Teaching Stoichiometry as Algebraic Word Problems, Part 4

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Abstract

This paper presents the subject of stoichiometry as a collection of algebraic methods of solving chemistry word problems. It should be clear by now that the central object of stoichiometry is the mole proportion.

1 Introduction

Stoichiometry is a basic topic of chemistry, concerned with solving for certain quantities of products and/or reactants in a balanced chemical equation,[1] given knowledge of other quantities in the equation. Such quantities of interests are typically moles, grams, and/or liters of particular substances.

All the problems in this paper are selected from the single textbook *Chemical Principles: Quest for Insight*, 3rd Ed, by Atkins and Jones [1].

The figures provided fulfill three specific purposes. One of which is to hold as much relevant information as can be fitting comfortably into them. The second is to assist in balancing invariant quantities throughout a given chemical process. And lastly, to facilitate extracting useful ratios, which is usually done either through the mole-counting line or the gram-counting line.

2 Problem 1: Converting to moles space and back again

Problem 1. p. F43 E.4 Given a quantity of $CuSO_4 \cdot 5\,H_2O$ in grams, determine how many grams of Cu are in this compound.

This is one of those problems that one has to go from grams to moles and back to grams. I won't actually solve this problem, but I do solve others like it later on. All I want to demonstrate here is a graphical representation of the solution steps so that the student gets a mental image of the logic involved.

[1] It seems that certain types of problems do not require the chemical equation to be balanced, so long as enough information is given to setup a relevant stoichiometric ratio.

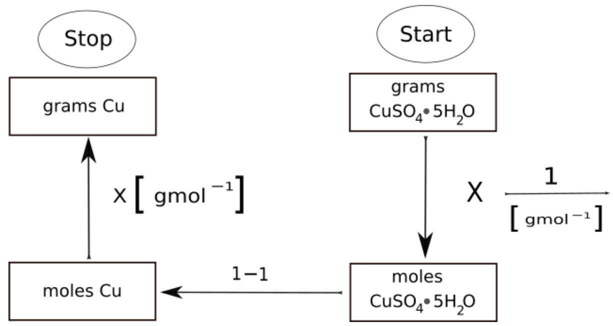

Figure 1. To solve this problem, we start off in gram-space and then convert to mole-space, do our calculation there, and then convert back to gram-space to get the final answer. Clearly, the conversion factors we need to employ have only been represented by the appropriate units.

3 Problem 2. p. F44 E.27

The density of sodium borohydrite ($NaBH_4$) [herafter referred to as the compound] is 1.074 $g \cdot cm^{-3}$. If 3.93 g of the compound contains 2.50×10^{23} H atoms, how many moles of H atoms are present in 28.0 cm^{-3} of the compound?

Given: $\rho_{\text{compound}} = 1.074 \text{ g} \cdot \text{cm}^{-3}$

Given: 3.93 g compound on order of 2.50×10^{23} H atoms

Given: $V_{\text{compound}} = 28.0 \text{ cm}^3$

Solution:

$$\text{grams of compound} = \rho V = 30.072\,\text{g}\,. \tag{1}$$

$$\begin{aligned}\#\text{ H atoms in compound} &= 30.072\,\text{g} \times \frac{2.50 \times 10^{23}\text{ H atoms}}{3.93\,\text{g compound}} \\ &= 1.913 \times 10^{24}\text{ H atoms}\end{aligned} \tag{2}$$

Therefore,

$$\begin{aligned}\#\text{ moles H atoms in compound} &= \frac{1.913 \times 10^{24}\text{ H atoms}}{6.022 \times 10^{23}\,\text{atoms mol}^{-1}} \\ &= 3.18\text{ moles}\,.\end{aligned} \tag{3}$$

4 Problem 3. p. F49 F.7

In an experiment, 4.14 grams of phosphorus combined with chlorine to produce 27.8 grams of a white solid compound. What is the empirical formula of the white compound?

SOLUTION:

Notation: The empirical formula of the white compound has the general form of P_aCl_b, where a, b are relatively prime positive integers, representing the moles of phosphorus and chlorine, respectively. Our job is to find a and b.

Note: Let the grams per mole of P and Cl be, respectively, [P] and [Cl].

The key to solving this problem is to realize that the “algebraic ratio” of the grams of P to the grams of the compound must equal the ratio of the actual wt of P to the actual wt of the compound, that is,

$$\frac{a[\mathrm{P}]}{a[\mathrm{P}] + b[\mathrm{Cl}]} = \frac{4.14\,\mathrm{g}}{27.8\,\mathrm{g}}\,. \tag{4}$$

We can do similarly for chlorine:

$$\frac{b[\mathrm{Cl}]}{a[\mathrm{P}] + b[\mathrm{Cl}]} = \frac{27.8\,\mathrm{g} - 4.14\,\mathrm{g}}{27.8\,\mathrm{g}} = \frac{23.66\,\mathrm{g}}{27.8\,\mathrm{g}}\,. \tag{5}$$

To simplify, divide (5) by (4) to get[2]

$$\frac{b[\mathrm{Cl}]}{a[\mathrm{P}]} = \frac{23.66}{4.14}\,. \tag{6}$$

Therefore,

$$\frac{b}{a} = \frac{23.66}{4.14}\frac{[\mathrm{P}]}{[\mathrm{Cl}]} = 5.715\frac{30.97\,\mathrm{g{\cdot}mol^{-1}}}{35.46\,\mathrm{g{\cdot}mol^{-1}}} \approx \frac{5}{1}\,. \tag{7}$$

So, the empirical formula of the white compound is PCl_5.

5 Problem 4. p. F49 F.9

L-Dopa, a drug used for the treatment of Parkinson’s disease, is 54.46 % C, 5.62 % H, 7.10 % N, and 32.46 % O. What is the empirical formula of the compound?

[2] I could have alternatively divided (4) by (5) but that would have produced a number less than 1. But, either way would work.

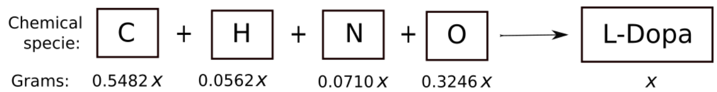

Figure 2. We imagine starting with an unknown amount of grams of L-Dopa, which we represent by the unknown x. Next, we convert the percentage of each element by weight into decimal amounts by weight, that is, in grams.

Now, all we care about is the combined ratios of these elements by weight, so we can divide through by x to get the corresponding ratios:[3]

$$.5482, \quad .0562, \quad 0.0710, \quad 0.3246\,. \tag{*}$$

Next, we divide each element by its respective grams/mole to get the combined mole ratios:

$$0.04568, \quad 0.0557, \quad 0.005069, \quad 0.02029\,.$$

Next, we divide through by the smallest number in this list and round off the results to their nearest integer: $9, \quad 11, \quad 1, \quad 4$

We're actually finished because the GCD of all these numbers is 1, therefore, there is no other common factor greater than one that can be divided out.

Thus, the empirical formula of L-Dopa is $C_9H_{11}NO_4$

But wait!! Why go to all this effort to write down a figure (Fig. 2) just to extract from it the obvious data one needs to solve this problem, which is the data on line (*)?

Well, I can't tell the reader when it should be written down, but the reader should be able to write it down as proof that he or she understands how to justify the data on line (*), and to understand what it means. From the beginning, this series of stoichiometry papers has been designed to teach stoichiometry problems as algebra word problems. What Fig. 2 demonstrates is that even in chemical processes, a total is equal to the sum of its parts, and that is how one justifies line (*).

6 Problem 5. p. F54 Ex. G.2

Suppose we were asked to prepare 250 mL of a solution that was approximately 0.0380 M $CuSO_4$ (aq) and we had available only Copper (II) sulfate pentahydrate $CuSO_4 \cdot 5H_2O$. What mass of the solid do we need?

[3]When taking ratios, one can always divide out a common factor.

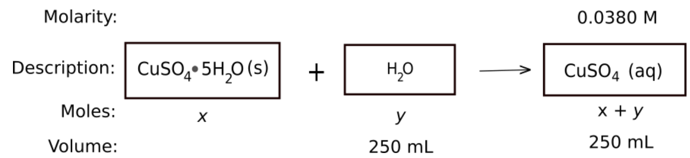

Figure 3. The moles line counts the moles of $CuSO_4$ in each group. (In any closed chemical process, the number of moles of a given chemical element is fixed.) Of course, in this problem $y = 0$.

Calculate moles $CuSO_4$:

$$\begin{aligned} x &= (0.250\ \text{L})(0.0380\,\text{M}) \\ &= 9.5 \times 10^{-3}\text{moles}\,. \end{aligned} \tag{8}$$

Hence, 9.5×10^{-3} mol of $CuSO_4$ corresponds to 9.5×10^{-3} mol of $CuSO_4 \cdot 5\,H_2O$. Therefore,

$$\begin{aligned} \text{Grams } CuSO_4 \cdot 5H_2O &= (9.5 \times 10^{-3}\text{mol})\big(249.7\frac{\text{g}}{\text{mol}}\big) \\ &= 2.37\,\text{g}\,. \end{aligned} \tag{9}$$

I'm not a lab technician, but I suppose the correct way to perform this process would be to put the dry chemical into a graduated beaker and then add pure water until the water level is at 250 mL, stirring as you go.

7 Problem 6: p. F55 Ex. G.4

We need to prepare 250 mL of 1.50×10^{-3} M NaOH (aq), using 0.0380 M NaOH (aq) stock solution. How much stock solution do we need?

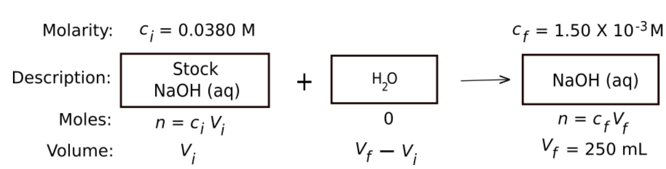

Figure 3. The moles line counts the moles of NaOH in each group. (In any chemical process, the number of moles of a given chemical specie is fixed.)

Initial State: $c_i = 0.0380$ M NaOH (aq).

Final State: 250 mL of $c_f = 1.50 \times 10^{-3}$ M NaOH (aq).

What we must do is to add a certain amount of pure water to the stock solution to end up with the desired volume of NaOH (aq). However, in the process of adding pure water, the number of moles n of NaOH will not change. Hence,

$$n = c_i V_i = c_f V_f \,. \tag{10}$$

Therefore,

$$\begin{aligned} V_i &= \frac{c_f V_f}{c_i} \\ &= \frac{(1.50 \times 10^{-3}\,\mathrm{M})(250\,\mathrm{mL})}{(0.0380\ \mathrm{M})} \\ &= 9.87 \times 10^{-3}\ \mathrm{L}\,. \end{aligned} \tag{11}$$

8 Problem 7. p. F61 Ex. H.17

Phosphorus and oxygen react to form two different phosphorus oxides. The mass percentage of phosphorus in one of these is 43.64%; in the other, it is 56.34%.

(a) Write the empirical formula for each phosphorus oxide.

(b) The molar mass of the former oxide is 283.33 g mol^{-1} and that of the latter is 219.88 g mol^{-1}. Determine the molecular formulas and name each oxide.

First, some notation. Similar to what we did in Problem 3, we let [P] and [O] represent the molar masses of phosphorus and oxygen, respectively.

(a) So, we need to find relatively prime integers x, y for P_xO_y. To get the ratio of x and y, we can use that the ratio of the "algebraic mass" of phosphorus to the whole compound is equal to the actual ratio of their corresponding masses. Then,

$$\frac{x[\mathrm{P}]}{x[\mathrm{P}] + y[\mathrm{O}]} = .4364\,. \tag{12}$$

To help simplify, set $\alpha = y/x$ which gives us

$$\frac{[\mathrm{P}]}{[\mathrm{P}] + \alpha[\mathrm{O}]} = .4364\,. \tag{13}$$

So, with [P] = 30.97 and [O] = 16.00, then $\alpha = 2.5 = 5/2$. Therefore, the first empirical formula of 'phosphorus oxide' is P_2O_5.

By similar reasoning for the second compound, we get for its empirical formula P_2O_3.

Now, back to P_2O_5. To derive the actual chemical formula of this 'phosphorus oxide' compound, we need the appropriate multiplication factor γ, which we get from the following ratio:[4]

$$\begin{aligned}\gamma &= \frac{\text{Actual }\ \text{g}\cdot\text{mol}^{-1}}{\text{Empirical }\ \text{g}\cdot\text{mol}^{-1}} \\ &= \frac{283.88\,\text{g}\cdot\text{mol}^{-1}}{2(30.97)\,\text{g}\cdot\text{mol}^{-1} + 5(16)\,\text{g}\cdot\text{mol}^{-1}} \\ &= \frac{283.88}{141.94} \\ &\approx 2\,. \end{aligned} \tag{14}$$

Hence, the true molecular formula of the compound must be P_4O_{10}. The second case follows similarly.

References

[1] P. Atkins and L. Jones. *Chemical Principles: Quest for Insight*, 3rd Ed. Freeman (2005).

[4]This γ is not standard. I had to choose something, so I chose it.