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ABSTRACT

Many studies of college chemistry students have found a gap between students' success in solving computational chemistry problems and their success in solving conceptual chemistry problems. This paper examines college students' understanding of the concept of stoichiometry, the particulate nature of matter, and chemistry problem solving. This study closely examined student learning and application of chemistry knowledge, both conceptual and computational, in an attempt to closely examine the disparity between conceptual and computational understanding. The results of this study have implications for science education at all levels, but specifically apply to undergraduate chemical education. Science educators must help students make the connections between the concepts of science and applications of those concepts. This study highlighted areas where those connections can be reinforced; an understanding of the particulate nature of matter and the models used to illustrate that nature; connections between the macroscopic, microscopic, and symbolic levels of chemistry; and completing the cycle of understanding by emphasizing conceptual understanding in the course assignments and assessments. (CCM)

Introductory College Chemistry Students' Understanding of Stoichiometry: Connections Between Conceptual and Computational Understandings and Instruction

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INTRODUCTION

Knowledge of chemistry is important to many occupations and fields of study, yet the content knowledge of chemistry students is often not what is expected or desired by chemistry educators (Kirkwood & Symington, 1996; Lythcott, 1990; Noh & Scharmann, 1997). For many educators the problem lies in the ability of chemistry students to apply knowledge of chemistry in solving chemistry problems (Bunce, Gabel, & Samuel, 1991; Bunce & Heikkinen, 1986; Camacho & Good, 1989; Gabel & Bunce, 1994; Gabel & Sherwood, 1983, 1984; Herron, 1990; Krajcik, 1991; Yarroch, 1985). Science education reforms (American Association for the Advancement of Science [AAAS], 1990, 1993; American Chemical Society [ACS], 1997; National Research Council [NRC], 1996; National Science Foundation [NSF], 1996) emphasize conceptual knowledge as an important part of science learning, further stressing that conceptual knowledge must be applied in computational problem-solving. The majority of these reforms (AAAS, 1990, 1993; ACS, 1997; NRC, 1996) address science teaching and learning in elementary and secondary schools, but some of the reforms have been extended to college and university science education (NRC, 1997; NSF, 1996).

Problem Solving in Chemistry

The understanding of chemical concepts as well as the ability to solve problems are important in the learning of chemistry and in the sciences and applied sciences that rely on chemical knowledge. The ultimate goal for chemistry knowledge is the ability to solve real-life problems (AAAS, 1990, 1993; Herron, 1996; NRC, 1996; NSF, 1996). For students to eventually apply their abilities in real-life situations they must see problems that parallel real-life situations.

> If students are expected to apply ideas in novel situations, then they must practice applying them in novel situations. If they practice only calculating answers to predictable exercises or unrealistic "word problems," then that is all they are likely to learn. (AAAS, 1990, p. 199)

To correctly solve a novel chemistry problem, meaning a problem that is different than one seen previously, students most often must have both conceptual scientific knowledge and procedural knowledge (Gabel & Bunce, 1994), and be able to apply both types of knowledge. Conceptual scientific knowledge is defined as the understanding of the ideas and theories that form the backbone of the scientific community's knowledge. Procedural knowledge is the understanding of how concepts are applied, primarily in mathematical models, to solve problems. To use conceptual and procedural knowledge sometimes requires that students first learn the qualitative conceptual models before they learn the mathematically-based models that are useful to scientists.

With the publication of several articles (Gabel, Sherwood, & Enochs, 1984; Nurrenbern & Pickering, 1987; Yarroch, 1985) a discussion began in the science education literature about the role of computational problem solving in chemistry. Gabel et al. examined the problem-solving strategies of a large number of students and found that most of the students used algorithms to solve problems and failed to apply conceptual understanding to their problem solving. Yarroch examined the chemical equation balancing techniques and chemistry understandings of high school students who were viewed as successful students by their instructors. Yarroch found that all of the students could successfully balance the equations given but more than half of his subjects had poor understanding of the laws that govern chemical reactions and the meaning of chemical equations and formulas. Nurrenbern and Pickering tested the conceptual and algorithmic abilities of college chemistry students on two campuses and found that the students had more success on the algorithmic problems than on the conceptual problems. The problems used by Nurrenbern and Pickering and a expanded set used by Nakhleh (1993) have since been used in several studies (Lin, Kirsch, & Turner, 1996; Mason, Shell, &

Crawley, 1997; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Noh & Scharmann, 1997; Pickering, 1990; Sawrey, 1990; Zoller, Lubezky, Nakhleh, Tessler, & Dori, 1995) where similar results have been found (see Noh & Scharmann for comparison of results). The conceptual/algorithmic gap seen in the original studies have prompted studies that examined trends in problem solving in different populations (Lin et al.; Nakhleh, 1993; Noh & Scharmann; Zoller et al.), examined problem-solving methods (Mason et al.; Nakhleh & Mitchell), and implemented strategies to enhance conceptual understanding (Nakhleh, Lowery, & Mitchell, 1996; Niaz & Robinson, 1992b; Noh & Scharmann; Phelps, 1996; Towns & Grant, 1997).

Conceptual Understanding

Developing better curricula for teaching chemistry problem solving bypasses an important question – Does facility in problem solving mean an understanding of chemistry concepts? Many chemistry educators appear to equate successful problem solving with good command of chemistry content knowledge (Gabel & Samuel, 1986; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering, 1987; Phelps, 1996; Sawrey, 1990). "Chemistry teachers have assumed implicitly that being able to solve problems is equivalent to understanding of molecular concepts" (Nurrenbern & Pickering, p. 508). While Gabel and Samuel argue that "a major reason why students are unable to solve chemistry problems successfully is that they do not understand the underlying chemical concepts" (p. 165), Nurrenbern and Pickering and Yarroch (1985) demonstrated that many students were able to give correct numerical answers without applying content knowledge in solving chemistry problems. Nurrenbern and Pickering, and Gabel et al. (1984), and Yarroch found that many of the students in the individual studies were able to successfully solve the problems by application of algorithms that did not necessarily rely on content knowledge.

Many educators (Gabel & Bunce, 1994; Krajcik, 1991; Nakhleh, 1992) have suggested that students' lack of an understanding of the particulate nature of matter makes solving novel problems difficult, especially problems involving chemical reactions, and gas laws. As Nakhleh (1992) stated: "Students should be reminded that if they can't explain a concept in molecular terms, then they really don't understand it" (p. 195).

Statement of the Problem

Many studies of college chemistry students (Bunce et al., 1991; Herron & Greenbowe, 1986; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Mason et al., 1997; Niaz, 1995a, 1995b; Niaz & Robinson, 1992a, 1993; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990; Zoller et al., 1995) have found a gap between students' success in solving computational chemistry problems and their success in solving conceptual chemistry problems. The greater success seen on the computational problems has concerned chemistry educators.

Many reasons for the discrepancy between conceptual and computational performance have been proposed. The suggested causes of this phenomenon are varied, as are suggestions of the relationship between algorithmic and conceptual learning in chemistry. The instructional emphasis on computational problem solving has been suggested as a cause (Phelps, 1996; Pickering, 1990; Pushkin, 1998; Sawrey, 1990), as well as the manner of assessment (Coppola, Ege, & Lawton, 1997; Nakhleh et al., 1996; NRC, 1996, 1997; Pushkin). Others (Anamuah-Mensah, 1986; Carter & Brickhouse, 1989; Kirkwood & Symington, 1996; Lythcott, 1990) suggest that the difficulty of chemistry as a subject may play a part. As stated by Ege, Coppola, and Lawton (1997), it is "too easy to reduce the subject to a manipulation of mathematical symbols and altogether remove the story of chemistry from a chemistry course" (p. 77). Gabel (1999) believes that the complexity of chemistry also plays a part. Niaz (1995a) suggested that the conceptual/ computational gap is not actually a gap, but is a continuum along which students evolve from computational learners to conceptual learners as they develop.

The purpose of this study was to examine college students' understanding of the concept of stoichiometry, the particulate nature of matter, and chemistry problem solving. The research questions examined were: 1) What are general chemistry students' understandings of the nature of matter as demonstrated by their perceptions of chemical reactions? 2) What is the link, if any, between general chemistry students' conceptual structure of stoichiometry and their ability to solve computational and conceptual problems? 3) What factors, if any, affect students' conceptual structure of chemistry as evidenced by their structure of stoichiometry?

Significance of the Study

Many of the studies done in this area (Anamuah-Mensah, 1986; Bunce et al., 1991; Gabel et al., 1984; Herron & Greenbowe, 1986; Lin et al., 1996; Lythcott, 1990; Mason et al., 1997; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz, 1995a, 1995b; Niaz & Robinson, 1992a; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990; Yarroch, 1985; Zoller et al.; 1995) have only diagnosed the problem, though several purport to be prescriptive (Bunce et al.; Gabel et al., 1984; Lin, 1998; Lin, et al.; Lythcott; Niaz & Robinson, 1992a; Zoller et al., 1995). Several researchers have proposed and implemented curricular changes that show promise (Nakhleh et al., 1996; Phelps, 1996; Towns & Grant, 1997) by actively engaging students in a constructivist manner (Roth, 1993), but have not closely examined student learning.

This study closely examined student learning and application of chemistry knowledge, both conceptual and computational, in an attempt to more closely examine the disparity between conceptual and computational understanding. After this disparity is more clearly understood, an examination of contributing factors can be accomplished.

This study closely examined these two areas and then suggests pedagogical changes to address the conceptual/computational disparity.

After gaining a deeper understanding of students' learning and contributing factors to the disparity described, educators can enhance pedagogical practices to more actively engage students in both the conceptual and computational facets of chemistry. After gaining greater understanding of these facets, students will then be able to apply this knowledge to their chosen fields making informed decisions when dealing with important chemistry related issues. In developing a more in-depth understanding of the relationship between computational and conceptual understanding of stoichiometry, chemistry educators may also be able to better assist students in connecting their understanding of the particulate nature of matter and the properties seen at the macroscopic level.

Definitions

For this research, algorithmic understanding is defined as the step-by-step process learned or developed to solve a problem or set of problems. Conceptual understanding is the understanding of the ideas and theories that form the backbone of the chemistry community's knowledge. Conceptual understanding includes the use of concepts to incorporate new ideas, to differentiate between ideas (NRC, 1997; Rouvray, 1997), or the application of concepts, especially in solving problems. In the literature several terms were used to describe problem types. Problems that rely on the application of a formula or algorithm are referred to as algorithmic problems, numerical problems, or computational problems. Problems that are intended to assess students' conceptual understanding are typically referred to as conceptual problems. Because of the debated issue of whether pictures can be used to assess conceptual understanding (Beall & Prescott, 1994; Niaz & Robinson, 1993; Noh & Scharmann, 1997) some are referred to as pictorial problems. In this study the categories are differentiated as computational problems and conceptual problems.

In much of the chemistry problem-solving literature, a distinction is made between exercises and problems (Bodner, 1987, 1991; Frank, Baker, & Herron, 1987). Problems are differentiated from exercises based on the definition from Hayes (1989): "Whenever there is a gap between where you are now and where you want to be, and you don't know how to find a way to cross the gap, you have a problem" (p. xii). Exercises are questions where the strategy to reach an answer is known or familiar, the distinction is dependent on the ability, education, and experience of the person seeking a solution (Bodner 1987, 1991; Frank et al.). In this study, all questions are referred to as problems, though many would be exercises for some students based on their knowledge and experience.

DESIGN AND METHOD

The study was done by utilizing qualitative methods to examine college chemistry students' problem solving, understanding of chemistry, and several factors that may affect their problem solving.

Topics of Study

The topics chosen for the study had to meet several criteria, the most important of which was that the topics were typically studied in college and university general chemistry courses. Other criteria included that the topics called for a conceptual understanding while having computational components that were taught at the general chemistry level. A final criterion was that proper knowledge of the topics should reflect an understanding of the particulate nature of matter (see Nakhleh, 1992). For this study, two topics were selected: balancing chemical equations and stoichiometry. Balancing chemical equations is a topic that can be learned on a strictly computational level as shown by Yarroch (1985) and Lythcott (1990) or in a conceptual manner. As shown in those studies, students' understanding of balancing chemical equations often reflected their understanding of the particulate nature of matter. Previous studies (Lin, 1998; Lin et al., 1996; Lythcott; Mason et al., 1997; Nakhleh, 1993; Yarroch) examined students' understanding of chemical reactions as shown in balanced equations, understanding of the symbolism in equations (Lythcott, Yarroch), and limiting reactant problems (Lin et al.; Mason et al.; Nakhleh, 1993). It is interesting to note that the Editor of the *Journal of Chemical Education* (Moore, 1997a, 1997b) placed a moratorium on the publication of articles proposing techniques, algorithms or computer programs that can be used to balance equations.

An acceptable understanding of the particulate nature of matter can aid in solving problems in stoichiometry, solutions, and gas laws (Gabel & Bunce, 1994; Krajcik, 1991; Nakhleh, 1992). Students' understandings of stoichiometry and the stoichiometrical calculations have been incorporated in many studies (BouJaoude & Barakat, 1999; Bunce et al., 1991; Chiu, Liang, & Chou, 1999; Gabel et al., 1984; Herron & Greenbowe, 1986; Lin et al., 1996; Lythcott, 1990; Mason, 1995; Mason et al., 1997; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz & Robinson, 1992a, 1993; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990; Yarroch, 1985; Zoller et al., 1995) that examined the conceptual/computational disparity. Stoichiometry and chemical change have also been the content examined in many studies (Ahtee & Vaijola, 1998; Andersson, 1986; Atwater & Alick, 1990; Ben-Zvi, Eylon, & Silberstein, 1986; Bodner & Domin, 1996; Boo, 1998; Hesse & Anderson, 1992; Huddle & Pillay, 1996; Niaz & Lawson, 1985) focusing on students' chemistry understandings. Stoichiometry is a fundamental part of chemistry because it is the method used by chemists to determine quantities of chemicals in reactions and the energy produced or absorbed in a reaction. Some stoichiometric problems can be solved without considering the particle makeup of matter (Gabel & Bunce, 1994), but the particulate nature of matter can assist in students' understanding of reactions and the quantitative macroscopic relationships seen in stoichiometry.

Research Subjects

The subjects of this study were students enrolled in a general chemistry course at a comprehensive university in the Pacific Northwest. This institution was chosen for two reasons: 1) its location made it convenient for study; and 2) the researcher was familiar with the chemistry instruction and curriculum at the institution, having been a graduate teaching assistant at the institution.

Subjects

The subjects were volunteers enrolled in the course examined. The course is described later. The potential subjects were approached in their lecture class with the cooperation of the course instructor. A short description of the study was presented to the students and they were asked for their cooperation. After the initial approach in the lecture class, two students volunteered for the study. Students were approached in their recitations with the cooperation of the teaching assistants to gather more volunteers. Four more students volunteered at that time.

Six individuals, four women and two men, were interviewed. Six students were interviewed because the number of subjects was limited to a manageable number. The interviews were conducted over a short period of time in an attempt to limit exposure to chemistry topics that might influence the understandings being examined. Six students were a manageable set of students to be interviewed given the time constraints. The number of students interviewed was also large enough to have a cluster of case studies to identify trends and patterns in the resulting data.

The Course

The course was one of five general or introductory chemistry courses offered at the university. This general chemistry sequence was intended as an introductory chemistry course for students with a working knowledge of algebra but no previous chemistry experience. The sequence was a three-quarter, yearlong sequence of courses beginning in the Fall quarter with a second sequence of the courses beginning in Winter quarter. Instruction occurred in three, 50-minute lectures; and a 50-minute mandatory study session (recitation) per week. During Winter quarter, one lecture section of the initial course in the sequence was offered and was made up of approximately 200 students; this course was selected for study. Usually, one professor taught the course for each quarter, with another professor taking over the course during each subsequent quarter. The recitation sections were taught by teaching assistants who were graduate students usually enrolled in a master's or doctoral degree program in chemistry and who had a bachelor's degree in chemistry or a related field.

Procedures and Methods of Data Analysis

The primary source of data was interviews with students enrolled in the chemistry sequence of interest. Other methods were used to gather data on the background of the subjects and information on the course studied. Data analysis followed a constant comparison model (LeCompte & Preissle, 1993).

Data Collection

Data collection occurred in three stages with several parts to each stage. In the initial stage, data were collected on the course and the instructor. The second stage consisted of collecting data on the students, including demographic information and views of an aspect of chemistry. In the final stage, data were gathered on the subjects' problem-solving methods and perceptions of the roles of problem solving and instruction in chemistry. The majority of the data gathered in the second and third stages were gathered in the individual interviews.

Stage I – Background of Course

Information on the sequence and instruction in the course was gathered in three ways: classroom observations, examination of course materials, and an interview with the course instructor.

Classroom observations were conducted by the primary researcher during Winter quarter of the year in which the student interviews took place. Classroom observations were done once every week during Winter quarter, except when instruction on the topic of stoichiometry or enthalpy took place and then all classroom instruction was observed. To minimize the observer's classroom influence, all observation data were collected as handwritten field notes and audiotapes. The tape transcripts and notes were typed after the observation. The observations of each class utilized the anecdotal record technique (Acheson & Gall, 1992) with a focus on instructional methods and interactions between the instructor and students. Special focus was given to problem-solving methods modeled by the instructor, how often and in what proportions the instructor discussed chemistry concepts versus the computational aspects of those concepts, and how the instructor presented the particulate nature of matter. Because several studies (Beall & Prescott, 1994; Phelps, 1996; Sawrey, 1990) have suggested that the manner of assessment may play a part in the conceptual/computational disparity, all exams from the course were examined as a part of instruction. The exams were investigated for the types of questions asked and focus on conceptual and computational chemistry.

Course materials, such as textbooks, provide a resource and reference for students enrolled in any course. The influence of textbooks has been examined in other studies (DeBerg, 1989; Niaz, 1998b) and may have a significant impact on students. The textbook and other resources that were used in the course studied were examined to determine what role they might play in the development of students' conceptual structure of chemistry. The text adopted was *General Chemistry* by Hill and Petrucci (1996). A software tutorial, *ChemSkill Builder* (Spain & Peters, 1997), was also adopted for the course and students were required to complete 25 assignments in the tutorial. The textbook and tutorial were examined for presentation of chemistry topics, especially presentation of the topics of interest. They were examined primarily for the ways in which computational and conceptual chemistry were presented.

An instructor with several years of instructional experience taught the course. To gather information on the instructors' philosophy of chemistry and philosophy of education, the instructor was interviewed about his views. The instructor was asked the following questions about his instructional philosophy: 1) What skills do students need to succeed in a general chemistry course? 2) When presenting a new topic how do you generally start presenting the new topic? 3) What aspects of a new topic do you focus on in the early presentation? In later presentations? 4) What do you feel are your students' greatest challenges in succeeding in general chemistry? And, 5) how do you approach an intuitively difficult topic, such as quantum mechanics? Probing questions were asked to follow up on points mentioned by the instructor, or to clear up any possible misunderstandings. An attempt was made to interview the instructor prior to student interviews, but due to researcher illness, the interview took place during the same period as the student interviews. The instructor was asked to complete the same card sort task done by the students. The card sort task will be discussed in detail later in the study description. The data gathered from the instructor were used to help answer the research question concerning the factors affecting students' conceptual structure of chemistry.

Stage II – Student Background

Individual interviews were employed to gather data from chemistry students. The student volunteers were scheduled for one-hour interviews following instruction on stoichiometry and enthalpy. The interviews were videotaped for data collection and all papers used by the student subjects were collected for analysis. The purpose of this information was to attempt to determine the cognitive structures built by the students to make sense of or as a consequence of the chemistry concepts studied.

Background data from the student subjects were gathered during the initial parts of the interviews. The subjects were asked to fill out a demographic questionnaire asking for the following information: age, gender, major, previous chemistry courses, previous science courses, and previous math courses. The individuals were also asked why they were enrolled in chemistry and what they hoped to gain out of the course.

The second piece of data gathered attempted to gain insight into the subjects' views of the discipline of chemistry by the use of a card sort task. Both concept maps (Pendley, Bretz, & Novak, 1994; Regis, Albertazzi, & Roletto, 1996) and card sorts (Kozma & Russell, 1997) have been used successfully to examine students' views of chemistry. A card sort task was chosen for the following reasons: 1) it could be used to effectively gather information on students' conceptual structures using several representations (Kozma & Russell), 2) it did not require training, as do concept maps (Herron, 1996; Pendley et al., 1994; Regis et al.), 3) card sorts provide a broader means of response than traditional methods such as fill-in or essay questions, and 4) card sorts can provide a means of conversation between the interviewer and subject. Rather than attempt to cover all aspects of chemistry in one card sort, the card sort was focused on the subject of stoichiometry with some added enthalpy material. To complete the Card Sort Task, each subject was given 26 index cards that contained representations (by picture, equation, or verbal description) of concepts or equations important to the understanding of stoichiometry. The subject was also given blank index cards and a marker so that he or she could add cards to the structure. The subject was asked to arrange the cards in a sequence or structure that made sense to him or her. He or she was given a large sheet of paper on which to arrange the cards and draw connections between cards if needed. As an illustration of a card sort structure, a small card sort structure on atomic structure done by the interviewer was shown and explained to the subject. After the subject was done with the task, he or she was asked to explain the representation to the interviewer. The final structure constructed by the student, along with comments made in explanation were recorded and transcribed for further analysis.

The content of the cards for the Card Sort Task were selected from the course textbook (Hill & Petrucci; 1996), other general chemistry texts, the science education literature, and science education reforms (AAAS, 1990, 1993; NRC, 1996). The cards covered the concepts presented in the textbook on stoichiometry and enthalpy. To ensure content validity of the material on the cards, and to ensure that the cards embodied an adequate representation of the subject, five educators (two science educators, and three chemistry educators not involved in the study) reviewed possible cards. The reviewers were asked the following questions for each card: 1) Is it important for a general chemistry student to know this aspect of stoichiometry? 2) Is the level of the content appropriate for a general chemistry student after instruction on stoichiometry? 3) Is the content clear and understandable? If the reviewer answered no to any of the questions for any card they were directed to reject the card. The reviewers were also asked to offer suggestions, if appropriate, for addressing the concerns to make the card acceptable. Each card was required to have at least 80% agreement to be included in the card sort task. Reviewers could also suggest cards for content they felt was missing or not completely covered. The final question asked of the reviewers was whether the content of the cards was a complete overview of stoichiometry appropriate for general chemistry students. Thirty-six cards were presented to the reviewers and of these 26 were approved after one round of validation. Some cards required minor revisions. The cards for the Card Sort Task are shown in Appendix A.

Stage III – Examination of Problem-Solving

The final part of the interview examined the subjects' problem-solving techniques and application of chemical concepts, especially the particulate nature of matter. The students were asked to solve several chemistry problems utilizing a think-aloud protocol. The subjects were asked to verbalize their thoughts as they solved the problem and were prompted by the interviewer, if necessary. The problems that the students were asked to solve were of three types: balancing chemical equations, conceptual stoichiometry problems, and computational stoichiometry problems.

The problems for this section of the interview came from several sources: the sequence textbook (Hill & Petrucci; 1996), other general chemistry texts, the science education literature, and problems created by the researcher. The problems are included in Appendix B. To ensure content validity five educators (two science educators, and three chemistry educators not involved in the study) reviewed the questions. The reviewers examined the questions for content, clarity, and academic level. Each problem was required to have at least 80% agreement to be included in the problem-solving task. For the conceptual and computational stoichiometry questions, the reviewers were also asked if the problem assessed conceptual or computational knowledge of stoichiometry according to the definitions provided. There must have been at least 80% agreement between the reviewers on the classification of the problem for it to be included. Eight problems, four conceptual and four computational, were validated for the interview. All problems were short answer or open-ended problems. One of the conceptual problems (Problem #5) required the subject to draw a representation of the response, similar to tasks used by Noh and Scharmann (1996), Novick and Nussbaum (1981), and Smith and Metz (1996).

The subject was first asked to complete the Balancing Task by balancing two easy chemical equations similar to those used by Yarroch (1985). It was assumed that all students would be able to successfully balance these equations, as was seen by Yarroch. After balancing the equations, the students were asked to explain what each equation represented. The next task was the Drawing Task where the student was asked to draw a picture of one of the reactions using labeled circles to represent atoms. Yarroch and

Lythcott (1990) previously used this task. Probing questions based on the student's responses were asked to gather further information about the student's macroscopic and microscopic views of chemical reactions. The terms macroscopic and microscopic were not introduced to the students. The questions incorporated quantities in moles, atoms, grams, liters, and molecules.

The next task was the Problem-Solving Task, which involved the solving of computational and conceptual problems on stoichiometry. To control for any influence that the order of problems might introduce (see Niaz, 1995b), the problems were given in a different order for each subject. The student was given each problem on a separate sheet of paper and was asked to solve the problem on that paper. The subject was asked to solve the problem in a think-aloud fashion and was prompted by the interviewer if no verbalization occurred after 60 seconds. Probing questions were asked of the student to further explore their understanding. The interviewer also provided hints or direction if a student was not able to continue on a problem.

After the solution of the problems, the student was asked how he or she prepared for exams, including how he or she chose the concepts that they paid attention to when preparing for an exam. Based on a conversation concerning course grades with the first subject, all subjects were asked for a prediction of their final course grade. The videotape was transcribed and all papers used by the student were collected for analysis.

Data Analysis

All interview data were transcribed for analysis and were categorized using a constant comparison method (LeCompte & Preissle, 1993). In each analysis, as the data were initially examined, preliminary categories were developed. This stage also incorporated preliminary hypothesis generation. After categories were developed, the categories were reexamined for the possibility of collapsing two or more categories into one category or other alterations of categories. The initial hypotheses were also examined in light of the categories and data for possible alteration. "Thus the discovery of relationships, or hypothesis generation, begins with the analysis of initial observations, undergoes continuous refinement throughout the data collection and analysis process, and continuously feeds back into the process of category coding" (LeCompte & Preissle, p. 256). Final categories for each task were developed and specific data were compared with data from other sources for triangulation and examination of similarities.

Instructor and Resource Data

The data gathered from the interview with the instructor, classroom observations, and examination of resources were analyzed first because this material did not change with instruction and could be analyzed before all student interviews were completed. These three sources of information were combined to develop a picture of the possible instructional influences on the students.

The first task to be analyzed was the card sort task done by the instructor. Prior to analysis of the instructor's card sort structure, the researcher completed the task. The researcher was the primary instrument for analysis of the card sort task, and because of this the researcher's conceptual views may be introduced into the analysis. The researcher's response to this task provides readers a source of data for the views of the researcher and so readers can use that information in their own evaluation of the hypotheses of the researcher. As a further aid for readers the researcher's card sort was analyzed. The analysis was the examination of the structure for patterns that showed how the researcher viewed stoichiometry. The analysis examined: 1) how the concepts were related to each other; 2) how conceptual and computational representations were related in the structure; 3) how the overall structure was related, i.e. number of links, hierarchical versus web-like structure; and 4) what concepts were included in the development of the structure. A descriptive analysis of the researcher's card sort structure was written and is included in the original study (Wolfer, 2000).

The instructor's responses on the card sort task were then analyzed. The analysis was the examination of the structure for patterns that showed how the instructor viewed stoichiometry. The analysis examined the same questions as the analysis of the researchers' card sort structure. A descriptive evaluation of the instructor's card sort structure was written for later comparison with other sources of data.

The next task was the analysis of the transcripts from classroom observations. Classroom handouts or required supplemental materials (course notes, etc.) were examined as a part of the classroom instruction. Exams were also included in this analysis. Analysis of the transcripts focused on the following aspects of instruction: 1) how the concepts were related to each other, for example, were links between similar concepts made explicit; 2) how conceptual and computational representations were related in instruction, were links between molecular interactions and connected mathematical models made explicit in instruction, or implied; 3) use of depictions and descriptions of matter; and 4) what topics were included in instruction of stoichiometry. A description of instruction on stoichiometry was written for later comparison with other sources of data.

The instructor's responses to the instructional/educational philosophy questions were then analyzed. The transcript of the interview was examined for answers that showed: 1) how the instructor viewed the relationship between computational and conceptual aspects of chemistry; 2) instructor views of students' limitations in learning chemistry; and 3) instructor views of students' ability to visualize the particulate nature of matter. A description of the instructor's views was developed from the responses to these questions and later compared to other sources of data.

The three previous data sources, instructor's card sort, classroom observations, and instructional views, were triangulated to develop an overall picture of instruction. Particular attention was paid to evidence of instructional behaviors showing the values and opinions espoused in the interview. The analysis also focused on evidence that the structure seen in the card sort task was reflected in instruction. A description of the instructor's views and actions was written.

The textbook (Hill & Petrucci; 1996) and the software tutorial (Spain & Peters, 1997) were examined for the following aspects: 1) how the concepts were connected to each other, for example, did the text make explicit references to chemically related concepts; 2) how conceptual and computational representations were connected in the text and other materials, such as direct connections between conceptual theories of the nature of matter and the mathematical models used to predict bulk behaviors; and 3) use of depictions and descriptions of matter. These sources of data were examined as a possible influence on students' conceptual structures. Descriptions of the textbook and tutorial were written and used for later comparisons.

Student Data

The student data were analyzed in five sections: background data, card sort structure data, reaction drawings, problem-solving data, and exam preparation answers. The data from each source were compared with specific data from other sources for triangulation, or in a search for trends. Each subject was assigned a code name for privacy protection as well as protection against introduction of researcher bias. Code names for student subjects were assigned at random and did not contain gender or other demographic information.

Case Study Descriptions

A case study approach was used for each student. Each task was analyzed for each student and a description for each student was written from the analysis of his or her interview results. The descriptions were later analyzed as a group for determination of similarities and differences among the subjects. The following paragraphs describe how each piece of data was analyzed for each case study.

The background data were used to develop a profile of the student based on their previous chemistry, science, and math study, as well as their reasons for enrolling in this chemistry course.

The student's card sort structure from the Card Sort Task was analyzed first; the analysis consisted of examination of the structure for patterns that showed how the student viewed stoichiometry. The analysis examined the same questions as were used in analyzing the researcher's card sort structure. A description of the subject's structure was written for future comparison with other data sources.

The Balancing Task and Drawing Task were analyzed next. Because all subjects were expected to be able to correctly balance the equations, the analysis focused on the drawings produced in the Drawing Task to represent the reactions. The drawing was examined and a description was written and used for later comparisons. The results from this analysis helped to answer research question 1.

The Problem-Solving Task was then analyzed. All problem sets were first examined on the basis of correct and incorrect answers. The methods used to solve the problem and the discussion around each problem were examined for clues to the thought patterns of the student and the student's understanding.

The final task to be analyzed was the student's answers to the question concerning their strategies for preparing for exams and solving problems, the Perceptions Task. Additionally, each student was asked for their estimate of the course grade they would receive.

The results from the Card Sort Task, Balancing Task, Drawing Task, Problem-Solving Task, and Perceptions Task were triangulated for each student to present a more complete picture of the student's views of the nature of matter and his or her problem-solving abilities and approaches. These comparisons were used to answer research question 2. For the students' understandings of the nature of matter, the reaction drawings were the primary data source with aspects of the card sort task and the conceptual problems as secondary data sources. In determining the possible links between conceptual understandings of stoichiometry and problem solving, the card sort task was the primary data source with additional data from the problem-solving task and the preparation questions. Other data from the interview, such as study strategies volunteered by the students while solving problems, was included where appropriate to complete a detailed picture of each student.

Comparison of Students

After descriptions of each student were written, the students' results were compared. The students were first compared on the results from each task, or problem, then compared on their descriptions.

Factors Affecting Student Understanding

Many factors, such as instruction and resources, were examined in this study. The final research question was what factors might affect students' conceptual structure of chemistry, so possible factors were compared with students' conceptual structures. The background factors were analyzed for possible effects. The description of instruction was compared with the descriptions of the students for examination of possible influences. These comparisons included effects of the instructor, the exams, and the resources. Together the analyses develop a profile of what influenced the chemistry understanding of the subjects.

RESULTS

The data gathered for this study were gathered in three stages that combined into a picture of the chemistry instruction, students' background, and students' problem-solving ability.

Instruction

Instruction for this course was conducted by Dr. Dalton, who has a Ph.D. in Inorganic Chemistry, and a M.S. in Science Education. He had previously demonstrated an interest in chemistry education beyond his teaching assignments. The course examined in this study had 196 students enrolled. The textbook for the course, *General Chemistry* (Hill & Petrucci, 1996), and the software tutorial, *ChemSkill Builder* (Spain & Peters, 1997), were the other instructional resources examined. The software tutorial was a set of three computer disks that contained a short tutorial and brief quizzes on topics covered in general chemistry that the students were required to complete.

Class Observations

Instruction in the course was traditional with example problems, demonstrations, and discussions with students. Dr. Dalton was an energetic, interactive instructor who displayed good rapport with his students. He often described problems as easy and then proceeded to talk the students through the concepts and math to illustrate why he thought the problems were easy.

One point that showed up early and was consistent throughout the observations was the instructor's emphasis on the resources available to the students, primarily the computer tutorial (Spain & Peters, 1997) and the textbook (Hill & Petrucci, 1997). Other aspects of instruction that were apparent were the instructor's practice of giving clear expectations for students' learning and for assessment, and his penchant for demonstrations. In the presentation of material, Dr. Dalton typically connected new concepts to previously covered concepts and everyday occurrences. The connections were usually made explicit by discussing the previous concept and its relevance. He often discussed ways in which the tutorial problems and textbook problems could be solved by solving them on the board, sometimes using more than one solution method.

Dr. Dalton frequently discussed the conceptual aspects of topics before presenting the computational aspects. This conceptual focus was also evident in the presentation of limiting reactants, as they were discussed qualitatively several times before any calculations of the limiting reactant were attempted. It is interesting to note that the instructor on several occasions referred to computational limiting reactant problems as the most difficult problems that would be seen in the course.

Microscopic depictions of matter were used throughout the course. These depictions were usually drawings done by the instructor, as he used the chalkboard exclusively for instruction. Ball-and-stick models were used on several occasions to depict reactions and structures.

Assessment in the course was primarily done through examinations with additional evaluations based on recitation quizzes and completion of tutorial assignments. There was no lab associated with the course. There were 450 points possible for the course and course grades were assigned on a criterion-referenced scale based on the percentage of points earned. The exams accounted for more than 80% of the possible points used for assessing the students and were an important part of the course. The exams were multiple choice with between 10 and 31 questions on each exam. Each exam was laid out with a brief description of the objective being assessed followed by one or two problems assessing the understanding of that objective.

The topic of stoichiometry was covered on Exam 2. The test contained 10, 10-point problems, all of which were computational. The problems on the exam covered molecular weights, Avogadro's number, mass percents, empirical formulas, writing and balancing of equations, limiting reactants, percent yield, concentration, and internal energy. An example of a problem from this exam was the following limiting reactant problem.

Identify the Limiting Reagent and Determine the Amounts of Reactants and Products Used and Consumed.
[1 Question – 10 Points]

7. A student places 5.6290 grams of lithium metal into 12.315 grams of water to produce lithium oxide and hydrogen gas:
   $2\ Li\ (s) + H_2O\ (l) \rightarrow Li_2O\ (aq) + H_2\ (g)$. The theoretical yield of lithium oxide is:
   (a) 10.217 g.
   (b) 12.117 g.
   (c) 20.433 g.
   (d) 24.234 g.
   (e) None of the above.

All of the problems on Exam 2 were typical computational problems that could be found in chemistry textbooks or on general chemistry exams. There were no problems asking for description at a microscopic level or for conceptual understanding.

After inspecting the exams, several points were identified. 1) The objective being assessed appeared to determine whether the problem would be computational or conceptual. 2) Some important topics, most notably enthalpy (AAAS, 1990; NRC, 1996), were covered in the course but were not assessed on the exams. 3) The conceptual problems were usually at a lower intellectual level than the computational problems. Most of the conceptual problems on the exams were Knowledge or Comprehension questions based on Bloom's Taxonomy, thus bringing into question whether they were truly conceptual questions. 4) All of the exam questions were straightforward, and due to the number of questions the exams were not overly long. And, 5) the computational problems could all be answered with memorized algorithms.

Instructor Interview

Dr. Dalton appeared to be very interested in discussing his philosophy of teaching and more time was spent in the interview than was originally scheduled. The researcher and the instructor had known each other for several years prior to this study and had discussed instructional philosophies prior to this study.

In the instructor's Card Sort Task, the instructor utilized an organizing principle that reflected his background but was different than that taken by the students. Dr. Dalton was presented with the same cards as the students and was asked to construct a structure that made sense to him. Dr. Dalton chose to organize the concepts into topics to be presented as part of the course.

Dr. Dalton discussed several limitations for students in learning chemistry such as the lack of computational skills, lack of study time, and the hierarchical structure of the concepts. The instructor felt that a major limitation for some students was their inability to use the mathematical tools necessary to solve computational problems. He felt that students needed to solve problems to understand how the computational and conceptual aspects tied together and to build an understanding of the aspects. The hierarchy or building up of the important aspects also hinders students' understanding if they failed to build the foundation necessary for the later concepts.

There was an area where there appeared to be a discrepancy between Dr. Dalton's philosophy and his instruction. That discrepancy was in the area of conceptual understanding. The instructor mentioned that the goal was to teach the concepts, and the understanding of concepts was evident in the card sort task, but there were no conceptual questions on the exams for any concept that could be assessed by a computational problem. This lack could be understood based on the interview and card sort task as he saw concepts building upon each other.

It could be seen from Dr. Dalton's answers that he was concerned for his students' success in his course and for their learning and enjoying of chemistry. He was concerned that they be able to apply the concepts that they learned to real-world applications and that they learned to think critically.

Resources

The resources used for this course consisted of the textbook, *General Chemistry*, by Hill and Petrucci (1996) and the software tutorial, *ChemSkill Builder* (Spain & Peters, 1997). Both resources were required for all students, and points were assigned for completing assignments on the tutorial.

The textbook was typical of texts for introductory college chemistry. It presented the concepts and computations in a straightforward manner. As was also found by DeBerg (1989) and Niaz (1998b), this textbook emphasized the computational aspects of chemistry.

The software tutorial, *ChemSkill Builder* (Spain & Peters, 1997), was presented to the students as a method to practice problem solving and as a way for them to earn "free" points toward their final grade. Informal conversations with three other instructors who have utilized this tutorial in this introductory course supported it as an effective means of encouraging students to practice problem solving. The tutorial presented several advantages for the students: 1) the questions were individualized so it would be unlikely that two students would have the same questions; 2) students were able to repeat a section to achieve a higher score if they scored less than 80%, and; 3) after two incorrect attempts to solve a problem the program showed the method of solution and the correct answer. An advantage and disadvantage for the students were that the problems were primarily short answer questions. The short answer questions were an advantage because the students had to solve the problems, as guessing was unproductive. The disadvantage was that answers had to be in the proper form including proper spelling, case, and number of significant figures. If the first attempt were incorrect, the second attempt would be worth 70% of the possible points.

A review of the stoichiometry section of the *ChemSkill Builder* (Spain & Peters, 1997) showed that: 1) The tutorial relied on the use of dimensional analysis in its solutions. This method matched with those used in the text and by the instructor. 2)

Almost all of the problems for the sections on stoichiometry were computational problems. The few problems that were conceptual in nature were of the type: "How many moles of hydrogen atoms are in one mole of methane (CH_4) molecules?" (Spain & Peters, 1997). 3) When discussing the mole concept, the tutorial connected atomic and macroscopic levels by the mole concept as was done in the text. And, 4) there were no depictions of matter used in the tutorials.

Student Interviews

Six student volunteers were interviewed for this study. Each student interview took place during the final week of the course or during Finals Week. An account of the results from each student was written and a profile of each student was developed. For analysis of the interviews, the subjects were assigned a subject number that did not reflect gender or other characteristics. For this discussion each subject was assigned a pseudonym for clarity.

Comparison of Students

In the following section, all six students are compared to highlight similarities and differences. For complete student case study descriptions see the original study (Wolfer, 2000).

Background

Three of the six students, Anna, Beth, and Frank, had not taken a chemistry course prior to enrolling in the course studied. Two who previously had taken college chemistry, Cara and Deb, admitted to struggling with the courses, and had withdrawn during the preceding quarter. Deb and Ed were the only students to have taken a high school chemistry course. All but Frank were pursuing degrees in the life sciences and so most of them had taken biology or applied biology courses. Four of the students had taken a physical science course other than chemistry. Only Frank had taken math courses beyond college algebra. Each student had a unique background prior to enrolling in this course, and no patterns appeared significant.

Card Sort

The card sort structures constructed by the students showed some interesting similarities and differences. Most of the students used a similar structure and organizing principle, while there appeared to be a continuum for the overall structure from an incomplete structure to an explicitly described structure.

A dominant feature in all six of the constructions was the grouping of the enthalpy cards. All but Anna placed the same seven cards (Cards #12, 27-32) in similar structures. The similar representations were paired in rows with the similar concepts, exothermic or endothermic, in two columns. Above the two columns was placed Card #12. Dr. Dalton's structure had the same grouping. Deb's grouping was slightly different because of the overall structure that she used and Beth and Cara switched the definitions in their structures. There were several possible reasons for the noted similarity. The first reason is that the students focused on the ΔH notation on five of the seven cards and grouped them by this factor. The students then placed the two definition cards in the same group since they defined a change in energy, which students linked to the ΔH symbol. Anna's structure demonstrated this trend differently than the others as the three cards with prominent ΔH notations were separated from the other enthalpy cards. The second possibility is that the students were familiar with two energy changes in chemical reactions: energy being released (exothermic) and energy being absorbed (endothermic). They then used these to divide the representations into two categories. Beth's description showed that she was thinking in this way. The third possibility is that the energy-related cards were clearly of three types with opposite concepts and so the students used the double column approach to organize these concepts. It was probable that all three contributed to the structures seen. It was interesting that, on Frank's and Beth's structures, the enthalpy grouping was separate from the other groups.

Another feature that was common to four of the structures was the perceived buildup from mole to limiting reactant. All card sorts except those of Anna and Cara showed some form of an overall path from mole to limiting reactant, and Cara had begun a similar overall structure before she became frustrated and quit the task. The structures of Beth, Deb, Ed, and Frank were each different in how the structure was constructed, but the overall connection could be seen. Beth and Deb explicitly made statements that showed this structure, while Ed and Frank did not use any explicit statements about the connections. This common factor implied that the concept of limiting reactant was the most important concept of stoichiometry in the minds of the students. It thus appeared that solving limiting reactant problems was the objective of stoichiometry to the students.

The card sort structures were placed in three categories based upon the connections perceived. The first category was the Lacking category. The card sorts of Anna and Cara were placed in this category because their overall structure was lacking a chemical concept-based coherence. Anna's structure had an organization because representations of concepts as definitions and numbers were separated from graphical and mathematical representations, but there was no chemical concept-based coherence. Frank's description of his structure showed some of the aspects of separation seen in Anna's structure, but there was more coherence in his structure. Anna's use of representation types rather than concepts as connecting factors was similar to the results seen by Kozma and Russell (1997) when using a card sort with novice chemistry problem solvers. Cara's structure was included in this category because she did not complete the task.

The second group was coded as Implicit structures. The structures in this category appeared to have an overall structure, but the students did not articulate an overall organization in their description. The structures constructed by Ed and Frank were placed into this category because their structures lacked overlying connections. Their structures showed connections between concepts within each group, including explicit connections in Ed's structure, but the between group connections were not discussed and so were implied.

The third category was labeled as Explicit. This category included the structures of Beth and Deb who were explicit in describing the connections between groups. There were also connections between concepts within each group, explaining why they were related. The students described how their structure was connected and included the connections between groups in their descriptions.

Balancing Task

It was assumed that all of the college students in this study would be able to correctly balance the given equations, but two of the students, Cara and Frank, did not correctly balance the equations. Frank's error was minor in that he did not reduce the coefficients to the least common stoichiometric coefficients as in the accepted method. His solution was coded as Minor, suggesting a minor error. Cara did not correctly balance either equation, and her solution was coded as Incorrect. She appeared to ignore or misunderstand the meaning of the subscript in the symbols for diatomic molecules such as hydrogen, H_2, and nitrogen, N_2 (see Figure 1). This misunderstanding led her to add an unneeded coefficient for those chemicals in the balanced equations. An interesting aspect of her errors was that diatomic hydrogen appeared in both equations, yet she neglected the subscript for hydrogen in the potassium equation and correctly incorporated it in the ammonia equations. The remainder of the students' responses were correct and were coded as Correct.

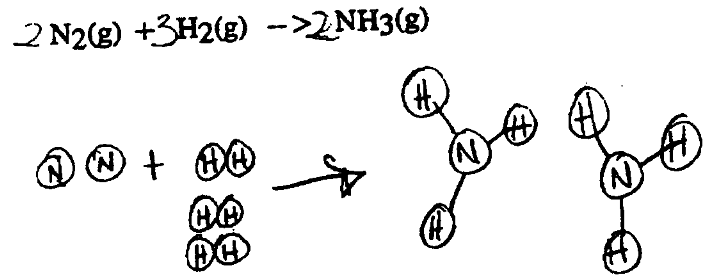

Figure 1. Cara's balanced equation and drawing

Drawing Task

The Drawing Task results fell into three categories: Correct, Incorrect, and Minor. The Correct representations were the drawings that were in agreement with a chemical view of the reaction. Anna, Deb, Ed, and Frank all had correct representations. Beth's drawing contained an error that she caught and corrected herself, and so was coded as Minor. She drew a line/bond between the nitrogen atoms in the ammonia molecules (see Figure 2). Cara's drawing (see Figure 1) further showed her misunderstanding of the

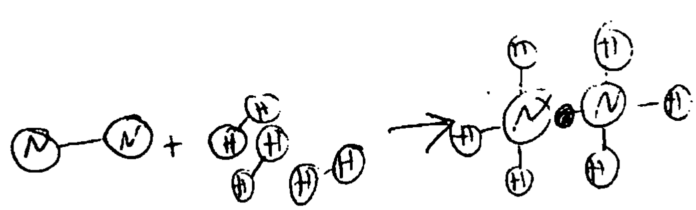

Figure 2. Beth's reaction drawing

meaning of the subscripts. She drew two separate nitrogen atoms rather than two diatomic nitrogen molecules as in her balanced equation or the correct representation of one diatomic nitrogen. Her solution was coded as Incorrect, for an incorrect representation. The solutions did not show the variety of misconceptions seen by Yarroch (1985) or Lythcott (1990), but there were fewer subjects in this study, and the current subjects were college students rather than high school students.

Problem-Solving Task

Because the focus of the interviews was on the students' problem-solving strategies and thought processes, and not on the number of correct or incorrect answers, it was not necessary for all of the students to attempt to solve all of the problems or even the same set of problems. Due to this focus and because of the 1-hour time limit and the structure of the interviews, not all problems were posed to all subjects. The students were allowed to take as much time as necessary to solve the problems and to complete the other tasks; and the flexible time led to a lack of time for problem solving in some of the interviews. The students were asked to solve an average of four problems with all of the students asked to solve Problems #2 and #5. All but Cara were asked to solve Problem #1, and Cara and Ed were not asked Problem #3. The following discussion focuses on the similarities and differences of problem solving strategies utilized on the four problems asked of most of the subjects (Problems #1, 2, 3, and 5).

Problem #1 was a conceptual problem similar to problems asked in the textbook and in the software tutorial. The correct solution required that the student understand that there were two moles of chloride ions for every mole of magnesium chloride, $MgCl_2$, therefore two moles of magnesium chloride would contain four moles of chloride ions. Ed solved this problem correctly immediately after being asked and was able to articulate his reasoning. Deb also solved the problem correctly, though her first response, two, was incorrect. She corrected her response and explained her method. Their responses were coded as Correct. Frank began his answer as Deb had, by answering two, but when asked for an explanation he changed to a computational strategy that appeared similar to the algorithm for determining mass percent. His response was coded as an Algorithm. Anna and Beth both attempted to solve the problem by use of the algorithm for converting grams to moles. After completing the incorrect computation they both became confused about how to proceed and stopped. Their partial solutions were coded as Algorithms.

Problem #2 was a traditional computational problem with a given mass of a reactant, 1.00 gram of ethane; the equation asked for the required mass of another reactant, oxygen. Both Deb and Beth correctly solved this problem following steps similar to those taught in their class. Their solutions were coded as Correct. Frank correctly performed the first step of calculating the molecular weight of ethane and using that molecular weight to convert grams of ethane to moles of ethane. At this point he began to have difficulties, and he attempted to work out a solution computationally. It appeared that he was randomly applying algorithms, rather than knowing a method of solution. Frank's method seemed to utilize the Rolodex Method described by Bunce et al. (1991). His answer was coded as an Algorithm. Ed also began by calculating the molecular weight of ethane and oxygen, but he did it incorrectly by incorporating the coefficients from the balanced equation, thus calculating a molecular weight of 60 grams per mole rather than the correct 30 grams per mole for ethane, and 224 grams per mole for oxygen rather than 32 grams per mole. He was unable to do any work beyond that point. His solution was coded as Incorrect. Anna and Cara were unable to start the problem without assistance from the interviewer. After prompting, Anna was able to calculate the number of moles of ethane and mentioned that the coefficients in the balanced equation were important for determining the number of moles of oxygen needed, but was unable to do the calculations. Anna and Cara's solutions were coded as No Answers.

Problem #3 was a conceptual problem that touched on material covered during the Balancing Task. The students were asked to describe what information could be taken from a balanced equation. Cara and Ed were not asked to solve this problem but were asked similar questions during the Balancing Task. Frank correctly answered this question and gave a good description of the ratio aspect of balanced equations. Because Frank was incorrect about the balanced equation indicating which reactant would be limiting, his response was coded as Correct with Error. Beth and Deb gave correct but incomplete answers so their responses were coded as Incomplete. Ed's responses to the earlier questions were also coded as Incomplete because it was similar in depth to those of Beth and Deb. Anna did not answer the question even after prompting because she claimed that the question was different than those usually asked. Her response was coded as No Answer. Cara's earlier responses were also coded as No Answer because of she failed to answer a similar question during the Drawing Task.

None of the students were asked to solve Problem #4, due to time constraints and the difficulty shown on the other computational problem (#2). All students were asked to solve Problem #5. Problem #5 was a conceptual problem, which asked the students to draw a representation of the product mixture resulting from a reaction between chlorine molecules and an excess of aluminum atoms. Beth and Frank both answered the problem correctly, incorporating the limiting reactant aspect of the problem. Their responses were coded as Correct. Anna, Cara, Deb, and Ed were all confused by the problem to some degree. All expressed concern that the numbers of aluminum atoms and chlorine molecules were not the same as in the balanced equation. Anna became frustrated and remembered that a similar diagram was used in the Card Sort Task and found that card; she then copied the product diagram from that card. This response was coded as No Answer, Confused. Cara eventually drew some aluminum chloride molecules and leftover aluminum atoms in numbers matching the balanced equation rather than the reactants. She also drew two aluminum chloride molecules joined together. Her solution was coded as Partial, Confused for a partial solution with confusion. Ed and Deb were both initially confused but overcame the confusion and drew representations with numbers reflecting the reactant mixture (see Figure 3).

> **Deb:** OK, I think from what . . . I tried to put it into something I could, I'm familiar with. And the way I figure it out is, each of these little squares, well the bond, or the little circles, for the chlorine it will get broken out of two groups, basically. Aw, this has boggled my brain. I had it figured out and then I lost it. We can only have two chlorine molecules or whatever, but because that'd be . . . here we go. Kay, this one goes with that one, that one goes with that, this middle one has to be split so it takes one of this two and puts it there and one in there. And, that's how you get the Cl_3. As to how to draw the product picture . . . . I don't understand why there are six of the black circles and three of the double circles, or I mean six of those. Because it's two and three. That's what got me confused.

Their drawings were incorrect because the chlorine-chlorine bonds were not replaced with aluminum-chloride bonds. Their solutions were coded as Mixed, Confused for mixed

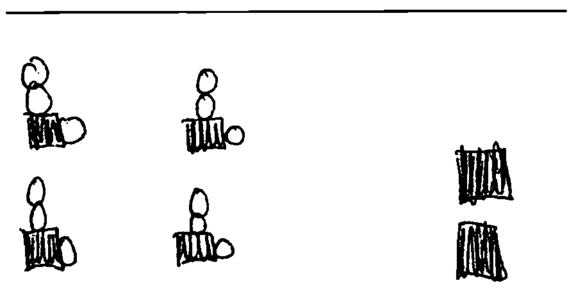

Figure 3. Deb's answer to Problem #5

results with confusion. Deb and Ed admitted that a major source of confusion was how the two chlorine atoms in each molecule could be split to give three chloride ions in each aluminum chloride. The reasons for the difficulties could be due to several conditions; the most likely of which was a superficial understanding of the significance and meaning of a balanced equation. Another possible explanation was that the difficulty stemmed from the students' failure to make connections between microscopic, macroscopic, and symbolic representations of matter as discussed by Gabel (1999) and Lee (1999). This explanation was supported by the students' ability to solve computational limiting reactant problems but not conceptual problems. The students also appeared to have a computational view of limiting reactant situations. They appeared to know that an algorithm existed to solve limiting reactant problems, but had little conceptual knowledge of limiting reactant reactions. The level of difficulty may have played a role because of the different aspects that the students had to pay attention to, such as the limiting reactant aspect, the rearrangement of atoms, and the stoichiometric coefficients.

The results from the interviews are highlighted in Table 1.

Table 1: Interview Results

Subject	Card Sort	Balancing	Drawing	Problem	Solving	Task	
	Structure	Task	Task	#1	#2	#3	#5
Anna	Lacking	Correct	Correct	Algorithm	No Answer	No Answer	No Answer, Confused
Beth	Explicit	Correct	Minor#	Algorithm	Correct	Incomplete	Correct
Cara	Lacking	Incorrect	Major%	–	No Answer	No Answer*	Partial Confused
Deb	Explicit	Correct	Correct	Correct	Correct	Incomplete	Mixed Confused
Ed	Implicit	Correct	Correct	Correct	Incorrect	Incomplete*	Mixed Confused
Frank	Implicit	Minor#	Correct	Algorithm@	Algorithm	Correct, Error	Correct

@ Initial attempt partially correct

*Problem was not asked, earlier answers were coded

#Minor labeled answers include partially correct answers with minor errors.

%Major labeled answers include answers with most of the answer correct, but that contain one major misconception.

Perceptions Task

The purpose of the Perceptions Task was to gain insight into the classwork habits of the students and gain knowledge of their views of chemistry and the learning of chemistry. Some of the students took the opportunity to go beyond the questions and gave their feelings and views of the course and chemistry. Several trends were seen in the Perceptions Task and related discussions. The comments concerned resources, such as the textbook and the software tutorial; chemistry in general, such as use of equations and examples; and the instructor's methods, such as his presentation of material and the course objectives.

Five of the six students referred to the textbook as a resource, but only Beth and Deb spoke of it in positive terms. Beth described reading the text material prior to lectures and Deb mentioned trying to remember text material during exams, implying that she used the textbook. Anna, Ed, and Frank mentioned that they had not made use of the textbook. They defended this practice by emphasizing the understanding gained from class lectures and the tutorial. Frank mentioned that with a different instructor he would have used the textbook differently, partially attributing his lack of use to want of immediate feedback when solving problems from the text. Ed mentioned that he felt that the textbook was not very useful, though he did not go into detail. Anna and Frank both praised the software tutorial for helping in learning the material. Anna liked it for the practice it gave her, and Frank liked the immediate feedback on problems.

The use of equations, algorithms, and examples came up in the interviews of most of the students. Deb mentioned that she had been focusing on learning the equations and "math-type stuff" and that had proven beneficial. Anna and Cara mentioned that they would be able to perform better if they had equations in front of them. They admitted to following steps in problem solving. Anna and Cara both discussed difficulties with understanding where the numbers that were used in equations came from. Having access to equations and examples was brought up by five of the students, referring to the notecards that they were allowed to use on exams. Anna, Beth, Cara, Deb, and Ed listed them as a valuable resource that helped in solving exam problems. Ed said that he tried to put every possible piece of information from the class notes onto his notecards, while Anna and Cara used them for equations, conversions, and worked out examples. Beth and Deb used their notecards primarily for information they had difficulty remembering. Anna, Cara, and Deb described their need for worked out examples for solving problems. Deb used worked out problems as a template or algorithm to help her work out problems and after a few attempts was able to work them out on her own. Anna and Cara implied that they were unable to solve problems without an example as an algorithm.

Most of the students praised Dr. Dalton's teaching. The praise was in two categories, his ability to make the content clear and his clear course objectives. Several of the students mentioned that they were able to solve problems by watching what Dr. Dalton did on the board and problem solutions made sense at that point. All but Deb mentioned the clear objectives for both the course and exams as a positive factor. Beth, Ed, and Frank specifically mentioned that Dr. Dalton made clear what parts of lecture material were important.

When discussing the expected course grades, all but Beth mentioned that they expected to earn a B for the course and all mentioned the possibility of earning an A for the course. Cara and Deb told of rejoicing if they were to receive an A. Cara suggested that she would frame the report if she were to earn an A.

DISCUSSION AND CONCLUSIONS

The students interviewed for this study had varying strengths and weaknesses in their chemistry knowledge and problem-solving abilities, but several trends were seen among the subjects. The trends included individual student's views of the nature of matter and the factors influencing their understandings.

Views of the Nature of Matter

Research question #1 asked what general chemistry students' understandings of the nature of matter were as demonstrated by their perception of chemical reactions. The subjects' views of the nature of matter varied with their conceptual understanding. All of the students were able to draw representations of the reaction represented in the balanced equation that were generally correct. Their representations were similar to those in the textbook and acceptable drawings from previous research (Lythcott, 1990; Yarroch, 1985) while showing some incorrect understandings. Based upon the Balancing and Drawing Tasks, except for those errors previously noted, the students' views of the nature of matter agreed with those of chemists. Essentially, the students understood that matter was made up of particles, but were unsure of how those particles were expected to behave in a reaction and had a weak understanding of the ties between the microscopic and macroscopic levels especially concerning limiting reactant situations.

Linking Structures to Problem Solving

The structures constructed by the students for the Card Sort Task offered insight into their thought processes relating to stoichiometry and chemistry in general, and exhibited several trends that answered research question #2 concerning a possible link between general chemistry students' conceptual structure of stoichiometry and their ability to solve computational and conceptual problems. The trends seen were: 1) each student's card sort structure was indicative of how they viewed stoichiometry, the connections made in problem solving, and their conceptual understanding; 2) the students with better conceptual understanding performed better on computational problems; 3) most of the students showed an organizing principle in their structure that placed limiting reactant problems at the pinnacle of stoichiometric problems; and, 4) few of the students showed strong connections between the microscopic, macroscopic, and symbolic levels of chemistry.

The individual structures provided a picture of how each student viewed chemistry and stoichiometry. There was evidence that the card sort structure was a good predictor of the problem-solving performance of the students. The two students with an explicit overall structure, Beth and Deb, were also the most successful problem solvers and the only two to show success on the computational problems. Ed and Frank appeared to have similar overall structures but did not communicate that structure in the interview. These two had some success on the conceptual problems, but limited success on the computational problems. Anna's and Cara's structures were the least structured and they had little success solving problems.

In a trend with similarities to the previous trend, the structures were good indicators of the conceptual understanding of the students. The students with stronger conceptual understanding, Beth and Deb, also had explicit card sort structures, while those in the middle group of conceptual understanding, Ed and Frank, had an implicit structure for the card sort. The two subjects with the weakest conceptual knowledge, Anna and Cara, had the least ordered card sort structures. The students' conceptual knowledge seemed to be linked to their organization of the concepts seen in the Card Sort Task.

Also linked to the previous trends was the tendency for students with better conceptual understanding to be better computational problem solvers. Beth and Deb were successful on both conceptual and computational problems while the remainder of the students struggled with the computational problems. Frank was an exception to this trend as he had a good conceptual understanding but performed poorly on the computational problems. This trend was similar to results found in several previous studies (Anamuah-Mensah, 1986; Anamuah-Mensah, Erickson, & Gaskell, 1987; Gabel et al., 1984; Lin, 1998; Lythcott, 1990; Mason et al., 1997; Nakhleh et al., 1996; Niaz, 1995b, 1998a; Phelps, 1996) including the statistical significance found by Niaz (1995b).

Factors Affecting Students' Conceptual Structures

The final research question asked what factors, if any, affect students' conceptual structure of chemistry as evidenced by their structure of stoichiometry. Several factors theorized to affect the students' conceptual structure of chemistry were examined in this study. The students' previous science and math coursework was examined, as were the possible influences of the textbook, the course, and the instructor. Various influences were found from the factors examined.

The previous science and math background of the students was examined and found to have little correlation with conceptual structure. In each pair of students grouped by their performance on the Card Sort Task, one had previously studied chemistry while the other had not. Deb, Ed, and Cara had all taken a prior chemistry course, while Beth, Frank, and Anna had not. A pattern concerning other science and math courses also failed to appear when the students' conceptual structures were considered.

One factor that might be tied to the students' backgrounds was that of confidence. Several of the students exhibited and admitted a lack of confidence in their chemistry knowledge. This lack was most evident in Deb, who changed correct answers to incorrect answers because she "second guessed" herself. Most of the other students did the same thing on one or more of the problems or tasks. Even Beth, the most successful of the students, showed a lack of confidence when she said that she was a little afraid of chemistry and when she downplayed her performance in the interview. This lack of confidence could have affected the conceptual structures, as the students were unsure of their understandings of the concepts.

The two resources available to the students, the textbook (Hill & Petrucci, 1996) and the software tutorial (Spain & Peters, 1997), had different effects on the students' understandings. The software tutorial was generally praised by the students for the practice it gave in problem solving, though Problem #1, which was similar to several tutorial problems, was only answered correctly by two of the students. Because the majority of the stoichiometry problems seen in the tutorial were computational, it could be assumed to have had a limited effect on the conceptual structures, but the computational focus of the tutorial might have contributed to the limiting reactant focus of the structures. The effect of the textbook was clearer. Those students that mentioned using the textbook often, Beth and Deb, had a clearer and more connected conceptual structure. Those students, Anna, Cara, and Ed, that mentioned rarely using the textbook because of the instructor's clear teaching, had less useable conceptual structures and were more focused on algorithms. There was a clear correlation between use of the textbook and the conceptual structures, as well as problem solving success. This connection could be due to the depth of material that the students were exposed to from the text, and that they would not be exposed to only from lectures.

Notecards were a factor that was not originally examined, but that showed an effect. The students who stated that they relied on them the most, Anna, Cara, and Ed, had the most difficulties in problem solving. They used the notecards as templates or algorithms, including problems that they might encounter.

The course exams were a major factor in the students' conceptual structures. Students had access to practice exams that reflected the material to be covered on exams and so knew what parts of the course materials to study. The exam questions covering stoichiometry were all computational, thus encouraging the students to focus on the computational aspects of stoichiometry but not conceptual aspects. This focus on exams went against the instructor's philosophy outlined in his interview, but did go along with his belief that the students' biggest obstacle was application of algebraic skills in problem solving. Nakhleh et al. (1996) and Phelps (1996) saw the powerful effect of exams, and given the percentage of the grade determined by the exams, it was not surprising to see a strong influence from the exams.

Though Dr. Dalton emphasized conceptual understanding in his interview and stressed understanding concepts in his lectures, there was a definite focus on the computational aspects of stoichiometry in the course. In the early lectures on stoichiometry and scattered throughout the unit, representations were used that focused on the concepts but there appeared to be the underlying awareness that if you could solve the computational problems then you understood stoichiometry. With the added emphasis from the exams it was clear why many of the students focused on learning algorithms, though the majority were unable to solve the computational problems in the interviews. The students' inability to solve the computational problems could be due to their reliance on algorithms without conceptual knowledge. They relied on algorithms that became unusable when short-term memory was gone. As many said in the interviews, they remembered parts of the algorithms, but not the entire algorithm. With conceptual knowledge, they might have been able to piece together a solution, as Beth and Deb did.

Thus, though Dr. Dalton tried to present the concepts and wanted the students to learn them, the implied emphasis was placed on solving computational problems. The students learned that to demonstrate knowledge of stoichiometry they needed to follow the algorithms and determine numeric answers; conceptual understanding was not seen as necessary for success.

Conclusions

Factors that might affect the students' conceptual structure were examined to determine possible influences and several patterns emerged in the data. 1) The science and mathematics backgrounds of the students showed little correlation with conceptual structures. 2) The lack of confidence exhibited by all of the students appeared to influence the students' conceptual structures by prompting them to question their understanding and solutions. 3) Textbook use showed a relationship to conceptual structures as those students who used the textbook frequently had more complete conceptual understanding. 4) The students saw the software tutorial, *ChemSkill Builder* (Spain & Peters, 1997), as a positive influence because it gave them immediate feedback on solutions, which encouraged them to practice problem solving more often. 5) Both the textbook and the tutorial may have encouraged a computational focus in the students because few problems were conceptual. Those problems that could be classified as conceptual rarely were above the comprehension level. 6) Notecards on exams appeared to be misused by the students who had the most difficulty in the interviews. They relied on information crammed onto notecards rather than understanding concepts. 7) The material covered on the course exams seemed to be a major influence on the understanding of the students interviewed; the students who struggled appeared to believe that knowing the material on the exam was all that they needed to succeed in the course. And, 8) the instructor appeared to have a strong influence because the students respected him and because they demonstrated problem-solving techniques taught in the course.

The trends seen in the data paint an interesting picture of the conceptual and computational knowledge of the students interviewed. The ways in which the students gathered and expressed that knowledge were also engaging. Many of the students described the difficulty of the subject of chemistry and implied that this difficulty was inherent in chemistry. Some researchers (Boo, 1998; Gabel, 1999; Kirkwood & Symington, 1996; Silberman, 1981; Tobias, 1990) have also expressed this opinion. There has been a large body of research done in an attempt to overcome both the perception of difficulty and the real difficulties inherent in chemistry concepts (see Bodner, 1991; Gabel, 1989; Gabel & Bunce, 1994; Herron, 1990; Krajcik, 1991). Deb described the difficulties in her interview:

> **Deb:** I think it's actually intimidation. You're dealing with something that you really can't see; you just have to believe it. That's my worst part. And then you can learn it in the classroom but when you go and apply it in the lab you do not think of it, this is what I'm doing all the time, I mean sometimes you do.

The ties between objects like atoms and molecules that cannot be seen and entities such as the evolving heat and chemical changes that can be seen or felt are often difficult to teach students, but are important for success in chemistry (Gabel, 1999; Herron, 1990; Jensen, 1998). Most of the students in this study had some knowledge of each of the three levels of chemistry, microscopic, macroscopic, and symbolic, but failed to make the important ties between the levels. How can chemical educators help students to develop these beneficial and critical ties?

Dr. Dalton used many strategies that should assist students. He tied real-world occurrences to the chemistry involved. He shared his enthusiasm for chemistry with his students and tried to assure them that they could do chemistry successfully. In his lectures he stressed concepts and computations rather than relying solely on computations, though there was a clear computational focus on the exams.

A related question is what should students do to learn chemistry at an acceptable level? Each of the students utilized some positive strategies to succeed; they attended class, solved practice problems on the tutorial, and prepared for the exams. They were engaged in their learning as much as they thought necessary. The students demonstrated a behavior that could be described as "learning to the test," where they learned only the material that would be assessed on the exams. Anna, Cara, and Deb made statements similar to comments made by surrogates studied by Tobias (1990) and students studied by Rop (1999) that indicated they wanted to learn the concepts behind the computations and be able to discuss those, but computational understanding was the material assessed. Anna's statement of the differences in her understanding of chemistry and of health was a good example.

> **Anna:** This is my first chemistry class that I have ever taken. A lot of it makes sense to me, like I can draw the little things, but like in the real world if I were to sit down and explain the process, they don't make sense to me. In some of my classes, like I have a health class and we have to write essays. I don't get the exact wording, but know the general concepts, so I can still write an essay about the general subject. But with this, I couldn't write an essay about what was going on. So, I could still do the problem, but I'm following steps, so I don't know why the problem works that way or what I'm doing or anything like that. That's something I've noticed with chemistry and math, in my other classes I know why something happens on the problems but in chemistry and math I don't know why. It doesn't make sense to me at that level.

The students appeared to miss the reason equations are used and what the models represented.

The use of algorithms in chemistry has been studied and discussed in science education literature since the beginning of the literature. Algorithms can be viewed as a structure or framework for students to use in solving problems, but algorithms can also be misused as a shortcut when understanding is limited or as a way to avoid expending cognitive energy in a solution (Herron, 1996). Boo (1998) found that "A more serious problem had also surfaced in this study: the fact that the vast majority of the students were unable to use a framework (whether scientific or alternative) consistently across [the problems]" (p. 578). Assisting students to develop useful frameworks and to consistently use them should be a priority in chemical education. Krajcik (1991) suggested that students need to develop an integrated conceptual framework to help them understand other chemical concepts. "Students learn bits of factual information; however, they do not develop an integrated conceptual framework that helps them understand other chemical concepts and phenomena" (Krajcik, p. 128).

Chemical educators should include in their instruction illustrations of the usefulness of a deeper understanding. Developing a pedagogical framework that would show the usefulness of a conceptual understanding is an important goal for chemical education. Several approaches have been suggested by educators, including constructivist approaches (see Bodner, 1986; Tobin & Tippins, 1993) and incorporation of instruction on the nature and history of science (Boo, 1998; Lin, 1998; Matthews, 1994; NRC, 1996; Niaz, 1995a, 1998a; Niaz & Robinson, 1992a; Orna, 1997) to provide a scaffold for aiding students in developing a conceptual framework.

Constructivist pedagogy provides a variety of frameworks for learners to experience the concepts and processes of science and incorporate those experiences into personal views of the world (Tobin & Tippins, 1993). Instructors should also provide opportunities for "students to represent their knowledge in a variety of ways throughout the lesson by writing, drawing, using symbols, and assigning language to what is known" (Tobin & Tippins, p. 11). By challenging students to experience and represent the important concepts and processes in chemistry, instructors aid them in constructing viable and productive understandings of chemistry that are useful in solving problems and incorporating new knowledge.

Incorporating the nature and history of science into curriculum and instruction has been suggested as a useful pedagogical method because it allows students to see how current scientific concepts have developed over time and to view science as a human endeavor (NRC, 1996). Students see that science is not static, but develops over time and is affected by societal issues such as economics and politics. By tying chemical concepts to the nature of science, students have a broader way of conceptualizing science and are challenged to incorporate scientific concepts and processes into their worldview. Carter's (1987; see Bodner, 1991; Herron, 1990, 1996) study demonstrated how students' views of the nature of chemistry affected their problem solving and suggested that addressing those views could improve problem solving. If students view chemistry as a formula-dependent science with little conceptual structure they will not pay attention to the important concepts of chemistry. If students do not understand the conjectural aspect of much of chemistry's portrayal of the microscopic world then they can have misconceptions of how the macroscopic and microscopic levels are linked (Boo, 1998).

The above suggested methods could prove successful in undergraduate chemistry instruction because they provide a framework for students to develop a conceptual understanding of chemistry that can be used in solving problems of all types. The instructional changes suggested by others (Coppola et al., 1997; Ege et al., 1997; Nakhleh et al., 1996; Towns & Grant, 1997; see Tobias, 1992) incorporated some of these approaches. These frameworks allow students to achieve the vision of "the something better" described by Rop (1999). "There is an almost mysterious chemistry that perhaps would help them in their future or even help them understand the real world better, lurking somewhere, as one student put it, for a select few who 'understand,' who 'like thinking about this kind of stuff,' or are not satisfied with just doing what it takes to get good grades" (Rop, p. 232).

Dr. Dalton used many of the pedagogical techniques that researchers (see Gabel & Bunce, 1994; Herron, 1996) have suggested positively influence students' chemical problem-solving ability, but many of the students interviewed were unsuccessful in the Problem-Solving Task. The students were successful in the course, each receiving a grade of B or better, but only Beth and Deb appeared to have an acceptable level of conceptual knowledge. It appeared that a major factor affecting students' understanding, and especially their lack of conceptual understanding, was assessment. Based on the interviews, it appeared that the students felt little extrinsic motivation to learn the concepts covered in the lecture and textbook. They were not held accountable to know concepts beyond the comprehension level on exams or in the tutorial, and they did not learn the concepts. The material to be covered on the exam was made clear to the students through practice exams on the course web page and the review sessions held prior to the exams. By seeing clear expectations, the students felt that if they prepared for computational problems, especially in stoichiometry, they could expect to succeed on the exams. Clear expectations are an important aspect of pedagogy, but expectations that sanction avoidance of learning important aspects of chemistry should be reexamined. Without being held accountable for conceptual understanding the students may not expend energy to learn them. The major motivation for the students to learn the concepts appeared to be intrinsic, and given the prior difficulties of some of the students, and the energy and time devoted to other courses, it was not surprising that they did not put in time learning and applying concepts. As BouJaoude and Bakarat (1999) suggested "the most important thing for students (parents too) is to 'pass the test'" (p. 24). Dr. Dalton was a good instructor and students showed respect for him in their interviews, and it should be noted that this course was not an easy course where all students succeeded easily. Based on exam score distributions, many of the students received failing or unsatisfactory grades.

Implications for Curriculum and Instruction

The results of this study have implications for science education at all levels, but all specifically apply to undergraduate chemical education. Science educators must help students make connections between the concepts of science and applications of those concepts. This study highlighted areas where those connections can be reinforced; an understanding of the particulate nature of matter and the models used to illustrate that nature; connections between the macroscopic, microscopic, and symbolic levels of chemistry; and completing the cycle of understanding by emphasizing conceptual understanding in course assignments and assessment.

An understanding of the particulate nature of matter has been suggested as an important aspect of chemistry students' understanding (Boo, 1998; Gabel, 1993; Gabel &

Bunce, 1994; Nakhleh, 1992), and the uses and limitations of the models of molecular structure and interaction are important for chemistry students to know (Harrison & Treagust, 1996, 1998). Students should be able to apply the different forms of molecular models, such as Lewis dot structures, physical models, and computer models, to predict behaviors based on the structures and to understand the limits of models. By understanding the models and their limitations, students should be able to demonstrate a more acceptable conceptual understanding of the nature of matter and how matter behaves at the microscopic and macroscopic levels.

Gabel (1999) emphasized the goal of understanding chemistry at the microscopic, macroscopic, and symbolic levels and encouraged chemical educators to help students build understanding at these levels. Failure to emphasize the levels and more importantly the connections between the levels leaves students with separate concepts with no cognitive connections between them. The disconnected understanding those students in this study exhibited must be addressed in curriculum and instruction. The gap may be narrowed through instruction that ties particle behaviors at the microscopic level with the macroscopic properties that can be measured and experienced by the students.

All science educators need to ensure that the work expected of students reflect the objectives of the course. Expecting conceptual understanding without asking students to practice or demonstrate that understanding is pedagogically unsound. Though Dr. Dalton stressed the importance of concepts in the interview, the students were not required to display conceptual understanding in any of the tasks required of them. The assessment structure did not provide any rewards for learning the concepts behind the computational problems. Expecting demonstration of conceptual understanding can complete the cycle of understanding that includes instruction on the concepts. As Yarroch (1985) stated, "Unfortunately, the mechanical manipulation of symbols is enough to satisfactorily pass the evaluation instruments prepared by most teachers" (p. 458).

As in studies by Yarroch (1985) and Lythcott (1990), the students in this study showed a weak understanding of the meaning of balanced equations. The balancing of chemical equations can easily be an algorithmic exercise to students (Niaz & Lawson, 1985; Moore, 1997a; Yarroch), and without curriculum and instruction emphasizing why balanced equations are necessary and useful students will learn the algorithms and follow certain rules because that was what their instructors expected of them (Yarroch). Students must be given the scientific reasons behind the methods of balancing equations and the physical meanings associated with stoichiometric coefficients and subscripts in chemical formulas. Students should be taught not only what scientists do, but also why they do it. The arguments for greater depth in instruction on balancing equations also apply to other fundamental principles of chemistry. Greater emphasis on "why" will help students develop the skills to solve what King and Kitchener (1994) referred to as ill-structured problems, essentially the real-world problems that educators want their students to be able to solve.

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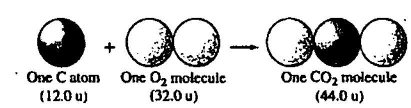
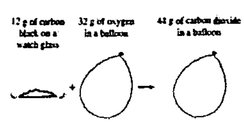
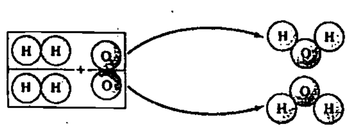
APPENDIX A: CARD SORT TASK CARDS

The cards below were given to the students and instructor during the Card Sort Task. Each representation was included on a 3"x5" index card. Cards 10, 11, 17, 19, 24, 26, 33, 34, 35, and 36 were removed in the validation process.

Card #1 **Molecular weight** is the average mass of a molecule of a substance based on a mass of 12 amu for carbon-12	**Card #2** C: 1 x 12.011 g/mol = 12.011 g/mol O: 2 x 15.9994 g/mol = 31.9988 g/mol CO_2 = 44.010 g/mol
Card #3 Sum of the masses of the atoms represented in a molecular formula	**Card #4** 6.022 x 10^{23} atoms/mol
Card #5 **Mole** is the amount of a substance that contains as many elementary units as there are atoms in exactly 12 g of the carbon-12 isotope	**Card #6**  (Hill & Petrucci, 1996)
Card #7  (Hill & Petrucci, 1996)	**Card #8** **Molar mass** – mass of 1 mole of a substance
Card #9 1 mol Na = 22.99 g Na = 6.022 x 10^{23} Na atoms	**Card #12** Reactants → Products ΔH
Card #13  (Hill & Petrucci, 1996)	**Card #14** C_3H_8 (g) + 5 O_2 (g) --> 3 CO_2 (g) + 4 H_2O (g) •1 mol C_3H_8 reacts with 5 mol O_2 •3 mol CO_2 is produced for every 1 mol C_3H_8 reacted •4 mol H_2O is produced for every 3 mol CO_2 produced (Hill & Petrucci, 1996)

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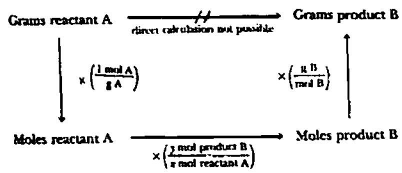
Card # 15

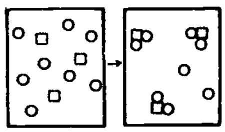


(Kotz & Treichel, 1999)

Card #16

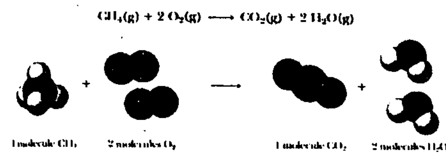
Limiting reactant is the reactant that is completely consumed in a reaction

Card #18



(Nurrenbern & Pickering, 1987)

Card #20



(Kotz & Treichel, 1999)

Card #21

$$224 \text{ g } SiCl_4 * \frac{1 \text{ mol } SiCl_4}{169.9 \text{ g}} = 1.32 \text{ mol } SiCl_4$$

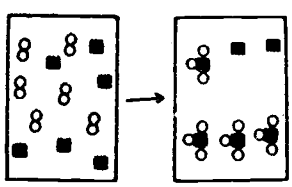
$$1.32 \text{ mol } SiCl_4 * \frac{1 \text{ mol Si}}{1 \text{ mol } SiCl_4} = 1.32 \text{ mol Si}$$

$$1.32 \text{ mol Si} * \frac{28.09 \text{ g Si}}{1 \text{ mol Si}} = 37.1 \text{ g Si}$$

Card #22

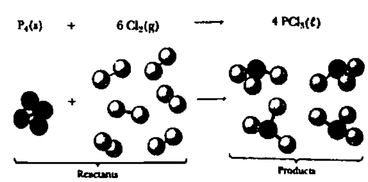
X grams of chemical A reacts with an excess of chemical B, and forms chemical C. How many grams of chemical C is produced?

Card #23



(Nurrenbern & Pickering, 1987)

Card #25



(Kotz & Treichel, 1999)

Card #27

$\Delta H > 0$

Card #28

$\Delta H < 0$

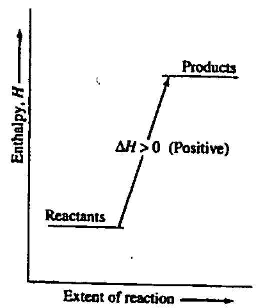
Card #29

Energy is released during a reaction

Card #30

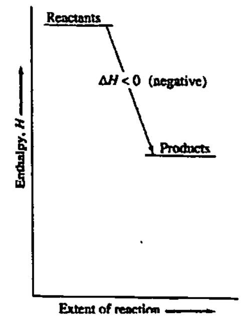
Energy is absorbed during a reaction

Card #31



(Hill & Petrucci, 1996)

Card #32



(Hill & Petrucci, 1996)

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APPENDIX B: EQUATIONS AND PROBLEMS FOR INTERVIEW

Equations for Balancing Task

$N_2(g) + H_2(g) \text{ --> } NH_3(g)$

$K(s) + H_2O(l) \text{ --> } KOH\ (aq) + H_2(g)$

$CH_4(g) + O_2(g) \text{ --> } CO_2(g) + H_2O(g)$

Problems for Problem-Solving Task

All problems were given to the students on separate sheets of paper. References were not included on student problems.

Problem #1 (Conceptual)
How many moles of chloride ions are present in 2 moles of magnesium chloride ($MgCl_2$)?

Problem #2 (Computational)
How many grams of oxygen would be needed to react completely with 1.00 g of C_2H_6?

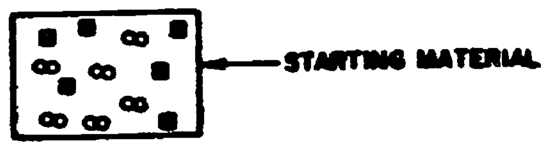
$2\ C_2H_6 + 7\ O_2 \rightarrow 4\ CO_2 + 6\ H_2O$

Problem #3 (Conceptual)
What information is provided by a balanced equation, such as the one below?

$CH_4 + 2\ Cl_2 \rightarrow CCl_4 + 2\ H_2$ (Kotz & Treichel, 1999)

Problem #4 (Computational)
When 8.00 g of hydrogen reacts with 32.0 g of oxygen, what will the final product mixture contain? (Ragsdale, 1999)

Problem #5 (Conceptual)
The equation for a reaction is $2Al + 3Cl_2 \text{-->} 2 AlCl_3$. Consider the mixture of Al (squares) and Cl_2 (00) in a closed container as illustrated below:



Draw the product mixture. (Nurrenbern & Pickering, 1987)

Problem #6 (Computational)
What is the enthalpy change when 12.8 g $H_2(g)$ reacts with excess $Cl_2(g)$ to form HCL(g)?

$H_2(g) + Cl_2(g) \text{-->} 2 HCl(g)$ $\Delta H = - 184.6$ kJ
(Hill & Petrucci, 1996)

Problem #7 (Conceptual)
The combustion of methanol is an exothermic reaction that produces carbon dioxide and water. What would you expect the sign of the enthalpy change to be for the formation of methanol from carbon dioxide and water?

Problem #8 (Conceptual)
When calcium carbide (CaC_2) reacts with water two products are formed, acetylene (C_2H_2) and calcium oxide (CaO). Draw a picture, based on the balanced equation below, that represents 2 molecules of calcium carbide reacting with 4 molecules of water.

$CaC_2(s) + H_2O(l) \text{-->} CaO(s) + C_2H_2(g)$

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