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Higuchi, Shinnosuke

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Essay

Bridging the Gap: Re-envisioning the Introduction of the Mole Concept in Secondary School Chemistry

HIGUCHI Shinnosuke

This essay explores a novel approach to introducing the concept of the mole in secondary school chemistry, addressing the common difficulty students have with this abstract concept. The author argues that the traditional introduction, which often follows atomic and molecular weights, fails to capitalize on students' prior knowledge of chemical reaction equations and their coefficients. This approach, called "cognitive drift", uses the easily understood concept of mass number to build a foundation for understanding relative molecular mass. Starting with the coefficients of a chemical equation—using methane combustion as an example, the author guides students to calculate relative mass ratios based on the sum of proton and neutron numbers. This "relative mass" is then related to macroscopic mass by defining a large number *N* of molecules whose combined mass in grams is equal to their relative mass. This *N* is later shown to be the Avogadro constant. The author posits that this method, while not initially perfectly consistent with the formal definition of the mole, allows for a more intuitive understanding and can be refined later, thus reducing the risk of "rational misconception". This paper concludes by advocating further research to validate this approach and explore its broader applicability.

Key words: amount of substance, mole, Basic Chemistry, courses of study, cognitive drift

1. Introduction

Introducing the concept of the mole is one of the most important yet challenging topics in secondary school chemistry (e.g. Yin & Ochs, 2001; Bindel, 2021). In Japan, many students are *not* introduced to the amount of substance, resulting in the mass production of chemistry haters. In particular, the Basic Chemistry course in science, which was announced in 2010 and implemented in 2013 (MEXT, 2010), has two credits, and the content has been "refined" by taking up two-thirds of the class time compared to Chemistry I, which previously took up three credits (MEXT, 1999). While considering the link between lower and upper secondary school, the course consists of more basic content and is considered a subject for learning basic concepts and methods of inquiry through observation and experimentation (MEXT, 2010). Later, from 2023, it became a subject based on the current courses of study, but the subject name is the same and the spirit of the subject has been inherited.

The subject of Basic Chemistry consists of three main parts: "Chemistry and Human Life", "Composition of Substance", and "Chemical Changes of Substrate and its Utilization". Among them, the amount of substance (unit: mol) is introduced at the beginning of "Chemical changes of substance and its utilization" (MEXT, 2018; MEXT, 2019), after introducing the amount of substance, atomic weight, molecular weight, formula weight, molar mass, etc. are treated, and the quantitative relationships in chemical reactions, as well as acids and bases and oxidation-reduction reactions, are studied. In most upper secondary schools, Basic Chemistry is usually taken in the first year (10th grade).

The courses of study are the legal standards for school education in Japan, and the approved textbooks are the teaching materials that conform to the courses of study. Textbook companies must prepare textbooks in accordance with the courses of study and pass certification by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). Schools select appropriate textbooks from the approved textbooks and use them in their classes. The courses of study provide a framework for educational content, and textbooks play the role of developing that content in concrete terms.

In this paper, I first point out the discrepancies between the courses of study and textbook descriptions regarding the introduction of the amount of substance in the subject Basic Chemistry, and consider the problems and solutions. Then, I propose a more appropriate way to introduce the amount of substance, taking into account students' understanding and motivation to learn, and describe its validity based on the concept of "cognitive drift". The teaching plan for the actual implementation of this lesson will be discussed in another paper (Higuchi, 2025).

2. The Flow of Amount of Substance Introduction in Textbooks and What Students Already Know

According to the current courses of study (MEXT, 2018), for the amount of substance and its unit, the 'mol,' should be introduced, and its relationship to atomic, molecular, and formula weights, as well as its relationship to molar mass, should be discussed. However, an analysis of the textbooks in use shows that they do not "introduce the amount of substance and its unit, the 'mol'", but instead introduce "atomic, molecular, and formula quantities" first, and then introduce the amount of substance in a new section. This is a feature common to all 12 textbooks produced by 5 companies (Aihara et al., 2022; Imoto et al., 2022a, b; Tatsumi et al., 2022a, b, c; Kinoshita et al., 2022; Mutai et al., 2022; Ogawa et al., 2022a, b; Yamauchi et al., 2022a, b) based on the Courses of Study (MEXT, 2018). In addition, in the science area of lower secondary school science, students learn about simple chemical reaction formulas (MEXT, 2018). In other words, they are supposed to deal with substances that are actually dealt with in observations, experiments, etc., such as the bonding of metals with oxygen, or chemical changes involving a small number of atoms that make up the substance. Notably, students may also be made aware that representing chemical changes in terms of chemical reaction equations is effective in capturing the types and numbers of atoms and molecules involved in chemical changes (MEXT, 2018), symbolized by the fact that the coefficients of chemical reaction equations are already related to the number of elements involved in the reaction. However, according to Yamada et al. (2021), students in junior high schools are not even required to understand the meaning of the coefficients of chemical reaction equations. In reality, however, lower secondary school students should be somewhat aware of the meaning of the coefficients attached to chemical reaction formulas, even if they do not fully understand them. This is because even in textbooks, illustrations of molecules are written under chemical reaction formulas, and the number of molecules is the same as the coefficient attached to the corresponding

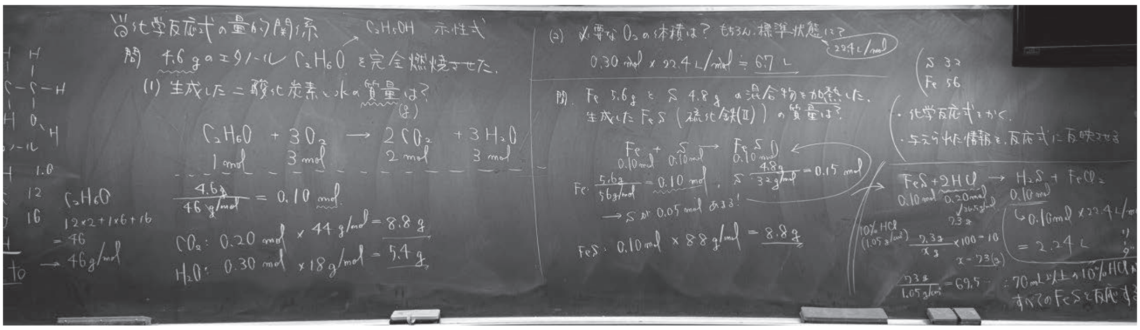

Figure 1. Example of a board with the equivalent lesson content of quantitative relationships in chemical reaction formulas.

chemical species (e.g., Ohya et al., 2021). Teachers certainly need to teach in this way in middle school classrooms. However, this point needs to be studied in the future to determine the actual situation
and what it should be.

The first “benefit” that comes with the introduction of amount of substance is the ability to look at chemical reaction equations to estimate the amount of chemical species that will react, and to deal with quantitative relationships for chemical reactions that over or under react. In many textbooks, this is introduced under the title “quantitative relationships in chemical reaction formulas” (Figure 1). The problem is that the achievement of being able to derive quantitative relationships from chemical reaction formulas is, so to speak, the conclusion of the unit, and the fruits of the unit can only be found after a series of training in atomic weight, amount of substance, concentration of solution, etc. In the meantime, students need to be patient, to say the least, with the history of unknowns—i.e., why think about atomic weight, amount of substance, and concentration of solutions?—the approximate class time estimated from the practical report by Higuchi (2025) is at least 8 class
hours. If the class meets twice a week for two units, students would have to wait a month after finishing the previous unit—chemical bonding. Then, even if they did not do anything wrong, they would contain errors—rational misconceptualization (after Higuchi, 2024). In this sense, it would be better to use the “tastiest part” of the relationship, the quantitative relationship derived by the chemical reaction equation, as a “prize” rather than as an introduction to the amount of substance. This is different from Sugimoto (2017), who points out that many teachers emphasize convenience and use its “usefulness” to introduce amount of substances. Rather, they use it because using the quantitative relationships of chemical reactions can provide students with more intrinsic meaning.

3. A Proposed Method of Introducing Material Quantities Considering Learning Motivation: Introduction Based on Mass Numbers

Introducing amount of substance based on mass number is a very natural approach for beginning students, but may not be for many teachers. However, this method should be the best way to weave a story while using known content, staying close to students' readiness, and landing in the right place. For more information on classroom practice, see Higuchi (2025).

(1) What we can learn from the chemical reaction equation for the complete combustion of methane.

First, we express the complete combustion of methane as a chemical reaction equation.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (1)$$

As mentioned earlier, students are already familiar with the meaning of the coefficients in a chemical equation. One molecule of methane reacts with two molecules of oxygen to form one molecule of carbon dioxide and two molecules of water. If necessary, it is a good idea to present students with molecular models that they may have used in the previous unit on chemical bonding to aid visual understanding.

Let us assume that we are actually conducting an experiment in which methane is burned. Normally, we deal with objects in terms of recognizable units such as mass (g) and volume (L). The problem is that each molecule has a much smaller scale. On the other hand, when it comes to mass, we already know what “mass-like” things are. This is the mass number, which is the total number of protons and neutrons. When students learn about the building blocks of the atom, they learn that almost all of the weight of the atom is in the nucleus, which is made up of protons and neutrons, because protons and neutrons have about the same mass, and electrons have only 1/1840th of that mass. Students are also familiar with notational conventions, such as the number of protons, or element number, being written in the lower left corner of the element symbol, and the sum of the number of protons and neutrons, or mass number, being written in the upper left corner of the element symbol.

To consider quantitative relationships in chemical reactions, we try to determine the “relative mass ratio” of each molecule by summing the mass number of each of the four types of molecules that appear in equation (1). This is a very natural idea since, as noted above, students have learned that the proton and neutron are responsible for almost all of the mass of a molecule—and that their masses are almost equal. Conveniently, the elements used in equation (1) are more than 99% occupied by a single stable isotope, so there is not much inconvenience with this operation for the time being. The case of multiple stable isotopes with high abundances can be considered, then cognitive drift will be discussed later.

Note that since the coefficients represent the ratio of the number of particles, the sum of the relative masses on the left and right sides is both 80, and the law of conservation of mass holds.

(2) Relative Mass Values Based on the Mass Number and Their Relation to Mass When Expressed in the Unit g

What we have considered so far are only relative masses, focusing on protons and neutrons, and assuming comparisons between single molecules. Here we consider that no matter how small the masses may be, if we collect very large quantities of them, they will be on a scale that we can recognize. That is, why not define N so that, for example, N molecules of methane (with a relative mass of 16) are collected to have a mass of 16 g? This manipulation is somewhat inductive, but it is still on a scale that we can imagine as a simple sense, and importantly, we are motivated to use the relative mass values of the molecules that we have already obtained as they are, so that we are not wasting—and incomprehensible to the student—manipulation. Then we are ready to express the number of other chemical species in the chemical reaction equation above using N. Referring to equation (1), we see that if we collect $2N$, N, and $2N$ units of oxygen, carbon dioxide, and water, respectively, we get 64 g, 44 g, and 36 g. Again, we check that the sum of the masses on both sides of equation (1) is 80 g, and that the law of conservation of mass holds.

(3) Introduction of the Avogadro constant N_A and amount of substance and calculation of number of particles

With a good definition of N, we could use the “relative mass” of the molecule, calculated with the structure of the atom in mind, to represent a very ordinary recognizable mass of a dozen or so grams.

With a good definition of N, we could use the “relative mass” of the molecule, which we calculated with the atomic structure in mind, to express a very ordinary recognizable mass of a dozen or so grams. We introduce this N as the Avogadro constant (unit/mol), write down its value—an integer with 24 digits, where the last 15 digits are zeros—and tell them that we will use 6.0×10^{23} for the usual calculation. Introducing the Avogadro constant here, based on the “relative mass” obtained in the procedure in the previous section, may be inconsistent with its definition. However, except for the old definition used before 2019, the discrepancy is not as serious as it could be, since the Avogadro constant has actually been the defined value since May 2019.

In the next lesson, students will be introduced to the relative masses of atoms and molecular weights, which take into account their abundances. Later in the lesson, I will introduce the history of the debate about the Avogadro constant and the amount of substance (unit mol). During this discussion, the students’ perception of the amount of substance and the Avogadro constant should be slightly modified and they should understand the relative mass of an atom and the atomic, molecular and formula quantities based on it in the same sense as it is generally accepted—in a simple and essential manner.

4. Conclusion and Future Issues

I would like to call the process described in this essay, in which a student’s preconceptions that are not based on an accurate understanding of a phenomenon or definition are then adjusted through further learning, "cognitive drift", as the term is used in educational contexts. The idea is similar to conceptual change (e.g. Inagaki, 2001; Thagard and Toombs, 2005) in that subsequent learning changes the concept one has, but the difference is that cognitive drift does not assume cognitive growth and the change occurs in a relatively short period of time, from a few minutes to a few weeks. It is also similar to conceptual refinement, but differs in that it focuses on cognitive misalignment and does not consider the goodness or badness of the direction of change. By being aware of cognitive drift, teachers can consider more flexible teaching methods and avoid "rational misconceptualization", in which false perceptions based on rationally derived knowledge are reinforced. That is, the introduction of the amount of substance by mass number stacking—counting the number of protons and neutrons in a molecule—proposed in this essay does not provide an accurate understanding based on definitions. Any misunderstandings that may arise will not be a problem if they are corrected later.

Is such a method generally applicable? Further educational practice and verification of this method is desirable.

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Additional information

Correspondence and requests for materials should be addressed to the author (higcheese@schools.kobe-u.ac.jp).