Solutions: Molarity.

A. Introduction

This handout introduces solutions, and one of the common mole-based units used to describe them. It requires mass-mole interconversion (and its prerequisites).

A solution is a homogeneous (uniform) mixture of two (or more) chemicals. The solutions of most common interest involve dissolving a solid solute in a liquid solvent. Solutions of sodium chloride in water or sugar in water are good examples of common solutions. We will focus our discussion on such solutions. Unless stated otherwise, we will consider aqueous solutions, with one solute.

To describe a solution we need to specify the amounts of two chemicals, the solute and the solvent -- directly or indirectly. The resulting description is called the concentration of the solution. There are several ways to express concentration. It is not important that you master all of them. What is important is that you realize the basis of the complexity, so that you are sensitive to the differences between different concentration units (especially when they have similar names).

We will focus on two common concentration units: molarity and (in the next handout) weight percentage. We will mention some others, to illustrate the variety of ways to describe concentration. (I will be happy to work with you privately on other concentration units that interest you.)

B. Molarity

Molarity is

$$\frac{\text{moles solute}}{\text{liters solution}}$$

We noted previously that there are many ways one might describe a solution. In the definition of molarity, all four words are important. The numerator is “moles solute”, not grams solute and not moles solvent; etc. You must know the meaning of molarity.

Expressing the amount of solute in moles, rather than in grams, aids the chemist. Remember that the mole is a certain number of molecules (or formula units); the chemist who wants equal “amounts” of two chemicals probably wants equal moles. Expressing the denominator in volume of solution makes it easy to measure out portions of the solution.

The units of molarity are mol/L. Molarity is commonly abbreviated M, but in problems you will usually need to expand the M to mol/L (or, more explicitly, mol solute/L solution) in order to see what is happening. Recognizing that molarity is mol/L, and then carefully following the units, will guide you through most molarity problems.

As a practical matter, molarity (moles solute/L solution) is a conversion factor -- between moles solute and L of solution. That may seem like a simple-minded statement. Perhaps it is. But it illustrates why it is so important to be clear what molarity is. It is a clearly defined relationship, and one that is very useful.

C. Making “molar” solutions

The key to making solutions that are described in molarity is to understand the term. The term molarity tells you what to do.

The following example describes how to make a “molar” solution, and how to calculate the amount of solute needed.

Example

Wanted: 0.25 L of a 3.0 M solution of NaCl.

$$0.25\ \cancel{\text{L}} \times \frac{3.0\ \text{mol}}{\cancel{\text{L}}} = 0.75\ \text{mol}$$

The calculation shows that we need 0.75 mol of NaCl. We have converted the amount in L to an amount in mol, using the molarity as a conversion factor. The unit molarity is written as mol/L in the problem, so we can see what cancels and what remains.

If we want the answer in grams…

$$0.75\ \cancel{\text{mol}} \times \frac{58.44\ \text{g}}{\cancel{\text{mol}}} = 44\ \text{g}$$

So we need 44 g NaCl. Add that to an empty measuring container, then add enough water to reach the desired volume of solution, which is 0.25 L (= 250 mL).

The two steps above are easily combined into one set-up. Let’s re-state the question: How many grams of NaCl do we need to make 0.25 L of a 3.0 M solution?

$$0.25\ \cancel{\text{L}} \times \frac{3.0\ \cancel{\text{mol}}}{\cancel{\text{L}}} \times \frac{58.44\ \text{g}}{\cancel{\text{mol}}} = 44\ \text{g}$$

Combining the two steps lets you see that the whole problem is going to work out (because the units work) before investing in any calculations. (It also avoids possible accumulation of rounding errors by writing down intermediate results.) I encourage combining steps such as here, and calculating only the desired final result. But, regardless of your specific approach, show clear work; show what you did do.

How do you know what order to write the three terms? One important part of the answer is that it doesn't matter. They get multiplied together, and you get the same result regardless of the order. However, the order reflects your thoughts about organizing the problem. Although no particular order is "correct", some are more logical. A good guide is to start by writing the given information. In this case, that includes the volume and the concentration. As you write these two givens, you begin to see a relationship between them. And then you see that you need the molar mass, to give the desired grams. (In this particular case, I find it helpful to think of the problem as a conversion from volume to mass; that perspective leads me to start with the given volume, then use the unit path volume → mole → mass.) As you are thinking through these steps, and writing parts of the problem, watch… Are the units you want to cancel canceling? Is the unit you want in the answer coming out -- in the numerator? If not, change something, try again.

The preceding paragraph probably doesn't make particularly good reading. But solving a problem by dimensional analysis is something of a trial and error process. What's nice about using dimensional analysis is that you do not need to envision the entire solution before starting. You can try something, and see whether it works. Maybe you need to include one more term, or maybe you need to turn a factor upside down from the way you first wrote it. Whatever, the solution takes shape as you try combining the factors in various ways. That's why we say dimensional analysis helps guide you to solve problems that you don't quite know how to solve.

Perspective. Molarity is a small extension from previous topics. You know how to interconvert g and moles; that includes calculating molar masses. And you know how to use dimensional analysis to let the units guide you through a problem. The only new part is knowing what molarity is, and the nice thing is that molarity is conveniently described as a combination of familiar units: mol/L. Use that definition, and your background with units -- with moles in particular -- and you will be able to do molarity problems.

Pitfall. Be careful with the units and their abbreviations. A "mole" is an amount of chemical; the abbreviation is "mol". "Molarity" is a unit of concentration, which means "moles solute/L solution"; the abbreviation is M, or mol/L when expanded. Mixing these up can make a mess of problems.

> [A lower case m has nothing to do with either (but means "meter"). There is a concentration unit that is abbreviated with an italicized *m* (Sect E, below). And of course the prefix m means milli- (mm = millimeter; the two m's mean different things). The point of all this: careful!]

Problems

Describe how to make the following solutions. Calculate the amount of solute needed, and briefly describe the steps involved in making the solution.

1. 2.00 L of 3.50 M potassium bromide, KBr.
2. 0.250 L of 2.00 M sodium nitrate, $NaNO_3$.

At this point, let's assume that you know the procedure for making the solution. For the following problems, calculate the mass of solute needed.

3. 0.500 L of 0.100 M magnesium chloride, $MgCl_2$.
4. 500 mL of 4.00 M sodium hydrogen carbonate, $NaHCO_3$.
5. 100 mL of a 10.0 M solution of lithium chloride, LiCl.
6. 5.0 L of 4.0 M magnesium sulfate, $MgSO_4$.

* 7. How much solute would you need to make the previous solution if the only magnesium sulfate available were the heptahydrate (common Epsom salts)?
* 8. 100 mL of a 10.0 mM solution of ATP (adenosine triphosphate). The available form is the dipotassium salt, $C_{10}H_{14}N_5O_{13}P_3K_2$.
* 9. How much glucose ($C_6H_{12}O_6$) is in 200 mL of a 0.300 M solution?
10. 8.0 M urea is used to denature proteins. How would you make 25 mL of this solution? (Urea is NH_2CONH_2.)
* 11. How would you make 1.00 L of a solution which is 3.00 M NaCl and 0.300 M sodium citrate, $Na_3C_6H_5O_7$?
12. Continuing… What would you change in your previous answer if the sodium citrate was available only as the dihydrate?
* 13. Given a 1.0 M solution of sodium sulfate, Na_2SO_4, what is the concentration of sodium ions?

D. Using "molar" solutions

Most problems above were phrased in terms of finding out how much solute we need to make a certain volume of solution. These problems are equivalent to "How much solute is in a given volume of solution?" (as in #9). That is, they are volume → amount problems. Another common molarity question is: What volume of a given solution do we need in order to get a certain amount of solute? Of course, "amount" may mean number of moles or number of grams. If you are careful to follow the units, these amount → volume problems are just a variation of the above.

Example

Given a 2.50 M solution of potassium sulfate, K_2SO_4… what volume do we need in order to get 0.545 mol of K_2SO_4?

Given: an amount, in moles; molarity (mol/L). Want: volume (L). It’s helpful to start the set-up with the given amount. That is, we convert the given amount in mol to the wanted amount in L.

$$0.545\ \cancel{\text{mol}} \times \frac{\text{L}}{2.50\ \cancel{\text{mol}}} = 0.218\ \text{L}\ (= 218\ \text{mL})$$

As an alternative, the problem might have been stated in terms of grams:

Given a 2.50 M solution of potassium sulfate, K_2SO_4… what volume do we need in order to get 95.0 g of K_2SO_4?

A logical approach would be to convert the given amount in g to moles (using the molar mass). In this case, you get 0.545 mol. You then convert moles to volume -- and this is the preceding example. Of course, you can combine these steps into one set-up:

Given: an amount, in grams; molarity (mol/L); we also know the molar mass (174.27 g/mol). Want: volume (L). Start the set-up with the given amount. That is, convert the given amount in g to the wanted amount in L.

$$95.0\ \cancel{\text{g}} \times \frac{1\ \cancel{\text{mol}}}{174.27\ \cancel{\text{g}}} \times \frac{\text{L}}{2.5\ \cancel{\text{mol}}} = 0.218\ \text{L}\ (= 218\ \text{mL})$$

Thus in general, we see that molarity provides a conversion between “amount” and volume of solution. Most directly, amount is in moles (M = mol/L), but moles and grams are easily interchanged, as you know from preceding work.

Problems

14. How much of a 2.0 M solution do you need to get 8.0 moles of hydrochloric acid, HCl?
15. How much of a 0.50 M solution do you need to get 35 g of potassium nitrate, KNO_3?
16. You have a 0.15 M solution of iron(II) chloride, $FeCl_2$. What volume of this do you need to get 100 mg of the salt?
17. You have a 10 mM solution of ATP. How much of this do you need to get 1.0 millimoles of ATP?
* 18. Continuing from previous question… How much (in mL) do you need to get 10 µmol of ATP?
19. Given a 2.00 M solution of glucose, how much do you need to get 12.5 kg of the solute? (See #9.)
20. How would you get 2.5 g of lithium perchlorate, $LiClO_4$, if you have a 0.20 M solution.
* 21. Given a 3.00 M solution of sodium chloride, NaCl, what is the concentration in g solute/L solution?

E. Other mole-based concentration units [optional]

Normality

Normality (abbreviated N) is an older unit, which is no longer accepted as an official unit. Nevertheless, you may see it, and it is even a logical and helpful unit. It is most commonly used for acids and bases, which we will talk about later in the course; N is especially convenient in titrations. But the logic of normality is illustrated by problem #13, above. The solution contains 2 moles of Na^+ ion per liter. From that information, we can't tell whether the solution is 2 M NaCl or 1 M Na_2SO_4. The term normality was introduced to refer to the ion concentration, without specifying (or even knowing) what the ion came from.

Normality is very much like molarity: moles per liter of solution. In fact, the reason N is no longer officially accepted is that it is so much like M that it isn't really needed. A little more about N later, in Strong Acids.

Molality

Abbreviated with an italicized lower case *m*. Molality is moles solute per kilogram of solvent. Note that the denominator not only is in mass, but mass of solvent, not solution.

F. Answers

(Relevant molar mass, in g/mol, is in parentheses.)

Section C

1. 833 g (119.00). Weigh out 833 g of KBr; add water until total volume is 2.00 L.
2. 42.5 g (85.00). Weigh out 42.5 g of the solute; add water until total volume is the desired amount.
3. 4.76 g (95.21)
4. 16.8 g (84.01)
5. 42.4 g (42.39)
6. 2.4 kg (120.38)
7. 4.9 kg (246.49) [Conservative approach… think about a conversion factor between moles of $MgSO_4$ (what you want) and moles of $MgSO_4 \cdot 7H_2O$ (what you have).]
8. 0.583 g (583.37)

9. 10.8 g (180.16)
10. 12 g (60.06)
11. 175 g NaCl (58.44); 77.4 g sodium citrate (258.07). Weigh both solutes, add water until total volume is 1.00 L. [The solution described here, adjusted to pH=7.0, is a 20-fold concentrate of a common lab solution called "SSC" ("standard saline citrate").]
12. Use 88.2 g of $Na_3C_6H_5O_7 \cdot 2H_2O$ (294.10).
13. 2.0 M (Each mole of sodium sulfate contains two moles of sodium ions: $Na_2SO_4 \rightarrow 2\ Na^+ + SO_4^{2-}$.)

Section D

14. 4.0 L
15. 0.69 L (101.11)
16. 5.3 mL (126.75)
17. 0.10 L
18. 1.0 mL
19. 34.7 L (180.16)
20. 0.12 L (106.39)
21. 175 g/L (58.44)

801/molar
9/1/02