Some Suggestions for the Teaching of the Mole Concept

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Abstract

The learning of formal operational concepts is a complex and difficult task for many students. One such example is the mole concept where due to its abstract, theoretical nature, is recognised as one of the most difficult topics to teach and learn within the chemistry curriculum. The purpose of this paper is to provide some insight into the many studies which explored difficulties or misconceptions in the learning and use of the mole concept. Instructional approaches that facilitate meaningful conceptual understanding of the mole concept will also be discussed.

Introduction

There is little need to tell most science educators that mole concept is a difficult topic of the chemistry curriculum to teach effectively. A growing body of research has shown that students have problems in understanding and using mole concept in chemical problems of quantitative and semiquantitative nature (Gabel & Sherwood, 1984; Herron & Greenbowe, 1986; Krishnan & Howe, 1994; Staver & Lumpe, 1995).

The difficulties that these students experience are usually the result of their lack of formal operational ability and prerequisite concepts as well as an inadequate level of conceptual understanding. Abstractness of declarative knowledge of the mole concept is also thought to have an influence on learning difficulty. Often, students have to be able to transfer understanding between the macro and atomic/molecular levels in solving quantitative problems. Indeed, theoretical concepts are inherently more difficult to learn than empirical ones.

Purpose

The authors' purpose in this paper is to report some studies which have examined difficulties or misconceptions for the learning and use of the mole concept in the areas of (a) the defining attributes of the mole itself and the cognitive requirements for comprehending the definitions used, (b) the functional nature of students' knowledge, and (c) the context and setting within which the mole is developed.

Implications for teaching the mole concept, which emerge as a result of the studies reviewed, will also be discussed.

The Mole

The mole is the Systeme International (SI) unit of measurement for "amount of substance". As defined officially by the SI, the mole is the "the amount of substance that contains as many entities as there are in exactly 0.012 kg of carbon-12 (12g of C-12 atoms)" (cited in Kotz & Purcell, 1987, pp. I-21). The International Union of Pure and Applied Chemistry (IUPAC) and the International Federation of Clinical Chemistry (IFCC) accept the SI definition of the mole (Lehmann, Worth, & Zinder, 1988).

Considering this SI definition, the key particle is the isotope of carbon with a mass of 12 atomic mass units (amu). The mass ^{12}C is the reference standard of the system of relative masses for elements in the periodic table. Scientists have assigned a single atom of ^{12}C a mass of exactly 12 amu and have determined the mass (in amu) of all the elements in the periodic table relative to ^{12}C. As such, knowing the relative mass of another atom or molecule compared to ^{12}C is as good as knowing the actual mass since one mole of ^{12}C is exactly 12 grams of ^{12}C.

Indeed, the numerical value (12) of the mass of a single atom of ^{12}C in atomic mass units and the mass of a mole of ^{12}C atoms in grams, its molar mass, is identical by design. So, if the ratio of masses of two samples of any two substances is the same as the ratio of the masses of their individual entities, then the two samples contain an identical number of entities. Entity refers to a range of specified microscopic particles such as electrons, protons, neutrons, ions, atoms, molecules and others.

Thus, understanding that a mole of any substance always contains the same number of entities and that the amount of a substance is proportional to the number of entities of that substance is important. The magnitude of this number is an empirically determined constant called Avogadro's number (6×10^{23} mol^{-1}).

However, unlike other basic units of measurement such as the meter, cubic centimeter or gram, the mole is more of that of a concept devised by the scientists where masses of chemical substances can be considered in terms of the relative number of particles present thereby aiding in chemical calculations. Indeed, the mole can be placed as an example of a theoretical concept (Staver & Lumpe, 1995; Larson, 1997), based upon the definition proposed by Lawson, Abraham and Renner (1989):"a pattern of regularity named by a term" stemming from perceived relations of imperceptible attributes. As such, the theoretical abstract nature of the mole concept may pose teaching and learning difficulties.

Literature Review

The research studies reviewed in this section would show that students lack a strong conceptual understanding of the mole concept. This could be due to a number of factors inter-played such as the terminology itself; formal operational ability; learners' cognitive levels and conceptions; teachers' and textbooks instructional approaches.

The two most frequently used definitions of the mole are (1) in terms of C-12 (SI definition) and (2) as Avogadro's number, 6.02×10^{23} of particles. These defining attributes carry a theoretical standing according to Lawson et al. (1989). The mole as a theoretical concept can be said to stem from perceived relations but the attributes themselves are not perceptible. The purpose of theoretical concepts is to explain events that have no directly perceivable causes.

Consider the definition of the mole in terms of C-12 where term "entity" is used. Entity is a specific microscopic particle such as the atom, molecule or ion and none of these is directly perceivable. However, C-12 represents a specific isotope, another theoretical concept. For the next definition of the mole as Avogadro's number, it seems simply that one mole is 6.02×10^{23} of anything. But students may not be able to directly perceive this very large number 6.02×10^{23}. However, this definition can be viewed as a theoretical concept (Staver & Lumpe, 1995). The basis is that abduction is used extensively in the textbooks to link 6.02×10^{23} with a more familiar counting unit, for example, the dozen. Abduction or reasoning by analogy according to Lawson et al. (1989) has a central role in the formation of theoretical concepts. So, both definitions, then, are theoretical in nature. This may call for the learners to be reflective rather than intuitive thinkers to comprehend either definition.

Novick & Menis (1976) have obtained students' conceptions of the mole by administering a multiple-choice mole test and conducting interviews. One of the major erroneous conceptions held by the students is that 'a mole is a certain mass and not a certain number'. This probably stem from quantitative operations based on mass measurements. Another misconception is that 'a mole is a certain number of particles of gas' probably due exclusively to the Avogadro's hypothesis.

Cervellati et al.s' (1982) study using multiple-choice test to determine how secondary school students perceived the mole has found that students are not familiar with the mole as amount rather than mass. However, most students are familiar with the magnitude of Avogadro's number.

Gabel & Sherwood (1984) have examined analog counterparts for moles problems using sugar granules and oranges as the analogs. They have found that students' difficulties in solving molarity problems is probably due to use of the term 'mole' rather than their lack of understanding of volume, mass, and a collection of particles.

In a follow-up to this study, Friedel et al. (1990) have investigated the use of analogs for chemistry problem solving related to mole concept. The results have shown that although students receiving the analogue instructions involving oranges and dozens, are able to match a higher percentage of the chemistry problems with their analogues, the matching is lower than expected.

Chandran et al. (1987) have found that variables like formal reasoning ability and prior knowledge are significantly related to chemistry achievement, but that field dependence/independence and memory capacity are not significantly related. This is in line with Krajcik & Haney (1987) and Atwater & Alick (1990) findings that formal operational thinkers are more successful in solving mole-related chemistry problems. Larson (1997) have also found that students experiencing math anxiety and /or low proportional reasoning ability do have difficulty in understanding the mole concept.

De Jong (1990) study on the strategies that the students used in solving chemistry problems, using the written responses that students give to problems that are solved in cooperative groups as well as from interviews have found that students in The Netherlands generally fail to give coefficients in balanced chemical equations a molar interpretation.

Staver & Lumpe (1995) report that an inadequate conceptual understanding of these two definitions of the mole concept can lead to a specific misconception, namely, that the gram and the atomic mass unit are equivalent. In this study, students are asked to define the mole and to explain why one mole of any substance has a mass in grams that is numerically identical to the mass of a single unit (atom or molecule) in atomic mass units. For example, 1 molecule of NH_3 = 17.0 amu; 1 mole NH_3 = 17.0 grams.

It is found that a number of students define the mole either as Avogadro's number of particles or as the atomic or molecular mass of a substance in grams even though the SI definition of the mole has been introduced and explained. Although these facts are correct, it is insufficient to provide a proper explanation of the numerical identity between the atomic or molecular mass of a substance and its molar mass.

As such, with regard to the functional nature of students' knowledge, it seems that students make use of their conceptions of the mole to try to explain the numerical identity issue and to solve problems. For example, a student may try to focus on the ratio of moles to atomic mass units as a one-to-one ratio as he tries to define the mole. After which he applies this idea to the numerical identity issue and in so doing, arrives at the misconception that moles and atomic mass units are equal.

In more recent case study by Larson (1997) on the development of students' conceptions of the mole following a period of chemistry instruction has revealed five areas of concerns related to students' inability to construct fully meaningful understandings of the mole concept. They are: (a) inconsistency between the instructional approaches of the textbook and teacher, (b) confusing mole concept vocabulary, (c) students' math anxiety and proportional reasoning ability, (d) learners' cognitive levels, and (e) lack of practice in problem solving.

As for the instructional approaches, the textbook develops the mole concept in incremental steps where it is applied as a chemists' counting unit and tool for expanding the understanding of chemical formulas. The teacher instead uses an integrated strategy grounded in constructivist perspective ignoring the attempt of the textbook authors to develop the concept in logical steps. However, most students demonstrate that they do not understand the formula mass/gram mass relationship and that many have not learned that Avogadro's number represented the number of atoms or molecules in a mole of a substance. This is expected since construction of meanings is idiosyncratic and so the students would have different perceptions of the mole concept. Indeed, the combination of the textbook's structure of the mole concept with the teacher's integrated approach in a way creates a situation of "logical contradictions" and "illogical consequences" for the students.

The mole concept can be placed as a formal operational concept "whose meaning is derived through position within a postulatory-deductive system" (Janick, 1993). As such, students whose learning is best characterised as concrete and intuitive rather than abstract and reflective may have difficulty in understanding and applying the mole concept. In other words, the students' cognitive level (in Piagetian terms) may not be enough for acquisition of the mole concept.

With regards to practice in problem solving, Lazonby, Morris & Waddington (1985) have also found that the structure of questions can affect students' abilities to show understanding of the subject and that intensive practice will be essential in teaching the individual steps of problem solving. Indeed, practice is an important prerequisite to mastering the mathematical operations of the mole and in Larson's (1997) study it is discussed that "the transfer of responsibility for learning to students and the attendant lack of accountability measures in this class may have led to some students' withdrawal from the culture of learning in the classroom and subsequent failure to learn the mole concept."

As for the context for developing the mole concept, there are two aspects to it. (Staver & Lumpe, 1993) Basically, one is the use of familiar analogies such as "pair" or the "dozen". In the textbook, such analogies are used extensively with little or no discussion on its limitations. This may in turn lead to students to believe that the Avogadro's number 6.02×10^{23} to be a fixed number rather than an experimentally determined value. A number of textbooks, for example, present the picture that just as one dozen of water molecules means 12 water molecules, to a chemist one mole of water molecules means 6.02×10^{23} water molecules.

The second aspect is introducing the mole as a means of counting objects far too small to be counted directly. Most books mention the counting of particles by weighing. However, Staver & Lumpe (1993) argues that although, the intent is to provide an advanced organiser, the students' poor conceptual understanding, problems noted by Herron (1990) and Abraham (1990), may prevent them from using beneficial strategies, thereby hindering the value of the counting by weighing context for some students.

Implications for Teaching

The reviews of these research studies provide ground for two important messages in the teaching of the mole concept. First, the importance of pedagogical content knowledge cannot be ignored (Shulman, 1987). This is knowledge about the content that is derived from consideration of how best to teach it, the mole in this case. Second, the construction and acquisition of metacognitive awareness need to be promoted. This includes knowledge of cognition and regulation of cognition.

Pedagogical content knowledge is knowledge of (a) what makes in this case the mole easy or difficult to understand - including certain preconceptions for example, the particulate nature of matter, chemical formulas, and balancing equations; (b) those strategies most likely to be effective in orientating and reorganising students' understanding to eliminate their misconceptions; and (c) a range and variety of effective ways of representing the ideas included in the mole - analogies, illustrations, concrete examples, explanations, and demonstrations.

With this in mind, students need to be exposed to the following three understanding levels: (a) the macroscopic level, which deals with sensory/visible phenomena; (b) the submicroscopic level, which deals with particles and (c) the symbolic level, which represents the matter in terms of formulae and equations (Johnstone, 1991). At the macroscopic level, a concrete activity using jelly beans (Dominic, S., 1996) can be used to enable students to understand that chemists count particles by weighing. Also, a combined verbal-visual analogous demonstration using a mole of water, sugar, sulphur, salt, copper, lead and potassium dichromate can be used to show that although each sample contains 6.02×10^{23} particles, but the molar masses differ. Another concrete approach is to introduce the recipe for making fruit salad by mixing equal numbers of cherries and grapes relating it to molar mass and Avogadro's number (Felty, 1985).

Various analogies can be used to visualise the magnitude of Avogadro's number. For example, using (a) Length analogy: If 6.02×10^{23} hydrogen atoms were laid side by side, the total length would be long enough to encircle the Earth about a million times; (b) Mass analogy: The mass of 6.02×10^{23} shotput balls would be about equal to the mass of the Earth; (c) Volume analogy: The volume occupied by 6.02×10^{23} tennis balls would be about the size of the Earth.

At both the submicroscopic and symbolic levels, visual representations of particles in the form of diagrams and concrete activities using 'magnetic buttons' for particulate nature of matter and chemical reactions can also be used. This is to make the connection between the symbolic representation provided by equations and the submicroscopic interpretation chemists employ to consider what an equation represents at a molecular level (Laverty & McGarvey, 1991; Gabel, 1993).

Indeed, the correct terms and usage need to be stressed when explaining the process. Appropriate instructional strategies can be used to make the learning of Mole concept at a more concrete level, e.g. the Piagetian-based learning cycle by Schlenker & Perry (1983) as suggested by Goh & Chia (1987). One also needs to be aware of the social construction of science (social constructivism) where the teacher has a crucial role in helping students construct meaning close to that consensually agreed among scientists. This role involves carefully considered instruction, diagnosis and intervention (Driver et al., 1994).

Besides, the encouragement of metacognition (Brown, 1987; Flavell, 1987), reflective awareness (Driver, 1989) or self-regulatory skills (Schraw & Dennison, 1994) is equally important. Ample opportunities should be given to students to know about their own memory (declarative knowledge), their repertoire of heuristics and strategies (procedural knowledge) as well as when and why to use such knowledge (conditional knowledge).

For a start, teachers could spend some time to discuss the importance of metacognitive knowledge and regulation, including the unique role it plays in self-regulated learning (Schon, 1987) in the class. Then, teachers should try to make a concerted effort to model their own metacognition for their students (i.e., how they think about and monitor their performance). The more explicit this modelling, the more likely it is that students will develop metacognitive skills. Finally, teachers should also allot time for cooperative discussion and reflection, despite the many pressures from heavy curricula and academic performance demands. Strategies such as the use of concept maps and 'what if' questions could help to support sustained reflection.

Many anecdotal reports suggest that summary matrices like the strategy evaluation matrix (SEM) may be an effective way to increase metacognitive knowledge and subsequently, improve learning (Jonassen et al., 1993). A sample of a SEM is shown in Figure 1 including information about how to use several strategies, the conditions under which these strategy are most useful, and a brief rationale for why one might wish to use them. Basically, students are asked, either individually or in a group, to complete each row of the matrix over the course of the school year.

For example, the teacher can introduce the SEM during the first week of school informing students that they will focus on one new strategy each month, and should try to practise four more strategies throughout the year that can be included in the SEM. Each week students will be given time to reflect individually and as a group about strategy use.

Although, SEM can improve knowledge of cognition, it may not impact regulation. For this purpose, a regulatory checklist (RC) as shown in Figure 2 can be used to provide the heuristics for the facilitation of the regulation of cognition. RC comprises three main categories namely, planning, monitoring, and evaluating. The explicit prompts in this checklist will help the students to be more strategic, focus and systematic when solving problems (King, 1991).

In summary, teachers should attempt to attend to both subject matter as well as pedagogical content knowledge. Discourse related to students' conceptions, its identification and the appropriate intervention strategies need also to be emphasised. Ample opportunities for students to experience the mole concept at the macroscopic, submicroscopic and symbolic levels should be provided. Indeed, this would call for an interactive design that would blend systematic instruction, teacher and expert student modelling, reflection on the part of both the students and teachers, and cooperative group activities that allow students to share their knowledge about cognition.

Figure 1. A strategy evaluation matrix

Strategy	How to Use	When to Use	Why to Use
Skim	Search for headings, highlighted words, previews, summaries	Prior to reading an extended text	Provides conceptual overview, helps to focus one's attention
Slow down	Stop, read and think about information	When information seems especially important	Enhances focus of one's attention
Activate prior knowledge	Pause and think about what you already know. Ask what you don't know	Prior to reading or an unfamiliar task	Makes new information easier to learn and remember
Mental Integration	Relate main ideas. Use these to construct a theme or conclusion	When learning complex information or a deeper understanding is needed	Reduces memory load Promotes deeper level of understanding
Diagrams	Identify main ideas, connect them, list supporting details under main ideas, connect supporting details	When there is a lot of interrelated factual information	Helps identify main ideas, organise them into categories. Reduces memory load

Figure 2. A regulatory checklist

Planning
1. What is the nature of the task?
2. What is my goal?
3. What kind of information and strategies do I need?
4. How much time and resources will I need?

Monitoring
1. Do I have a clear understanding of what I am doing?
2. Does the task make sense?
3. Am I reaching my goals?
4. Do I need to make changes?

Evaluating
1. Have I reached my goal?
2. What worked?
3. What didn't work?
4. Would I do things differently next time?

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