



Unit 3: Quantities in Chemical Reactions

6.6: The composition of Unknown Compounds

Law of definite proportions

As we know H_2O molecules always comprise of 1 hydrogen atom and two oxygen atoms no matter what their source. It could be liquid as water, solid as ice, of gas as water vapor.

A French chemist Joseph Louis Proust called this as “Law of definite proportions”.

- He proposed that a chemical compound always contain the same proportions of elements by mass. For instance, the proportion of carbon and oxygen stays constant in carbon dioxide.

Mass percent of an element: According to the law of definite proportions, all compounds have the same mass percent of an element, which can be calculated by:

$$\% \text{ composition} = \frac{\text{mass of element}}{\text{mass of compound}} \times 100\%$$

Example: what is mass percent of hydrogen in water?

$$\text{Step 1: mass of } H_2 = 2 \times (1.01g/mol) = 2.02g/mol$$

$$\text{Step 2: mass of } H_2O = 18.02g/mol \text{ (Molar mass)}$$

$$\text{Step 3: \% mass of } H_2 = \frac{\text{mass of } H_2}{\text{mass of } H_2O} \times 100\% = \frac{2.02g/mol}{18.02g/mol} \times 100\% =$$



There will be two types of problems:

1. Percentage composition from a chemical formula

If you already know the chemical formula for a compound, you can calculate its percent composition

- a) Calculate the molar mass of each element and compound formula unit
 - a. Assume sample size is one mole
 - b. Multiply the molar mass of the element by its subscript in the chemical formula
- b) Divide the mass of the element by the molar mass of the compound unit and multiply by 100

Sample problem 1: Determine the percentage composition by mass of aluminum hydroxide.

Sample problem 2: Determine the percentage composition by mass of aspirin, $C_9H_8O_4$.

2. Percentage composition from Mass Data

Sample problem 3: A sample of a compound that is found in gasoline has a mass of 35.8g. the sample contains 30.1g of carbon and 5.70g of hydrogen. What is the percentage composition of the compound?

Sample problem 4: A sample of an unknown compound contains 84.05g of carbon, 5.00g of hydrogen, 42.02g of nitrogen, and 96.08g of oxygen. Determine the percentage composition of the compound.



Review Questions

- 1. K/U** Samples of carbon dioxide are taken from the atmosphere and from a block of dry ice. Are the chemical formulas for the carbon dioxide in the two samples different? Explain.
- 2. K/U** When determining the percentage composition of a compound from its formula, the calculations are usually based on 1 mol of a sample. Explain why this is the most convenient amount to use.
- 3. K/U** Acetylene, $C_2H_2(g)$, is made up of two carbon atoms and two hydrogen atoms. Explain why acetylene does not contain 50% of each element by mass.
- 4. T/I** What is the mass percent of each element in sucrose, $C_{12}H_{22}O_{11}(s)$?
- 5. C** Draw a flowchart that shows the steps needed to determine the percentage composition of a compound, using the masses of the elements in the compound.
- 6. T/I** A sample of an unknown 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. Determine the percentage composition of the compound.
- 7. T/I** A 19.00 kg sample of an unknown compound contains 0.06 kg of hydrogen, 11.01 kg of gold, and 7.93 kg of chlorine. Determine the percentage composition of the compound.
- 8. K/U** In your own words, explain the difference between mass percent and percentage composition.
- 9. T/I** Phosphoric acid, $H_3PO_4(l)$, is used in some carbonated beverages to give them a tangy flavour. Determine the percentage composition of phosphoric acid.
- 10. T/I** Determine the percentage composition of magnesium phosphate, $Mg_3(PO_4)_2(s)$.
- 11. T/I** What mass of boron would be in a 35.0 g sample of sodium tetraborate, $Na_2B_4O_7(s)$?
- 12. A** Calcium carbonate, $CaCO_3(s)$, can have many different forms. Coral, shown below, as well as marble and chalk, are substances that have $CaCO_3(s)$ as a principal component.



- Determine the percentage composition of this compound.
 - When acid rain reacts with the marble in a statue, carbon dioxide gas is formed. What does this do to the mass percent of carbon and oxygen in the statue?
- 13. A** Washing soda is the common name for a compound that is used to make soap and glass. Washing soda contains 43.4% sodium by mass and 45.3% oxygen by mass, as well as one other element. If the molar mass of washing soda is 105.99 g/mol, identify the other element.
 - 14. A** A typical soap molecule is made up of a polyatomic anion associated with a cation. The polyatomic anion contains hydrogen, carbon, and oxygen. One soap molecule has 18 carbon atoms and contains 70.5% carbon, 11.5% hydrogen, and 10.4% oxygen by mass. It also contains one alkali metal ion. Identify this alkali metal ion.



Unit 3: Quantities in Chemical Reactions

6.7 & 6.9: Empirical Formula and Molecular Formula

Molecular formula: the formula for a compound that shows the number of atoms of each element that make up a molecule of that compound.

Empirical formula: a formula that shows the **smallest whole-number ratio** of the elements in a compound.

Empirical formula may or may not be the same as the molecular formula:

- If the two formulas are different the molecular formula will always be a simple multiple of the empirical formula.
- The empirical formula for hydrogen peroxide is HO

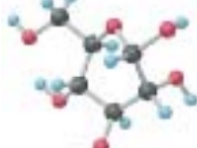
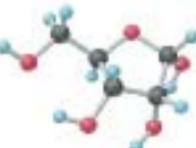
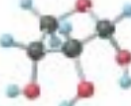
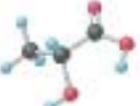
The molecular formula for hydrogen peroxide is H_2O_2

More

examples:

Table 6.1 Six Compounds with the Empirical Formula CH_2O

Name	Empirical Formula	Molecular Formula	Whole-Number Multiple	<i>M</i> (g/mol)	Use or Function
Formaldehyde	CH_2O	CH_2O	1	30.03	Is used as a disinfectant and biological preservative
Acetic acid	CH_2O	$\text{C}_2\text{H}_4\text{O}_2$	2	60.06	Is used to produce acetate polymers; is a component of vinegar (5% solution)
Lactic acid	CH_2O	$\text{C}_3\text{H}_6\text{O}_3$	3	90.09	Causes milk to sour; forms in muscles during exercise
Erythrose	CH_2O	$\text{C}_4\text{H}_8\text{O}_4$	4	120.12	Forms during sugar metabolism
Ribose	CH_2O	$\text{C}_5\text{H}_{10}\text{O}_5$	5	150.15	Is a component of many nucleic acids and vitamin B ₂
Glucose	CH_2O	$\text{C}_6\text{H}_{12}\text{O}_6$	6	180.18	Is a major nutrient for energy in cells



CH_2O $\text{C}_2\text{H}_4\text{O}_2$ $\text{C}_3\text{H}_6\text{O}_3$ $\text{C}_4\text{H}_8\text{O}_4$ $\text{C}_5\text{H}_{10}\text{O}_5$ $\text{C}_6\text{H}_{12}\text{O}_6$



Part 1: Determine the Empirical Formula:

Rules for determining Empirical Formulas:

- 1.** Convert percentage composition data into mass data by assuming that the total mass of the sample is 100 g.
- 2.** Determine the number of moles of each element in the sample by dividing the mass by the molar mass of each element.
- 3.** Convert the number of moles of each element into whole numbers that become subscripts in the empirical formula by dividing each amount in moles by the smallest amount.
- 4.** If the subscripts are not yet whole numbers, determine the least common multiple that will make the decimal values into whole numbers. Multiply all subscripts by this least common multiple. Use these numbers as subscripts to complete the empirical formula.

Sample problem 1: determine the empirical formula for a compound that is found by analysis to contain 27.37% sodium, 1.2000% hydrogen, 14.30% carbon, and 57.14% oxygen.

Practice: Determine the empirical formula for a compound that contains 69.88% of iron and 30.12% of oxygen.



Part 2: Determine the Molecular formula:

First of all, you should have empirical formula, then you use the molar masses of the empirical formula and the molecular formula to find the whole-number multiple, x , which related the empirical formula to the molecular formula.

Sample problem 2: A compound with the empirical formula CH was analyzed using a mass spectrometer. Its molar mass was found to be 78g/mol. Determine the molecular formula.

Sample problem 3: Chemical analysis indicates that a compound is 28.64% sulfur and 71.36% bromine. The molar mass of the compound is 223.94g/mol. Determine the molecular formula.



Determining Empirical and Molecular Formulas

Convert percentage composition to mass by assuming the sample is 100 g.

Find the amount in moles of each element.

Divide by the lowest mole amount.

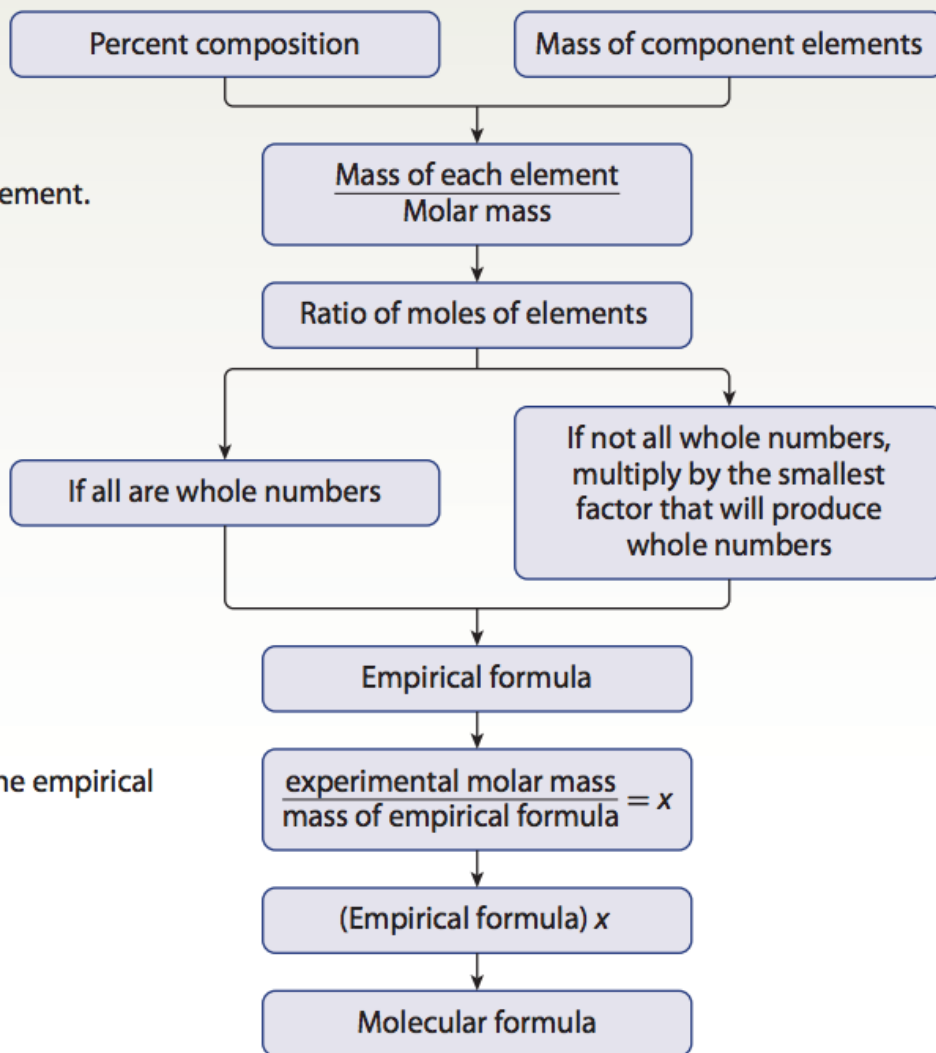
Examine the mole ratio.

Write the empirical formula.

Determine the integer that relates the empirical and molecular formulas.

Multiply the subscripts by x.

Write the molecular formula.



**Practice Problems**

- 41.** The empirical formula for glucose is $\text{CH}_2\text{O}(\text{s})$. The molar mass of glucose is 180.18 g/mol. Determine the molecular formula for glucose.
- 42.** The empirical formula for xylene is $\text{C}_4\text{H}_5(\ell)$, and its molar mass is 106 g/mol. What is the molecular formula for xylene?
- 43.** The empirical formula for 1,4-butanediol is $\text{C}_2\text{OH}_5(\ell)$. Its molar mass is 90.14 g/mol. What is its molecular formula?
- 44.** The empirical formula for styrene is $\text{CH}(\ell)$, and its molar mass is 104 g/mol. What is its molecular formula?
- 48.** A compound that contains 6.44 g of boron and 1.80 g of hydrogen has a molar mass of approximately 28 g/mol. What is its molecular formula?
- 49.** The molar mass of a compound is 148.20 g/mol. Its percentage composition is 48.63% carbon, 21.59% oxygen, 18.90% nitrogen, and the rest hydrogen.
- Find the empirical formula for the compound.
 - Find its molecular formula.
- 45.** Calomel is a compound that was once popular for treating syphilis. It contains 84.98% mercury and 15.02% chlorine. It has a molar mass of 472 g/mol. What is its empirical formula?
- 46.** The molar mass of caffeine is 194 g/mol. Determine whether the molecular formula for caffeine is $\text{C}_4\text{H}_5\text{N}_2\text{O}(\text{s})$ or $\text{C}_8\text{H}_{10}\text{N}_4\text{O}_2(\text{s})$.
- 47.** An unknown compound contains 42.6% oxygen, 32% carbon, 18.7% nitrogen, and the remainder hydrogen. Using mass spectrometry, its molar mass was determined to be 75.0 g/mol. What is the molecular formula for the compound?
- 50.** Estradiol is the main estrogen compound that is found in humans. Its molar mass is 272.38 g/mol. The percentage composition of estradiol is 72.94% carbon, 10.80% oxygen, and 8.16% hydrogen. Determine whether its molecular formula is the same as its empirical formula. If not, what is each formula?



Part 3: Hydrate and their chemical formulas

A **hydrate** is a compound that has a specific number of water molecules bound to each formula unit, such that $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ is copper (II) sulfate _____hydrate.

An **anhydrous** compound has no water molecule attached.

The molar mass and percent composition of a hydrate must take into account the bound water molecules.

Sample problem 4: A 50.0g sample of hydrated barium hydroxide contains 27.2g of $\text{Ba}(\text{OH})_{2(s)}$. calculate the percent by mass of water in hydrate barium hydroxide and find out how many water molecules are attached?

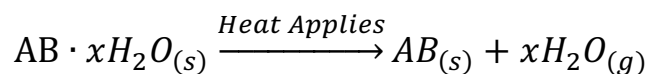
Practice:

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Analyzing hydrate:

Since hydrates can be converted into the anhydrous form by heat, we can easily determine the number of water molecules bound to a salt and hence the chemical formula of the hydrate.



Sample problem 5: A 3.34g sample of the hydrate form of strontium thiosulfate has the formula $SrS_2O_3 \cdot xH_2O$ and contains 2.30g of the anhydrous salt. Find the percent by mass of water and find the value of x.