula, multiply the formula subscripts by this value.

Empirical formula	efm	Molar mass/efm	Molecular formula
CH_4N	30.0	60.0/30.0 = 2	$C_2H_8N_2$

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

The molecular formula has the molar mass of the compound.

Practice Problems

38. Find the molecular formula of ethylene glycol, which is used as antifreeze. The molar mass is 62 g/mol and the empirical formula is CH_3O.

39. Which pair of molecules has the same empirical formula?
a. $C_2H_4O_2$, $C_6H_{12}O_6$
b. $NaCrO_4$, $Na_2Cr_2O_7$

Interactive Textbook

Problem-Solving 10.38 Solve Problem 38 with the help of an interactive guided tutorial.

with ChemASAP

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 ($Ca(C_2H_3O_2)_2$).

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 ($C_5H_{10}O_5$)
b. ethyl butyrate ($C_6H_{12}O_2$)
c. chlorophyll ($C_{55}H_{72}MgN_4O_5$)
d. DEET ($C_{12}H_{17}ON$)

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.

Interactive Textbook

Assessment 10.3 Test yourself on the concepts in Section 10.3.

with ChemASAP

312 Chapter 10

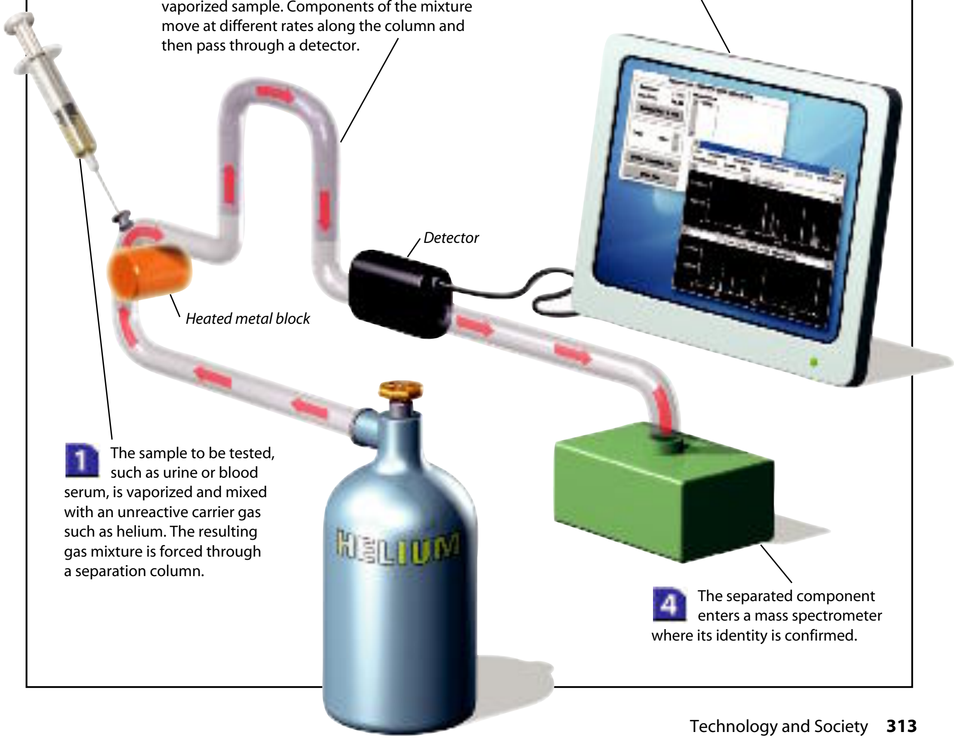
Technology & Society

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?***

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



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.