# Making Assumptions Explicit: How the Law of Conservation of Matter Can Explain Empirical Formula Problems

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# Making Assumptions Explicit: How the Law of Conservation of Matter Can Explain Empirical Formula Problems

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I know no other law found in the introductory chemistry curriculum that is so undervalued than the law of conservation of matter. While there are many correct ways to express this law, many textbook authors refer to the conservation of the number or mass of atoms or elements when writing about this topic: "atoms are neither created nor destroyed during any chemical reaction" (*1*) or "when two or more elements react to produce a compound, the total mass of the compound is the same as the sum of masses of the individual elements" (*2*).

One can speculate on why the law of conservation neither gets much emphasis in chemistry lectures and textbooks nor drives activities in the laboratory. For example, it might be because the arithmetic algorithm of counting atoms that the law is based upon is mathematically trivial, or that the notion that matter cannot be created or destroyed but only transformed is discussed adequately in the high school curriculum. It could also be because the theme of conservation is generalizable and echoed in other science courses where students will receive exposure. Whatever the reason, I contend that using the law of conservation of matter could provide the rationale behind many of the steps that students use to solve empirical formula problems. While other authors have discussed the law of conservation of matter in the context of laboratory experiments (*3*), demonstrations (*4, 5*), and the relationship of mass to energy (*6*), none have adequately described how this law provides a theoretical foundation for empirical formula problems that introductory students encounter.

If one examines a typical empirical formula problem that students are assigned (*7, 8*), it will be evident that a series of steps are needed to find the ratio of atoms within an unknown compound (left side of Table 1). While all these steps might not have to be solved by the student (many might be given), they do represent a method that many textbooks and lab manuals use to solve such a problem (*9, 10*). The right side of Table 1 describes how conservation is related to each step the student follows to solve an empirical formula problem. When this table is created in the classroom, it is assumed that students have an understanding of atoms and molecules, the mole, atomic weight, the conversion of grams to moles, and of course conservation on both qualitative and quantitative levels.

To elucidate the connection between the right and left sides of Table 1, let's use a laboratory example, namely the synthesis of zinc iodide from its elements, zinc and iodine (*11*). This synthesis involves the mixing of granular zinc and iodine crystals in the presence of water until a colorless solution is produced; with the evaporation of the water a white solid of zinc iodide is formed. The identity of this compound is found qualitatively or given to the students. At this second step in the table, it is assumed or concluded that the product contains the atoms of the reactants that underwent chemical transformation; in other words, the identity of the reacting atoms is conserved as the product.

In the third step, the masses of the two reactants that undergo chemical change as well as the mass of the product can be measured. A comparison of these two values within experimental error demonstrates that mass is conserved through a chemical reaction. If one of the reactants cannot be easily measured, then the conservation of mass is used to determine the mass of the unmeasurable reactant.

The conversion of grams of the elements in the compound to moles using the atomic weights (step 4) brings up the connection between the atomic and macroscopic levels. The atomic mass written under each element in the periodic table refers to the relative mass of one atom of that element

**Table 1. The Role of Conservation within a Typical Empirical Formula Problem**

| Method<br>*Procedural steps to determine the empirical formula of an unknown compound* | Theory<br>*Conservation assumptions associated with procedural steps* |
|---|---|
| 1. The identity of the reactants must be given. | — |
| 2. Determine the identity of the product in question. | Atoms of reactants are conserved in the product. |
| 3. Determine the mass of the product and the mass of the elements within the product. | Conservation of mass is usually used to find the mass of one species that cannot be directly measured or it is used to compare mass of reacting species with mass of product. |
| 4. Convert the mass of elements in the product to moles. | Using atomic weights in the periodic table assumes that mass is conserved from one atom to a group of atoms. |
| 5. Convert the number of moles to integers. | Assume matter consists of atoms. |
| 6. Write the integers as subscripts in the product. | Conservation of moles is maintained from reactants to products since the mole ratio of atoms that initially react is equal to the mole ratio of atoms in the product's chemical formula. |

expressed in amu as well as the relative mass of one mole of that element expressed in grams. The premise that connects the atomic and macroscopic levels is simply that the mass of an atom is constant. Therefore if one atom of an element is twice as heavy as an atom of a different element, then 1 mole of atoms of the first element is twice as heavy as 1 mole of the other atoms. The use of the atomic weights with its inherent relationship between the macro and atomic levels rests on the idea that the mass of an atom is conserved.

In steps 5 and 6, the moles of zinc and elemental iodine in the compound of zinc iodide are expressed as integers and then written as subscripts in the product. This is done by dividing the mole values of the elements in the compound by the smallest mole value. These two steps allow the subscripts to represent the mole ratio of the elements that make up the product. Changing the mole ratio changes the chemical and physical properties of the reactants. The mole ratio of elements in the compound is equal to the moles of atoms that initially react. Therefore, conservation of moles is maintained from reactants to products. The ratio of these subscript values is proportionally changed from macroscopic values in terms of moles to a value that reflects the atomic level. In other words, non-integer mole values are changed to integer values corresponding to atoms, such as seen in the zinc iodide product, $ZnI_2$. This change is in keeping, not with conservation, but with atomic theory. Because matter is particulate rather than continuous, atoms combine as whole units, not as fractional parts of a unit.

## Infusing Conservation into Lessons Involving Empirical Formula Problems

There are a number of ways of making the chemical assumptions that underpin the methods we use to solve empirical formula problems explicit to our students. In my own classes, students are given an incomplete version of Table 1 that has only the procedural steps written out. Working in groups, students have to provide the assumptions that correspond to the steps. While this approach has not been formally evaluated, the class discussion does allow students to articulate their understanding as well as misconceptions of theoretical constructs.

References to the history of chemistry can also be used, especially Lavoisier's quantitative work with gases. For example, I quote Lavoisier's *Traité Élémentaire de Chimie* to my class (*12*):

> We must lay it down as an incontestable axiom, that in all the operations of art and nature, nothing is created; an equal quantity of matter exists both before and after the experiment. …Upon this principle, the whole art of performing chemical experiments depends.

Another way of emphasizing the importance of conservation is simply to have students perform a laboratory activity on this subject. Questions concerning conservation placed throughout subsequent activities such as an empirical formula activity could help students relate new chemical reactions to the conservation principles as discussed in this paper.

The language in which we describe chemistry problems can also be a way to articulate some of the assumptions underlying these problems. By infusing a "conservation" vocabulary into lessons, a direct association can be made to the steps involved in solving stoichiometry problems. For example, conservation vocabulary can be infused into lessons by asking students "to conserve a chemical equation" instead of "to balance a chemical equation". The important role of conservation is underscored by Baker and Piburn in their textbook for science teachers where they write (*13*):

> Success with stoichiometry critically depends on the assumption of equality of the two sides of a chemical equation. Unfortunately, many people do not see the necessity to conserve quantity when thinking of chemical transformations.

## Limiting and Excess Reactant Problems

Calculating the amount of product from the identification of limiting and excess reactants is dependent on first writing a balanced chemical equation. Knowing the empirical formula of the product allows one to balance the equation with coefficients. Manipulating coefficients reiterates the observation that the number of atoms of each reactant is maintained as they undergo chemical change to products. Simply put, the number of atoms/elements on the reactant side must equal the number of atoms/elements on the product side. The coefficients represent the amount in a chemical recipe when all reactants are fully transformed to a specified amount of products. They are usually expressed as integers, but sometimes as fractions.

After the balanced chemical equation is completed, additional steps can be discussed in terms of conservation. For example, the mass of the product can be theoretically calculated from the limiting reactant. In my estimation, this is the most difficult aspect of stoichiometry—where a student must identify the limiting and excess reactants. So how does conservation support these difficult steps? Support is levied in two ways. First, if we view this general type of stoichiometry problem as an extension of the prototypical empirical formula problem, then students can realize that the conservation principles accompany and theoretically support these additional methods. This is not unreasonable, since finding out how much of a product can theoretically be produced assumes that the identity and composition of the product are known. The second manner in which conservation relates to stoichiometry problems that ask for the mass of a product concerns the coefficients of the balanced equation. Maintaining the coefficient ratio of reactants to product in the calculations involving proportions or dimensional analysis is one of the most important steps when determining limiting and excess reactants. This is because the coefficients dictate the stoichiometry of the reaction. Coefficients as already stated are predicated on the conservation of atoms during chemical change.

## Conclusion

That the conservation of matter is mathematically trivial should not detract from its importance in understanding empirical formula problems. Utilizing the law of conservation should not add to the complexity; rather, it should promote understanding by providing the rationale for operations used to solve empirical formula problems. This is an argument for linking theory to method. We don't want students who can simply go through a series of steps and arrive at an answer without knowing why these steps can be performed, what assumptions they involve, and how they relate to other chemical concepts. Practically all chemistry textbooks in print emphasize the connection between the writing of coefficients and the conservation of matter, but none that I know of connects the methods of finding the empirical formula to conservation principles. Perhaps it is time to make the connection and in so doing help students to make meaning of the steps they perform when problem solving.

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