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ABSTRACT

Due to its abstract, theoretical nature, the mole concept has been recognized as one of the most difficult topics to teach and learn within the chemistry curriculum. The purpose of this study was to chronicle the development of high school students' conceptions of the mole following a period of instruction in a chemistry class. This investigation is part of an ethnographic study of curriculum modulation that documents class activities through participant observation. An analysis of the chemistry textbook's presentation of the mole concept and a comparison to the teachers' instructional techniques are discussed. Students' understandings of the mole concept are examined in relation to the textbook presentation and teacher influences. The findings indicate that students may fail to construct meaningful understandings of the mole concept for the following reasons: (1) inconsistency between the instructional approaches of the textbook and teacher; 2) confusing mole concept vocabulary; (3) students' math anxiety and proportional reasoning ability; (4) learners' cognitive levels; and (5) lack of practice in problem solving. (Author/DDR)

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CONSTRUCTING UNDERSTANDINGS OF THE MOLE CONCEPT: INTERACTIONS OF CHEMISTRY TEXT, TEACHER AND LEARNERS

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CONSTRUCTING UNDERSTANDINGS OF THE MOLE CONCEPT: INTERACTIONS OF CHEMISTRY TEXT, TEACHER, AND LEARNERS

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The purpose of this 'case study of learning' was to chronicle the development of high school students' conceptions of the mole following a period of instruction in a chemistry class. As part of an ethnographic study of curriculum modulation, the investigation first documented class activities through participant observation. Next, the chemistry text's presentation of the mole concept was analyzed and compared to the teacher's instructional techniques. Finally, students' understandings of the mole concept were examined in relation to the text and teacher influences. Five areas of consideration were revealed by a general failure of students to construct meaningful understandings of the mole concept: (1) inconsistency between the instructional approaches of the textbook and teacher, (2) confusing mole concept vocabulary, (3) students' math anxiety and proportional reasoning ability, (4) learners' cognitive levels, and (5) lack of practice in problem solving.

Constructing Understandings of the Mole Concept:
Interactions of Chemistry Text, Teacher, and Learners

Objectives

Because of its abstract, theoretical nature, the mole concept has been recognized as one of the most difficult topics to teach and learn within the chemistry curriculum. The objective of this study was to trace the development of student understandings of the mole concept within a high school chemistry class. As part of a larger ethnographic study of curriculum modulation, this section's goals were to define and compare the intended curriculum of text and teacher, describe implementation and enactment in classroom interactions, and illustrate students' construction of conceptions of the mole in the learned curriculum.

Significance

High school chemistry has been a rich source of research on student learning "due to the greater importance of formal-operational concepts in the whole chemical knowledge and the fact that the process of learning them is more complex and difficult" (Janiuk, 1993, p. 828). Measurement of achievement has been the most common method for researching students' mastery of concepts. In addition, individual interviews to determine knowledge structures, often in combination with psychological examinations to assess cognitive levels, have been employed to more deeply define students' responses in the process of learning chemistry. This study proposes to describe the process of learning chemistry by broadening the focus to include contextual factors that influence learners' conceptions of the subject matter. The investigation concentrates on a specific topic - the mole concept - in a single classroom. In this way, a fine-grained analysis of teaching and learning can discolose elements of the chemistry education process which foster or hinder successful construction of scientifically acceptable understandings of the mole concept.

Theoretical Framework

The supporting structure of this study is the theory of curriculum modulation, which envisions the curriculum naturally changing shape and emphasis as it progresses from its intended form, through implementation by the teacher, to enactment in the classroom setting and subsequent learning by students. Each curriculum domain - intended, implemented, enacted and learned - intersects with the next to form a sequence in which instructional materials, teacher and students are major participants and determinants of the curriculum. Therefore, each classroom, as a unique blend of materials and individuals, produces a complex set of factors that influences learning.

Student learning in the science curriculum is viewed in terms of five major objectives - (1) skills such as manipulative, inquiry, and communicative; (2) concepts such as theoretical model and taxonomic category; (3) cognitive abilities like critical thinking, synthesis and evaluation; (4) understanding the nature of science; and (5) attitudes (Shulman and Tamir, 1973). Therefore, a comprehensive study of a chemistry curriculum modulation must consider all these aspects of the teaching-learning process.

As a theoretical concept, the mole concept is a challenging component of the chemistry curriculum. Tracing its development through the intended, implemented, enacted and learned curriculum allows the researcher to construct a case study of learning that highlights the role of all participants in the process and their influence upon the construction of knowledge.

Design and Procedures

An ethnographic methodology was chosen for this investigation. Data collection was accomplished primarily through participant observation in a high school chemistry class for an entire school year. Additional data sources included the researcher's personal journal, formal and informal interviews of the teacher Mr. London (a pseudonym), interviews of six students representing high, middle and low achievement levels in the class, and artifacts such as tests, labs, and student Learning Logs.

An American school on a United States military base overseas served as the setting. The enrollment of Victory High School was about 700 students in grades 7 through 12. Three chemistry classes with an average of 20 students each were taught daily. Most chemistry students were juniors concurrently enrolled in advanced mathematics. Mr. London, with sixteen years of experience teaching physics and physical science, volunteered for the study in which he would be teaching chemistry for the first time with a newly adopted curriculum. As a participant observer, I took part in daily activities with the class, recording copious field notes and working with student groups to complete assignments, conduct labs and take tests. Daily transcription of notes allowed me to continuously develop questions for subsequent observations and interpretation, according to methods outlined by Erickson (1986). In addition, Spradley's domain analysis (1980) was employed to describe the cultural environment of the classroom, using perspectives of the participants as starting points for interpretation. A final data source was supplied by student Learning Logs in which students wrote answers, without the pressure of grades, to conceptual questions developed by Mr. London and me. This activity enabled us to assess student understandings of topics which had been studied in class.

Case Study 1: Science Concepts - The Mole

The mole concept was selected as the subject of this case study of learning because my study revealed common features in the teaching and learning of chemistry concepts in Mr. London's class. However, this case study is not typical of the teaching and learning of all chemistry concepts we studied. First, as the following vignette illustrates, the mole concept is one of the most challenging chemistry topics for both teacher and student, and Mr. London's practice was not as fluid as it was with other concepts such as matter, energy, or atomic structure . Next, the realization that students did not understand the mole concept led Mr. London and me into an uncharacteristic extension of my role from participant-observer to participant-collaborator, at his request. The vignette describes this process and explains our efforts to modify his instruction to increase students' understanding. By examining the teaching and learning of a conceptually difficult concept, this vignette illuminates more of the problems inherent in the process of education, and chronicles teacher's and students' efforts to overcome them. Following the vignette, a more detailed examination of the context, associated meanings, and curriculum processes is presented.

"I Don't Know"

I sit at my dining room table, surrounded by a pile of notebooks, eager yet apprehensive to read what the students in the chemistry class have written in their Learning Logs today. We have been studying moles through nine days of instruction. We have had a few mini-lectures by Mr. London; we answered over twenty questions from Chapter 8; we conducted a lab on determining gram atomic mass of an element; and another lab on determining empirical formulas of compounds using the mole concept. Mr. London, at my request, has collaborated with me in creating a question for the students to answer, at no evaluative cost to them, in their Learning Logs. At first he wanted to challenge the kids with questions about a school with a mole of rooms and a mole of desks in each room. How many students would the school hold? I, however, felt the question should be more basic, more concrete. I wasn't sure the class understood another feature of the mole, that is, how to measure one, say, for a lab experiment. Rather than challenge the class in problem solving, as I interpreted Mr. London's question, my goal was to assess their knowledge. Perhaps I had less confidence in Mr. London's teaching, the book's presentation, and/or the students' motivation or capacity to learn the mole concept than he did. Then again, did our personal conceptions of the mole guide us in our choices of questions? Upon reflection, I realized that Mr. London conceives of the mole in terms of Avogadro's number, like the analogous dozen, which represents a collection. I think of the mole as a unique measurement which must be calculated for each substance by determining the gram atomic or gram formula mass. I determine to explore this difference in the research literature.

In the end, Mr. London agreed with me and suggested we have students describe how to collect a mole of sugar. "Oh, let's make it easy. Let's use salt!" I countered. So at the end of the period, Mr. London passed out the Learning Logs and wrote on the board: "You need a mole of NaCl for an experiment. (a) List the steps you take to measure out one mole. (b) How many NaCl molecules are in the mole?"

Now I have no idea what to expect in the Logs. Will most students refute my suspicion and answer both parts of the question correctly? Will one part be answered correctly more frequently than the other? How would students who didn't know the answers respond? Would they even be aware that they did not understand? I open the log on top of the pile:

Log 1: 1st: look at the periodic chart, find Na & Cl divide by 2
2nd: measure out both Na & Cl as shown on the chart
6.02×10^{23}

(Where did the division come from?)

Log 2: 1 mol of NaCl:
Look at per. chart and find the g/mol number
Na = 22.9 and Cl = 35.4
Measure 58.3 g. of sodium chloride
b. 6.02×10^{23} molecules in a mole.

(Pretty good - from the top student in the class.)

Log 3: To find a mole of sodium chloride I would:
1. add the mass of sodium to the mass of chloride.
Then measure out sodium chloride till you get that weight.
How many sodium chloride molecules are in a mole.
2. two because you have two molecules.

(Half right.)

Log 4: To get a mole of sodium first I would get the atomic mass and I would subtract the number of mass of both.
The number of Na molecules in a mole - one molecule per molecule.

(Does she know she doesn't know?)

Log 5: 1) I would 1st measure 1 gram of sodium chloride.
2) Since a mole of any element equals 6.02×10^{23} (mole)
3) I would get enough sodium chloride to get 6.02×10^{23} grams.

(At least using Avogadro's number.)

Log 6: Find a mole of sodium chloride.
Measure mass of sodium and divide by grams of chloride.
NaCl molecules in a mole? 6.02×10^{23}

(We are finding every imaginable mathematical function in these descriptions!)

Log 7: To find a mole of sodium chloride add the gram atomic mass of both elements.
To find how many molecules are in NaCl you take the gram atomic mass and multiply by 6.02×10^{23}.

(Another creative version.)

Log 8: 1 mole of sodium chloride:
I don't know

(At last, an honest person!)

The above log entries are typical of the twenty we received. Only four students answered both sections correctly. Interestingly enough, just one student admitted her ignorance of the topic. Also, Avogadro's number was easily memorized, it appears, but it is useless if one does not understand its meaning or application. I suddenly realize that if we had used Mr. London's question about a mole of desks in a mole of school rooms, we may have had more correct answers. In the end, the question that appeared simpler revealed a surprising lack of understanding of the mole concept.

Back to the drawing board. Both Mr. London and I were surprised at the lack of consistency and accuracy in the students' logs. What went wrong? How does one teach the mole? What are the most important features of the concept? In what order does one teach these features so that students can construct meaningful conceptions? Using suggestions from another teacher, we devised a concrete laboratory activity to facilitate understanding of the first question in their Learning Logs:

Weigh out <u>one</u> mole of each substance
($CaSO_4$, NaCl, $CuSO_4$, S)
Describe the size of a mole in volume
Describe the substance
Find out how many molecules you have
Find percent composition by mass

The lab was a success! As a laboratory activity, it was concrete, used basic math and measurement skills, was visually pleasing with yellow powder, white crystals, white powder and blue crystals. The students were involved and interested. Surely they understand more about the mole concept now!

<u>Conceptions of the Mole: Interactions of Text, Teacher, and Learners</u>

This case study of learning begins with a background section on the mole concept and Mr. London's introduction of the topic before its formal assignment to students in Chapter 8. Next, the three strands of text, teacher and learner contributions to formulations of meanings of the mole are investigated separately - (1) the text's incremental approach to teaching the mole concept; (2) the content and sequence of Mr. London's contrasting integrated approach; and (3) a description student constructions of the mole concept. In the final section of the case study, recent science education research on teaching and learning the mole is related to the experiences of the chemistry class. Finally, the essential tensions between Mr. London's theory and practice are examined with respect to their influence on the enacted and learned conceptions of the mole.

Background of the Mole Concept

The mole is one of seven basic units in the Systeme International (SI), officially defined as:

> ..the amount of substance which contains as many elementary particles as there are carbon atoms in 0.012 kg of carbon-12. The elementary entity must be specified and may be an atom, a molecule, an ion, an electron, etc., or a specified group of such particles (Kolb, 1978, p. 729).

Termed "the chemist's counting unit", the mole is more than a unit of measurement, however. Unlike the gram, meter, or cubic centimeter, the mole is enveloped within a concept, "an accepted way of comprehending the mole" (Stromdahl, Tullberg and Lybeck, 1994). Staver and Lumpe (1993) explain that the mole is an example of a theoretical concept, 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. Thus, the theoretical abstract nature of the mole anticipates the difficulty of its understanding, especially by high school students.

By the end of the first semester, Mr. London's chemistry class had studied chapters 1 through 7, including an introduction to chemistry, measurement, problem solving, matter, energy, structure of the atom, and chemical formulas. Only the final two chapters involved what could be described as "real chemistry," the other topics having been introduced to students in earlier grades, especially in physical science. The next chapter the class would study, Chapter 8, The Mathematics of Chemical Formulas, would begin after semester exams. Mr. London decided to lay the groundwork for the mole concept early, however, and he used the first ten minutes of a pre-exam class to "go through a couple things in chapter 8." First he reviewed the atomic structure of calcium, demonstrating how to find the atomic number on the periodic chart. Next, he reviewed the arrangement of valence electrons, "two to give and become positive", and how calcium combined with the hydroxide ion. Considering oxidation numbers of Ca^{+2} and OH^{-1}, he and the class created the formula Ca(OH)2 for calcium hydroxide as he wrote it on the chalkboard. Next, he found the "atomic mass" of the molecule by adding 40 atomic mass units for calcium, two 16's for the oxygen atoms plus 2 for the hydrogens, totaling 74 atomic mass units.

> You don't work with one atom, though. No one can even see one atom. They work with a cupful. With sand, scales are not accurate enough. You could weigh a cup for example 30 grams per cup. I've been lying because I've been saying one atom. They work with a bucket full (he holds up a trash can). They work with a mole. So with this we're working with 74 grams per mole. This mole - how many atoms is a mole? This guy Avogadro found out - on the average

> a mole is (writes on board) 6.02 times 10^{23} things. That would be 6.02 and on out to 21 zeros. That many atoms - this is later - remember chemistry is very old - now we could say 74 u is also 74 per 6.02 times 10^{23} things. Things are $Ca(OH)_2$. Understand? You can't work with one so we work with a whole moleful. How did we find that out? Experiments by Avogadro. First came the 74 atomic mass units, then he used that per mole - then they found out a mole is this many. (He picks up the text and reads aloud from page 181 about the mass of 2.5×10^{18} atoms of uranium barely registering on a laboratory balance.) (FN9,9)

The mini-lecture ended with no request for questions, and Mr. London went on to the reviewing for the first semester final exam. A notation in my journal indicates my response to Mr. London's typical "rapid fire" technique that employs no questions - I am confused, so I copy down the chalkboard notations and decide to check with the text and "figure it out later." I am concerned, however, for students who have not paid attention or written in their notebooks. Have they learned anything?

An analysis of Mr. London's mole introduction reveals that many aspects of the concept were included. The text defines the mole as "the chemical unit used by chemists to 'count' particles of matter, to relate the mass of an element or compound to the number of particles in a sample, and to relate the volume of a gas to either the mass of a sample or the number of particles in the sample" (Dorin, Demmin & Gabel, 1992, p. TG-130). Mr. London expanded upon this and touched upon the mole as an amount of a substance; its computation as a total of atomic masses of constituent elements; its use as a counting unit for chemists; its empirical nature, determined by Avogadro, to be 6.02×10^{23} "things"; and its macroscopic feature compensating for the sub-microscopic size of atoms. All of these characteristics of the mole are considered essential for its understanding by students.

When we returned for second semester, Mr. London referred the class to chapter 8 in the text and listed a series of assignments that students were to complete during group sessions. He began subsequent class periods with six mini-lectures related to the sequence of topics in the text. Two associated labs from the laboratory manual were conducted before the chapter test. Since Mr. London deferred to the text for his intended curriculum, he followed the presentation of topics, but chose to omit certain topics and terms as he saw fit. The following comparative analysis details the sequence of topics introduced in chapter 8 of the textbook followed by Mr. London's related teaching of the mole concept.

<u>Chapter 8 The Mathematics of Chemical Formulas - An Incremental Approach</u>

The textbook does not have a chapter entitled "The Mole". Instead, the mole is treated as a tool for stoichiometry, described in the first of ten sections of the chapter. Considering that this is most likely the students' first experience with the mole, the authors are careful to develop the mole concept in incremental steps. Although Mr. London did not consult the introductory section of the Teacher's Edition, he would have discovered that teaching suggestions in the teacher's guide advocate a careful review of concepts, practice with related mathematical functions, and concrete demonstrations. In

Chapter 8, following a definition of stoichiometry, the next two sections, entitled "Formula Mass" and "Gram Atomic Mass and Gram Formula Mass" define these terms and demonstrate how to determine formula mass of elements and compounds. The objective is to relate the relatively abstract atomic mass to the more concrete idea of gram-atomic/gram formula mass. A list of defined terms includes: formula mass, molecular mass, gram atomic mass, gram-atom, gram formula mass, gram molecular mass. At this point the term mole has not been mentioned.

Lab 12 - Determining the Gram Atomic Mass of an Element is next recommended by the Teacher's Guide. This activity demonstrates the concepts taught in the text by having students determine the gram atomic mass of Ag_2O. The Pre-Lab Discussion mentions the basis of atomic masses of elements in carbon-12, and chemists' use of the gram atomic mass, or gram-atom, as a unit of measure connecting microscopic and macroscopic interpretations. For the first time, the term "mole" is introduced: "A gram-atom is the mass in grams of 1 mole of atoms. A gram-atom of an element is, therefore, the mass of 6.02×10^{23} atoms of that element. The mass in grams of 1 gram-atom of an element is numerically equal to the atomic mass of that element" (Wagner, 1992, p. 61). The definition is complex, yet it is not developed further; students are asked only to calculate the gram atomic mass and gram-atoms of O and Ag at the end of the lab. The Conclusions and Questions section requests the definition of a mole, but the mole is not associated with gram-atoms in the questions that follow.

The next three sections of the chapter - 8-4 The Mole, 8-5 Moles and Atoms, and 8-6 Moles and Formula Units, now build upon the mole concept. First, mass ratios of rice and sugar are compared to demonstrate concrete relationships between mass and number of particles. Next, Avogadro's number, "also known as 1 mole", is described as an empirically determined number represented by N and denoting 6.02×10^{23} atoms or molecules. This is followed by an analogy to the dozen as a counting unit. Sections 8-5 and 8-6 provide practice problems in determining the mass of moles of substances and, conversely, calculating the number of moles present in certain masses of elements and compounds.

The concept of the mole established, the textbook now moves on to the mole's value in chemistry as a "bridge" that connects descriptions of chemical quantities such as mass, volume, and number of particles. A mole diagram depicts conversion factors between these characteristics of matter and practice problems provide experience in the computations.

Sections 8-8 Percentage Composition, 8-9 Determining the Formula of a Compound, and 8-10 Another Way to Determine Empirical Formulas, conclude the chapter with extensions of applications of the mole concept within the mathematics of chemical formulas. Lab 13 Determining an Empirical Formula, again using "gram-atom" in place of "mole", directs students to use mass relationships to "show that magnesium and oxygen combine in a definite whole-number ratio by mass" (Wagner, 1992, p. 65).

In summary, the textbook develops a careful, structured approach to the mole concept based upon its application as a chemists' counting unit and tool for expanding the understanding of chemical formulas. The next section details Mr. London's contrasting approach to instruction of the mole concept.

Mr. London's Teaching of the Mole Concept - An Integrated Approach

As evidenced in Mr. London's mini-lecture preceding the actual assignment of the chapter, he conceived of the mole as an integration of a group of related concepts. Rather than represent the mole as a tool for stoichiometry, he taught the concept as an independent unit of measurement, making it the centerpiece of the chapter. To avoid overwhelming the students with a foreign term, he never mentioned stoichiometry or its definition in section 8-1. Further, although the text developed the mole in incremental steps, Mr. London often combined those steps in his mini-lectures and demonstrations of practice problems.

Instruction on Chapter 8 began on the initial day of second semester. Mr. London first assigned review questions and practice problems 1-11, based upon sections 8-1 through 8-3, for the next day, and problems 12 - 27, from sections 8-4 through 8-6, for the following day. As usual, students were expected to read the chapter, answer the questions, and refer areas of concern to Mr. London.

In the day's discussion, termed Lecture 2, he demonstrated, with trips to the periodic chart on the wall, how to determine carbon's atomic mass of 12, which therefore was equivalent to 12 grams per mole, also called gram mass. Next, he computed the mass of a mole of carbon dioxide by adding the 12 atomic mass units for carbon and the 16 x 2, or 32, mass units for oxygen to get a total of 44 grams per mole. Referring back to the carbon, he extended the concept by quickly explaining that 12 g/mol = 12 atomic mass units = 12 per 6.02×10^{23} particles. "Let that sink into your brain a little bit" (FN1A.3). Thus, even though the assigned sections of the chapter had not mentioned the mole or Avogadro's number, Mr. London integrated them with the concept of gram atomic mass (and gram formula mass, which he did not differentiate in the case of CO_2.)

In Lecture 3 the next day, Mr. London elaborated on the mole concept and introduced the factor-label method for determining moles. Of interest here is his prior experience as a student coming to terms with the mole:

> Make sure you understand. If not, you're always confused. I was confused in high school. In my day we wrote 148 atomic mass units. But they got lazy and now it's 148 u. It is based on carbon-12. In number 5, (in the text) the answer is 148 grams per mole. The book skips over this. ..It cannot be grams unless you have a moleful. That's because that's where I got confused. You should automatically say grams per mole. To relate the chart into grams, you had to have a mole of it - it's grams for having a mole (FN1A,4)

That Mr. London ignored the attempt of the textbook authors to develop the mole concept in logical steps is obvious. For this reason, he thought the text mistakenly omitted the grams per mole reference in question 5. He also chose not to involve the students in the book's often tortuous explanation of multiple terms, but sometimes his strategy led to students' misunderstanding. For example, Celeste asked, "This confused me in the reading - are gram formula mass and gram atomic mass the same thing?" (FN1A,4). Mr. London quickly replied, "Yes" (an incorrect answer), picked up a bottle of sulfur and asked the class how many moles were present in the 500 g bottle. Mr. London's concern was with manipulation of the aspects of the mole, and he avoided what he perceived as the confusion of specific terminology.

Lab 12, Determining the Gram Atomic Mass of an Element, was a source of frustration for Mr. London. Preferring, again, to present a unified conception of the mole, he could not understand why the lab manual used the term gram-atom instead of mole. In response, he instructed the students to replace "gram-atom" with "mole" in their lab write-ups, explaining that the former term created unnecessary confusion. His own confusion about the book's choice of the term was so bothersome that he queried me and a former chemistry teacher in the department about the importance of "gram-atom." Mr. Anderson confirmed his idea that gram-atom was unnecessary, an old term. This was acknowledged when we checked the previously adopted chemistry text and found no mention of gram-atom. Mr. London was satisfied that he had taken the correct course of action in substituting the more meaningful "mole" in the lab write ups.

Lecture 4, after three days of lab, expanded upon the mole as a bridge. Mr. London wrote conversion factors of mole to mass, volume of a gas, and Avogadro's number on the board. In order to make the idea of 22.4 liters of gas per mole more concrete, he asked, "How many 2-liter Coke bottles would you have to burp to get one mole of gas?" After a brief review of measurement of atmospheric pressure, he reminded the students, "If you miss anything in this chapter, everything else is gonna get harder. I want to be able to help you. Ask questions. Now get started on your homework" (FN1A,12).

Mole Lecture 5 repeated the conversion factors and served as an overview of the procedures and concepts in Lab 13 Determining an Empirical Formula. Mr. London used a question from the book to demonstrate the calculations involved in ascertaining the empirical formula of a compound with 18 g of carbon and 21 g of nitrogen. The lab the next day would involve students' formation of MgO and determination of its empirical formula. Interestingly, since the mole had by now been established in the text, one would expect to use that term in the lab, but gram-atom prevailed. Mr. London repeated his instructions to cross out gram-atom and replace it with mole.

During the lab, I asked my partners, "What's a mole?" My suspicion that they did not have a clear understanding was confirmed by their confusing, illogical answers such as "something times 10 to the 23rd." Mercedes stated she understood, "Most of it. As long as I understand most of it and not none of it, I will be OK this year in chemistry" (FN1A,19). (This experience was the impetus for our Learning Log entry which spawned the Mole Lab mentioned in the vignette.)

Mr. London was satisfied that he had assigned and explained the chapter, and that the students had taken the responsibility of answering the questions and completing the labs. He scheduled the test for the Tuesday after our Friday Learning Log activity. Since the Learning Logs revealed that the students did not have a clear understanding of the mole concept, on Monday, the day before the test, he reviewed the mole as a quantity of a substance and the method of its measurement. Hoping this was sufficient to alter any misconceptions, he went ahead with the test on Tuesday. Entirely mathematical in nature, the test consisted of seventeen problems in calculating gram formula mass, mass of moles, number of atoms in moles, empirical formulas, molar volume of gases, and percentage composition. The students' scores were abysmal. Many had not completed all the questions, and most had correctly answered less than half.

On Wednesday, the Mole Lab of the vignette was presented to help students clarify the concept. A section of my field notes for the lab (L refers to Mr. London):

> L says, "I want to see it all laid out on white paper," and he distributes four pieces of paper to each pair of students. A brief moment of panic, followed by a 'How do we do this?" look around the room confirms to me that the mole is not a real concept to the kids. L gives some hints, and soon there is a group of students beside the large periodic chart, noting atomic masses. I do not jump in with instructions, but wait and watch in order to take their lead. Soon we four are hunched over the back pages of the book, writing down atomic masses, multiplying when necessary, and adding to get gram formula masses. Mercedes and Katja go over to Mr. London. "We have a question. In copper sulfate, do you count one or four oxygens?" L doesn't answer directly. Instead, he asks, "If you're being weighed, and you have four coins in your pocket, do I take the weight of one coin or of them all?" No answer is given, the girls just look at each other, one smiles and says, "I told you so", and they return to their station.
>
> Kids are busy weighing now; it is a do-able and fun lab. L is busy asking questions, probing for ideas such as, "How much do you have of that?" pointing to a blue pile, "Of that, that?" "Which is the bigger mass? Why? Which has more molecules?" I recognize that as a key question, and I hear L say, "Good!" when Tyler at the next station, says, "They are all the same." L is at the end of the room now, asking, "Why does this have more mass if it takes up less space?" He explains that "the molecules are bigger - like the difference between little girls and big guys. These are all moles - the only difference is the amount of space and mass. The number of molecules is all the same." Later I hear him say, "Do you have a better feeling for a mole?" (FN2A,4)

I felt that this lab revealed Mr. London at his best, moving from group to group, asking relevant, thought-provoking questions. His work was rooted in his understanding of his students' misconceptions which he had gleaned from the Learning Logs.

Because the students' test scores were so low, Mr. London allowed students to correct their tests the day after the lab, hoping a more scientifically accurate conception of the mole engendered by the lab would enable students to gain extra points. He began class with Lecture 7, holding up beakers of a mole of sulfur and of NaCl that were measured out the day before.

> The yellow looks like it's more, but which is heavier per mole? Which has more molecules? If you say salt, you're wrong. If you say sulfur, you're wrong. They have the same number of molecules or atoms. In sulfur the molecules are further apart and in salt they are closer together. Don't you find that interesting - this has more mass, this has more volume? (FN2A,7).

He continued with the mole-dozen analogy, reviewed a percent composition problem, and STP. At the end of the correction period, I noted that many students had still not completed the seventeen problems on the test.

Student Constructions of the Mole Concept

A constructivist perspective of learning envisions the student combining existing knowledge with the experiences of the classroom to construct personal meanings. Tomanek (1994) asks, "What happens to the content of instruction as teachers and students experience the curriculum? And what understandings about the content are students likely to develop as a result of the experiences?" (p. 73). She answers these questions within "cases of content" that first describe the meanings students construct for selected content and then relate those interpretations to "curriculum processes", a "complicated set of content, classroom, curriculum, and teaching processes" that generated them (p. 74). The following description of students' conceptions of the mole concept is followed by an analysis of such related "curriculum processes".

Mr. London's ideas about teaching science appear to be grounded in a constructivist perspective. His chemistry class activities were designed to allow hands-on experiences with materials, to provide a system of negotiation, input and feedback within group work, and to present teaching and learning strategies which appealed to different styles of learning. Interactions with the text, teacher, and other class members, as well as reading, reviewing and studying on an individual basis provided the basis for students' personal constructions of knowledge. If a student chose to participate in the activities, s/he could begin to build conceptions, monitor learning, ask questions, and compare personal meanings with accepted scientific definitions of the mole.

Since construction of meanings is idiosyncratic, it is expected that chemistry students' perceptions of the mole concept would differ in many ways. The Learning Logs proved this to be true. Most learners demonstrated that they did not understand the formula mass/gram mass relationship, and many had not learned that Avogadro's number represented the number of atoms or molecules in a mole of a substance. My questions to my lab partners generated similar responses. When Mr. London asked for questions, however, few students requested clarification of any components of the mole concept. In the group settings in which I was involved, most students attended to social talk, and review questions were not discussed in depth. If someone had an answer, it was usually copied by group members with no question. Therefore, from a participant-observer's viewpoint, it was difficult for me to determine more specific personal understandings that developed. It appeared that students did not exert much effort on constructing meanings for the mole.

Of special note, however, is the fact that when my classmates sought help from me, each approached me individually. Students did not discuss their lack of understanding in group sessions, and they did not request Mr. London's assistance in the whole class setting. Their confusion and lack of understanding were kept private, despite Mr. London's requests for questions. As a result, I could never be certain that my assistance resulted in a clearer understanding for the students.

The Mole Concept: Curriculum Processes and Considerations of Meaning Making

If the Learning Logs, test scores and student comments are examined, it is apparent that not many students mastered the mole. Is this to be expected? What curriculum processes may have contributed to misconceptions? What changes should be made in implementation to increase understanding? Analysis of the case study of learning the mole concept has revealed five areas of consideration that have appeared in science education research.

1. Teaching Strategies in Developing the Mole Concept

A review of the presentation of the mole by text and teacher reveals different approaches, the text using an incremental approach and Mr. London employing an integrated strategy. The effectiveness of each type of instruction ultimately depends on the developmental level and corresponding learning styles of individual students (Krajcik and Haney, 1987; Staver and Lumpe, 1993). However, the juxtaposition of both approaches and the combined influence on construction of meaningful conceptions of the mole is also an important avenue of investigation. Should Mr. London have relied exclusively on the book, following the development of information, emphasizing and distinguishing the varied terms, practicing the mathematical calculations in a step by step fashion? Or should he have abandoned the text and developed the concept according to his own unified conception of the mole?

In their studies of twenty-eight educators' explanations of the mole, Stromdahl, Tullberg, and Lybeck (1994) derived four categories of description. Stating that these descriptions are based on personal "centre of gravity" conceptions of the mole, the authors found that the mole has different connotations, and correspondingly, educators' conceptions drive their teaching of the subject (also Tullberg, Stromdahl, and Lybeck, 1994). In addition, interviews of students revealed that their conceptions usually are reflections of those of their textbooks and educators, but are not nearly as well-formed or articulate.

The four categories of mole explanations are described herewith. Category F0 is actually a non-category, because the mole is not related to physical quantities or physical units at all - it is simply a name for a concrete portion of a substance. Category F1 connotes the mole as a specific mass, synonymous with gram atomic weight. The next category, F2, was most commonly expressed by the educators in the study. It depicts the mole as equivalent to Avogadro's number. The final category is considered the most accurate. F3 describes the mole as a "unit of physical quantity amount of a substance" (p. 21). By employing this definition, the educator reveals an understanding of the mole's relation to mass, volume and number of particles. The mole becomes a bridge connecting these physical quantities which can be derived through use of proportionality constants (Stromdahl, Tullberg and Lybeck, 1994).

The conception of the mole as an amount of substance, as in F3, appears to be the "gravity point conception" of both Mr. London and the textbook. The difference lies in the route each took to develop the concept with the students. Stromdahl, Tullberg and Lybeck (1994) caution educators who adopt "fragments" of different categories of meaning into their basic mole conceptions. "Typical is the educators' unawareness of the illogical consequences of such inclusions" (p. 20) that can result in erroneous student conceptions. Stromdahl, Tullberg and Lybeck (1994) therefore suggest:

> a conscious separation of the fundamentals is absolutely essential. If such a separation fails to appear, no clear and logical comprehension of the mole either in agreement with SI and quantity calculus (F3)..or in agreement with historical conceptions (F0 - F2) is possible (p. 25).

In order to encourage students to construct a logical conception of the mole, Tullberg, Stromdahl and Lybeck (1994) propose that the educator must be "explicitly aware of her own conception and of how it compares with that which is presented in the textbooks or held by the scientific community...otherwise the teacher is bound to run into logical contradictions" (p. 155).

It is exactly these "logical contradictions" and "illogical consequences" which were exhibited in the chemistry students' Learning Log explanations, poor test scores, and lack of student participation in constructing ideas of the mole. The combination of the textbook's structure of the mole concept with Mr. London's more integrated approach created a difficult situation for the learners. According to Stromdahl, Tullberg, and Lybeck (1994), the chemistry students may have constructed more scientific conceptions of the mole if Mr. London had emphasized the text's incremental approach, which he had not recognized as different from his own, rather than attempting to integrate the multiple features of the mole.

2. Vocabulary

My perspective as a student in the chemistry class allowed me to delineate other areas of confusion in presentations by both Mr. London and the textbook. As part of the collective experience of the students in the class, the combination of two types of instruction prompted common responses and misconceptions. For instance, although the authors of the text were careful to break down the mole concept into its elemental segments, their inclusion of and emphasis upon terminology was a source of confusion. What Novick and Menis (1976) call "the phonetic similarity of terms" is certainly at issue here. The text introduces, defines and explains in great detail: formula mass, atomic mass, molecular mass, gram atomic mass, gram-atom, gram formula mass, gram molecular mass. Some of these terms are unnecessary when replaced by another. Gram-atom was considered to be obsolete by some teachers and other chemistry texts. Mr. London believed that such verbiage is a source of confusion and he therefore did not emphasize the terms. However, students like Celeste, taking seriously their responsibility to read, practice and learn the content, expressed confusion about the terms they thought they were expected to learn. As we saw with Celeste's question, Mr. London never did clarify gram formula mass and gram atomic mass.

3. Mathematics Anxiety and Proportional Reasoning Ability

The title of chapter 8 - The Mathematics of Chemical Formulas - identifies it as mathematical. For those students experiencing math anxiety and/or low proportional reasoning ability, the difficulty of understanding the mole is apparent. Gabel and

Sherwood (1983) used an aptitude-by-treatment interaction design to study the effectiveness of instructional strategies in teaching problem solving to high school chemistry students. Results showed a negative correlation between mathematics anxiety and science achievement and indicated that success in problem solving is dependent upon students' proportional reasoning ability (Gabel and Sherwood, 1983). In another study specifically related to the mole concept, Gabel and Sherwood (1984) used four forms of an analog test to determine skills and concepts necessary for solving mole problems. They concluded that the lack of understanding of basic mathematical principles is a "real impediment to solving mole problems correctly using reasoning methods and should be considered by chemistry teachers when presenting students with problems to solve" (p. 850). Success in mole concept problem solving is directly related to a student's mastery of mathematical concepts such as scientific notation, two-step problems, and division problems. This was evident in Mr. London's class. After students' experiences reading the text, completing practice questions, watching lecture demonstrations on the overhead, and asking questions after the test, some students continued to exhibit confusion.

4. Students' Developmental Levels

Notably, a few students obtained very high scores on the test even though the majority of the class demonstrated a lack of understanding of the mole concept. Staver and Lumpe (1993) offer an explanation:

> First, the cognitive requirements of both definitions (of the mole) most frequently developed in textbooks are very high, largely due to their abstract, theoretical nature. Thus, students whose learning is best characterized as concrete and intuitive rather than abstract and reflective may have great difficulty with the mole concept (p. 335).

Janiuk (1993) separates chemical concepts into two groups - concrete-operational, related to hands-on experience with objects and events, and formal operational concepts "whose meaning is derived through position within a postulatory-deductive system" (p. 828). The mole concept falls within the latter group, thus, it is recognized that learning the concept is a complex and difficult task for many students.

In a correlational study of reasoning skills and achievement in high school chemistry, Krajcik and Haney (1987) concluded that formal operational reasoning patterns are directly related to success in chemistry. As a consequence, the authors advise, "High school chemistry teachers must realize that nonformal operational students will probably have difficulty comprehending material requiring the use of this reasoning pattern... Typically, nonformal operational students will try to memorize this material, often becoming confused and learning to dislike science." (Krajcik and Haney, 1987, p. 31).

Gabel and Sherwood (1983) recognize the cognitive complexity of the mole concept and reason that

> because a high percentage of high school students are not formal operational and because these students' proportional reasoning ability will develop over

time, these students may elect to take another chemistry course at a later time if they are taught problem solving in such a way that they experience success (p. 176).

Novick and Menis (1976) report on studies which concluded that "the mole concept and its application may be inherently too difficult for the average 15-year old pupil" (p. 720). Their own research supported this theory, and the authors hypothesized that the students' cognitive level (in Piagetian terms) was not sufficient for acquisition of the mole concept.

To help the concrete, intuitive learners understand the mole concept, Novick and Menis (1976) advise a less complex development of the mole concept in the early part of a chemistry class. A "combined verbal-visual approach" is suggested by Gabel and Sherwood (1983). Staver and Lumpe (1993) advise instructional use of concrete activities and analogies. Krajcik and Haney (1987) recommend hands-on activities and computer-assisted instruction. As this case study illustrates, within his developing pedagogical content knowledge of the mole concept, Mr. London began to understand the importance of simplifying explanations and incorporating concrete demonstrations to meet the needs of students at various developmental levels.

5. Practice in Problem Solving

Mr. London's conception of teaching science emphasized his responsibility to be a 'tutor' for student learning. Through questioning, clarifying and guiding students, he intended to promote understanding of scientific topics. This belief, however, was influenced by another aspect of his perceived responsibility as the teacher of a college prep class. In this view, the 'professor's' duty extended from instruction on chemistry concepts to college survival skills. Besides providing advice on professors' expectations and practices, Mr. London felt an obligation to present students with experiences similar to those they would have in college. To this end, he placed much of the onus of learning on students. For example, he assigned homework but did not check it. Mr. London expected his class to complete assignments, work together in groups, and independently seek guidance and clarification of confusing topics from him. He rarely discussed lab conclusions in a whole class format. This reasoning was logical except when one considers the age and maturity of the chemistry students and their ability to monitor and regulate their learning.

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. For example, practice is an important prerequisite to mastering the mathematical aspects of the mole. In a study of questioning format and student success with the mole concept, Lazonby, Morris and Waddington (1985) found that the structure of questions can affect students' abilities to show understanding of the subject. Extensive practice is proposed as essential in teaching the individual steps of problem solving. With increasing confidence, then, students can move on to more complex operations. From the students' perspective in this study, Mr. London abandoned the role as tutor and did not collect the homework. Therefore for students creating "evaluative maps" of the classroom climate(Marx and Walsh, 1988), it became "safe" to ignore textbook questions and problems assigned by the professor. In the absence of student self-discipline, Mr. London could have fostered the growth of understanding of the mole through tighter measures of accountability that would have engaged the students in extensive practice of mole problems.

Carter and Brickhouse (1989) distributed two surveys on perceptions of the chemistry course to general chemistry students and faculty members at Purdue University. Perceptions of difficulty were divided into three categories - student-controlled, faculty-controlled, and factors within the nature of chemistry. The student-controlled factor deemed "most related" to the difficulty of chemistry by students was "not doing homework." In the faculty-controlled set, students attributed "not enough examples, applications, and problem solving in class," a factor also rated highly by the faculty. Of interest here is the recognition of practice in learning chemistry and students' willingness to take responsibility for their perceived difficulties in chemistry by admitting their failure to complete homework and prepare for exams and quizzes.

The mole concept may have been mastered by a greater percentage of students if Mr. London had established a more structured division of responsibilities for learning. His duty to guide learning could have been extended with the authority to collect and check homework, to give periodic quizzes over material, and to check notebooks more frequently, providing essential practice in mole problem solving and scaffolding construction of scientific knowledge.

Summary

The abstract theoretical concept of the mole, differences in individual learning styles, an educator's teaching strategies and classroom management techniques contribute to "curriculum processes" (Tomanek, 1994) that identify the mole concept as one of the strongest challenges faced by the high school chemistry teacher and his students. Mr. London and his class were no exception. Faced with a difficult concept involving mathematical reasoning, many of the students participated only marginally in the classroom activities, and withdrew from the challenge of confusion. Rather than ask questions of other students, me, or Mr. London, they either developed unrealistic conceptions of their mastery of the topic ("6.02 times ten to the something"), or, like Linda, admitted "I don't know." The misconception of his students' understanding of the mole, extended by their reluctance to ask questions, encouraged Mr. London to assume the students would do well on the test. The Mole Lab, designed to correct their misinterpretations, seems to have appeared too late in the learning experience. Most students had given up. Mr. London's experiences in relating his "centre of gravity" mole concept to that of the textbook will be the basis for reflection on his curriculum design in the coming year. His pedagogical content knowledge was enriched with revised theories on teaching and learning chemistry content, assessing student conceptions, and delegating responsibility for learning as a result of his confrontation of his assumptions and the reality of student learning, his seeking assistance and compensatory practice.

Thus, the failure of the chemistry students to understand the mole concept may be attributed to a combination of factors created by the interactions of the textbook, teacher and learners. These findings serve as suggestions for changes in implementation and enactment of the chemistry curriculum, because the teacher emerges as the crucial link between all domains and stakeholders in the process of chemistry curriculum modulation.

A far as the students are concerned, however, their experience with the mole is finished:

> **Ethnographer**: Now, describe something that you learned in chemistry class that you will never use to explain an event outside of school.
>
> **Shelly**: Moles! I could never see the purpose of moles! 6.02 times 10 to the 23rd is the moles per gram (SIC). I don't see myself explaining that to anyone (SC, p.6).

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