AN ABSTRACT OF THE THESIS OF

Adam J. Wolfer for the degree of Doctor of Philosophy in Science Education presented on March 9, 2000. Title: Introductory College Chemistry Students' Understanding of Stoichiometry: Connections Between Conceptual and Computational Understandings and Instruction.

Abstract approval: __________________________
Norman G. Lederman

Previous research has shown a gap between chemistry students' conceptual and computational understandings of chemistry topics such as gas laws, equilibrium, and reactions. This qualitative study examined the conceptual and computational understandings of stoichiometry of college students enrolled in a large lecture Introductory Chemistry course. Factors that might influence students' understandings were examined to determine their influence.

Possible influential factors examined included students' prior coursework, and their current chemistry instruction. Instruction on stoichiometry was examined through classroom observations, an instructor interview, and review of the course resources. Course exams and out-of-class assignments were also examined for their influence on students.

Student volunteers (n=6) were interviewed to gauge their understanding of stoichiometry. Students' understanding was assessed through tasks that included a card sort, solving conceptual and computational problems, drawing representations of reactions, and answering questions concerning their philosophy of learning chemistry.
Results indicated that students had an acceptable understanding of the particulate nature of matter but did not apply this knowledge to problem solving. The students were most comfortable solving computational problems where they could apply algorithms learned from their instructor. The students also applied algorithms in answering conceptual problems. There appeared to be a connection between the students' conceptual structures of stoichiometry and their ability to solve computational problems. The lack of conceptual questions in assessment appeared to be a major contributing factor in the students' lack of conceptual understanding because the students discounted the importance of learning aspects of stoichiometry that were not included on exams. Other contributing factors included the computational focus of instruction on limiting reactant problems, textbook presentation, and student exercises.

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DEDICATION

Dedicated to the memory of Louis "Big Lou" Wolfer
1935 – 1998

He taught me life's biggest lessons.

Adam: "I don't know how to do that."

Dad: "Son, you won't be able to say that when you're done."
CHAPTER 1: 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

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. The *Benchmarks for Science Literacy* (AAAS, 1993) proposes the sequence of conceptual to computational for important chemistry concepts such as gas behavior, which can be understood at a molecular model level or a mathematical model, such as $PV=nRT$ (Nakhleh, 1992; Niaz & Robinson, 1992a). Many researchers have found that chemistry students' understanding of the particulate nature of matter is lacking (Ben-Zvi, Eylon, & Silberstein, 1986; Boo, 1998; Gabel, 1993; Gabel, Samuel, & Hunn, 1987; Novick & Nussbaum, 1981; Yarroch, 1985; see Nakhleh, 1992) and this lack of understanding has been proposed as one cause of the gap between conceptual understanding and problem-solving ability (Boo; Gussarsky & Gorodetsky, 1990; Herron, 1990, 1996; Nakhleh, 1992, 1993; Noh & Scharmann, 1997). In several reviews of research (Gabel, 1989; Gabel & Bunce; Herron, 1990, 1996;
Krajcik, 1991) students' difficulties in problem solving are linked to lack of conceptual knowledge.

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 that continues today (Pushkin, 1998). But, the role of mathematical applications has not been a recent addition to chemical education; having been discussed in the mid-1920s in several articles published in the early years of the *Journal of Chemical Education* (Bradshaw, 1926; Brinkley, 1925, 1927; Ward, 1926). As Brinkley (1927) stated, "Unless a very careful selection [of computational problems] is made, the problems are likely to become 'mathematical puzzles' in which the students see no connection with the subject-matter under consideration" (p. 1283).

**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 (1979), Gabel (1981), 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. According to Herron (1996), "algorithms are carefully developed procedures for getting right answers to exercises and routine tasks within problems with a minimum of effort" (p. 64).

Researchers and teachers have assessed chemistry knowledge with the use of problems that require the manipulation of formulas to determine a numerical answer. For some problems, instructors teach an algorithm or encourage students to develop their own algorithm to solve the problem (Kean & Middlecamp, 1994; Kean, Middlecamp, & Scott, 1988; Middlecamp & Kean, 1987). Anamuah-Mensah (1986) suggested that many teachers found it easier to teach problems through algorithms and formulas, thus ignoring conceptual knowledge. In a review of chemistry problem-solving research, Gabel and Bunce (1994) stated this finding as: "In lieu of solving problems on the basis of conceptual understanding, they use algorithms and formulas to arrive at 'correct answers' " (p. 305). Some students used what was referred to as a Rolodex approach, whereby they searched through memorized formulas until finding one where the units in the data matched the units in the problem (Bunce et al., 1991).

It has been suggested that the problem-solving discontinuity may be perpetuated in chemistry and other sciences because educators allow students to hide their lack of understanding behind numerically correct answers (Phelps, 1996; Pushkin, 1998). There then exists a reward system for students to ignore the difficult concepts and develop the Rolodex system (Bunce et al., 1991). While discussing instructional reform, Coppola, Ege, and Lawton (1997), cautioned that "If examinations do not consistently and exclusively reflect goals, reform efforts are ignored by the learners for whom they are intended" (p. 87). The NRC (1996) recommends that educators probe for "students' understanding, reasoning, and the utilization of knowledge" (p. 82), to ensure that students learn the concepts rather than exclusively learning problem solving.

In chemistry, as in other sciences, qualitative and quantitative models are developed to predict the behaviors of chemical species under given circumstances. These
models have limitations that are often not discussed or understood by those learning the models. In chemistry the quantitative models are generally only viable under a limited set of conditions. For example, in environmental chemistry, a current area of concern and interest (see Schwarzenbach, Gschwend, & Imoden, 1993), one mathematical model of a chemical's properties in a medium (for example: solubility of DDT in lake water) will give one answer, but another model based upon another set of parameters may give a contradictory solution. Conceptual understanding of the models, their limitations, and the chemistry will help students predict what the observable behavior of the chemicals may be. Conceptual understanding gives a basis for the application of the algorithmic answers (AAAS, 1990, 1993; Herron, 1990; NRC, 1996, 1997).

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).

There are several difficulties associated with developing a chemical view of the nature of matter; according to Bunce and Gabel (1994), the primary difficulty is the abstract nature of the concepts. How chemical educators present this material may have a positive effect (Lin, 1998; Noh & Scharmann, 1996), but it is also important that the textbooks reflect the microscopic and macroscopic views of matter (Jensen, 1998a, 1998b, 1998c; Lee, 1999; Niaz, 1998b). DeBerg (1989), in a textbook analysis, noted that the treatment of the qualitative properties of gases in chemistry textbooks was minimal and typically was used to develop the quantitative properties of gases. Jensen (1998b, 1998c) suggested that textbooks fail to truly reflect the structure and history of chemistry, which leads to students' failure to focus on the overall chemical knowledge that instructors wish them to attain. Kuhn (1970b) suggested that: "More than any other single aspect of
science, that pedagogic form [textbook] has determined our image of the nature of science and of the role of discovery and invention in its advance" (p. 143).

Jensen (1998a, 1998c) and Gabel (1999) have published reflections discussing models that may prove useful in chemistry education. In Gabel's (1999) discussion, chemistry understanding is viewed at three levels – macroscopic, microscopic, and symbolic (Johnstone, 1991). At the macroscopic level are the observable phenomena we experience, such as the violent reaction between potassium metal and water. The microscopic level contains the interactions between atoms, molecules, and electrons that are believed to cause the observable phenomena studied in chemistry. The symbolic level is the way in which meanings are communicated, such as in chemical equations. Gabel (1999) believes that helping students to understand these three levels and their interactions has potential for improving conceptual understanding, and research (Lee, 1999) supports her position.

Jensen (1998a) also divides chemistry understanding into three levels – the molar level, the molecular level, and the electrical level. The molar level is the same as the macroscopic level, while the molecular and electrical levels make up the microscopic level. The logical structure of chemistry also has a second dimension made up of three dimensions – the Composition & Structure Dimension, the Energy Dimension, and the Time Dimension. Jensen (1998a) believes that if chemistry educators communicate the interactions between the levels and dimensions, the conceptual understanding of students will increase.

In his influential book, The Structure of Scientific Revolutions, Kuhn (1970b) suggested how scientists learn the formulas in their field:

Scientists, it should already be clear, never learn concepts, laws, and theories in the abstract and by themselves. Instead, these intellectual tools are from the start encountered in a historically and pedagogically prior unit that displays them with and through their applications. (p. 46)
Niaz (1995b, 1998a) and Niaz and Robinson (1992a) have suggested that students go through similar transitions while learning the formulas necessary in chemistry, while Jensen (1998a, 1998b, 1998c), Laing (1996), and Lin (1998) suggest that a greater focus on the historical development of chemistry will aid students in proper applications of conceptual knowledge.

**Statement of the Problem**

Many studies of college chemistry students (Bunce et al., 1991; Herron & Greenbowe, 1986; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Mason, 1995; Mason & Crawley, 1994; Mason, Shell, & Crawley, 1997; Niaz, 1995b, 1995c; Niaz & Robinson, 1992a, 1993; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990; Zoller, Lubezky, Nakhleh, Tessier, & Dori, 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 et al., 1997; Nakhleh, Lowery, & Mitchell, 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. The
developmental level of chemistry students has also been suggested as a possible influence, whether based on Piagetian theories (Gabel et al., 1984; Niaz & Robinson, 1992a, 1992b, 1993) or the scheme of William Perry (1970/1999) (Pushkin). In a recent commentary, Pushkin listed four possible reasons for this disparity between conceptual and computational understanding of chemistry: 1. General chemistry students tend to follow a set of procedures and rules in solving problems. 2. Students are either dualistic and see their roles as submissive in accepting what their instructors tell them without question, or students are multiplistic and accept what instructors tell them only under testing conditions (see Perry, 1970/1999). 3. Novice learners are subjected to science curricula and pedagogy that discourage critical and conceptual thinking. 4. Those who teach introductory chemistry and physics place more value on algorithmic learning than on conceptual learning, giving learners the impression that science is 'math in disguise' (Pushkin, p. 809). Pushkin feels that instructors fail to challenge their students to critically examine knowledge and fail to emphasize the concepts that inform computations. One study (Niaz, 1995b) and a commentary (Pushkin) suggest 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. "This happens primarily because conceptual learners evolve over a period of time from their learning experiences; their understanding is a manifestation of collected knowledge, not immediate knowledge. Conceptual learning is an evolution beyond fundamental competence" (Pushkin, p. 809).

Niaz (1995b, 1995c, 1996a, 1996b, 1998a), and Niaz and Robinson (1992a, 1993) have examined this question in numerous studies, many of which (Niaz, 1995b, 1995c; Niaz & Robinson, 1992a, 1993) attempted to support reasons for the computational/conceptual disparity. They have also proposed educational strategies for addressing the problem (Niaz, 1995a, 1996a, 1996b, 1998a, 1999; Niaz & Robinson, 1993). Though the studies listed have added to the science education literature, the
methods used in data collection and analysis show some design problems (e.g., low reliability, multiple significance tests, and no reported validity) that limit their integrity.

In these studies, data were collected by including computational and conceptual problems on regularly scheduled exams in college chemistry courses. The data were primarily the number of correct and incorrect responses on the test items, though in three studies, Niaz (1995b, 1996a, 1998a) did examine the problem-solving strategies used by the subjects. In these studies (Niaz, 1995b, 1995c, 1998a; Niaz & Robinson, 1992a, 1993) the data were quantitatively analyzed to support the authors' hypothesis. The authors presented the following results: algorithmic success was not a predictor of conceptual success (Niaz & Robinson, 1993); students' path to conceptual understanding was similar to that found in the history of gas law development (Niaz & Robinson, 1992a); the relationship between algorithmic and conceptual understanding was a continuum, not a dichotomy (Niaz, 1995b); the path to conceptual understanding taken by students was similar to the "problemshifts" proposed by Lakatos (1970) (Niaz, 1995b, 1998a); conceptual success was a predictor of computational success, and closely related conceptual problems built on each others' success (Niaz 1995c, 1998a). In the studies done by Niaz, and Niaz and Robinson, the logical connections between the data and the theories that they supposedly supported were often tenuous, and sometimes difficult to accept. Other results from these studies were less logically difficult, but were tainted by low reliability of instruments.

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, Kirsch, & Turner, 1996; Lythcott, 1990; Mason, 1995; Mason et al., 1997; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz, 1995b, 1995c; 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. This strategy hopefully addresses Pushkin's (1998) primary concern, which was determining "the distinction between conceptual and algorithmic learning" (p. 809). 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. The results may help chemistry educators understand Pushkin's first two developmental reasons for the disparity and address his third and fourth pedagogical reasons and provide students of all levels a better understanding of the beauty and value of chemistry.

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 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.
CHAPTER 2: REVIEW OF THE LITERATURE

The issue in the research to be reviewed is the truth of the statement from a popular song: "Some long ago, when we were taught, that for whatever kind of puzzle you got, just stick the right formula in, a solution for every fool" (Saliers, 1994). The research reports reviewed used both qualitative and quantitative research, and approached the question of students' conceptual knowledge of chemistry with respect to their algorithmic problem solving abilities. Many of the authors disagreed with each other, and often found fault with other reports in this area, but most pointed in the same direction—that the majority of chemistry students solve problems by means of algorithms without application of conceptual knowledge.

The reports reviewed cover research that defined the problem, explored students' problem-solving abilities, attempted to categorize problem solvers, examined student perceptions, examined the role of the history and philosophy of science, and examined strategies for enhancing both conceptual understanding and problem-solving ability.

Problem Definition

The articles in this section represented the acknowledgement of a possible problem in chemical education. The problem is students' lack of conceptual knowledge, hidden behind algorithmic success. The articles were not necessarily the first to find the difficulties they describe, but these reports sparked interest in the science education literature that is still present more than 10 years later. These studies were all done at colleges and universities in the United States and were reported in the science education literature. The question of these studies can be stated in the question: "Does the ability to solve a problem imply any understanding of the molecular concepts behind the problem?" (Pickering, 1990, p. 254).
Nurrenbern and Pickering (1987) studied the chemistry problem-solving abilities and conceptual knowledge of general chemistry students at the University of Missouri-Kansas City and the University of Wisconsin-Stout. The purpose of the study was to test the widely held assumption that "being able to solve problems is equivalent to understanding of molecular concepts" (p. 508).

The classes studied included the following levels of general chemistry: preparatory, terminal, and both terms of a two-semester course. In the initial study each student was asked to answer a traditional problem and a conceptual question on gases utilizing Boyle's Law, Charles' Law, or the combined gas law as part of a Unit Test or a Semester Final (see Figure 1). The traditional questions could be answered using algorithms while the conceptual question could not be answered with algorithms. The second part of the study utilized similarly paired limiting-reagent problems with different samples and a different topic, stoichiometry.

The authors found that the students had much greater success answering the traditional problems when compared to the conceptual questions. The authors proposed that the difference in correct responses in the gas law problems showed that "these answers do not reflect an accurate view of the behavior of gases, even though students are proficient at solving gas law problems" (Nurrenbern & Pickering, 1987, p. 509). The results showed similar, yet smaller, differences for the stoichiometry problems, though these problems were given to three different classes of students. The authors theorized that the students used "plug-and-chug" or algorithmic methods to solve the problems rather than understanding chemical changes at the microscopic level. "The present
research argues that teaching students to solve problems about chemistry is not equivalent to teaching them about the nature of matter" (Nurrenbern & Pickering, p. 509).

Traditional Question

Boyle's Law

A quantity of gas occupies 76.8 mL at a pressure of 772 mm Hg. What will be the volume of the gas at 760 mm Hg (standard pressure)?

Conceptual Question

The following diagram represents a cross-sectional area of a rigid sealed steel tank filled with hydrogen gas at 20 °C and 3 atm pressure. The dots represent the distribution of all the hydrogen molecules in the tank.

Which of the following diagrams illustrate one probable distribution of molecules of hydrogen gas in the sealed steel tank if the temperature is lowered to -5 °C? The boiling point of hydrogen is -252.8 °C.

(A)  
(B)  
(C)  
(D)  

Figure 1. Examples of Traditional and Conceptual Questions (Nurrenbern & Pickering, 1987, p. 508-509)

Sawrey (1990) responded to the assertions of Yarroch (1985) and Nurrenbern and Pickering (1987) that students correctly answered chemistry problems without utilizing
conceptual knowledge. The author felt that the previous studies raised concerns that could have important impact on the chemical education community:

Many instructors, myself included, have believed (or hoped) that teaching students to solve problems is equivalent to teaching the concepts. If, as is now being proposed, this axiom is not true, then we all must rethink our approach to chemical education. (p. 253)

The author pointed out two apparent limitations in the earlier studies that she wished to remedy. Yarroch and Nurrenbern and Pickering conducted their studies on relatively small classes and the latter study was conducted with a non-mainstream heterogeneous population. The author felt that with an average to above-average homogeneous student population, the difference between conceptual and numerical understanding would be less evident because the students would be bright enough to do both well.

To accomplish this purpose, Sawrey (1990) repeated the Nurrenbern and Pickering (1987) study with a larger and more homogeneous group of students at a well-known university. In addition she examined whether the students in the top 27% and the bottom 27% of the class performed differently on conceptual versus numerical problems. The upper and lower portions of the class were determined by overall performance on the exam containing the research problems. The questions devised by Nurrenbern and Pickering, altered to be multiple choice, were given during regular tests in the first quarter of a yearlong general chemistry course for science majors. The results showed that the students had greater success answering the traditional problems than the conceptual problems. This problem was evident at all levels, thus failing to support the author's hypothesis that the trend would not appear with better students.

Pickering (1990) endeavored to replicate the results of his earlier study (Nurrenbern & Pickering, 1987), which had generated considerable interest in the chemical education community. The purpose of this study included trying to answer several questions concerning college chemistry students. The questions were:
What happens to the students when they get to other courses in chemistry, organic for instance? Are there two kinds of students, some who possess an ability to do conceptual problems and some who can do mathematical problems without molecular understanding? Is the difference between the groups a difference of ability or just a gap in knowledge? (Pickering, p. 254)

To answer these questions, the author followed a group of Princeton students from freshman chemistry into their sophomore organic chemistry course and analyzed their achievement in both courses. The subjects were administered the gas questions from the Nurrenbern and Pickering (1987) study as part of the first exam in the lower-level freshman chemistry course.

The author found that the results were similar to those found by Sawrey (1990) and Nurrenbern and Pickering (1987) for the conceptual problem. The students who answered both problems correctly were grouped as Successful (N=38) and those who answered only the traditional problem correctly were grouped as Nonsuccessful (N=95). The average grades for the first exam (minus the points for the concept problem) and the total for all non-laboratory work were compared for the Successful and Nonsuccessful groups utilizing a t-test. The difference between the means were statistically significant at the p<0.01 level for both measurements.

The subjects were followed into organic chemistry and their final exam and course grades were compared. The means were tested with a t-test, and a small but not statistically significant difference was found. Not all subjects continued in organic chemistry, so the group sample sizes dropped to 20 Successful (from 38) and 28 Nonsuccessful (from 95). Because the differences found might be due to the successful students on average being better students in freshman chemistry and the possible carryover to organic chemistry, the author compared the groups in a pair-wise manner. Each subject from the Successful group was paired with a subject from the Nonsuccessful group that had a nearly identical freshman chemistry score. The slight difference in means disappeared with this matched grouping. The author stated that this lack of difference
when compared in matched pairs "argues strongly that the difficulty with the conceptual
questions is the lack of some specific factual knowledge about gases, not some arcane
ability difference" (Pickering, p. 255). The author argued that the similar results in the
previous studies (Nurrenbern & Pickering, 1987; Sawrey, 1990) supported his claim.

Nakhleh (1993) hoped to identify chemistry students who have the ability to study
chemistry but are not attracted to it as a field of study. These students were labeled as
"second tier" students in the work of Tobias (1990).

In an attempt to accomplish this, Nakhleh (1993) devised a simple test to
investigate differential performance on conceptual and problem-solving questions. The
test consisted of five matched pairs of questions covering chemistry areas that were
covered in the chemistry courses investigated. The five areas were: 1) gas laws, 2)
equations, 3) limiting reagents, 4) empirical formulas, and 5) density. Each pair consisted
of one question that could be answered by manipulating a formula or by use of an
algorithm, and one question that required conceptual knowledge to be answered correctly.
Pairs 1, 3, and 5 contained a conceptual question that required interpretation of a drawing,
while pairs 2 and 4 contained conceptual problems that required interpretation of text
alone.

The study was conducted at a large Midwestern university in four general
chemistry courses. The four courses were (class sizes in parentheses): remedial (167),
science/engineering majors (830), chemistry majors (56), and honors (37). The questions
were randomly incorporated into the first-semester final exam for these courses. The gas
law questions were adapted, by adding a fourth distracter, from those used by Nurrenbern
and Pickering (1987). There were three omissions in the questions, as the limiting reagent
problems were not included for the engineering/science majors course, and the empirical
formula problems were not included for the remedial course and the engineering/science
majors course.
The numbers of correct answers for each topic and for each course (except noted above) were included. The answers were categorized as A1 for a correct algorithmic question, A0 for an incorrect algorithmic question, C1 for a correct conceptual question, and C0 for an incorrect conceptual problem. Four possible categories were available for each student on each matched pair:

- A1C0: algorithmic correct, conceptual incorrect
- A0C1: algorithmic incorrect, conceptual correct
- A1C1: both correct
- A0C0: both incorrect

The possibilities placed the students in the scheme shown in Figure 2.

<table>
<thead>
<tr>
<th>Conceptual Thinking</th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithmic Problem</td>
<td>Meaningful problem solving, good understanding (A1C1)</td>
<td>Many successful chemistry students (A1C0)</td>
</tr>
<tr>
<td>Solving</td>
<td>Second Tier students who are more interested in why chemistry students than how (A0C1)</td>
<td>Many unsuccessful chemistry students (A0C0)</td>
</tr>
</tbody>
</table>

Figure 2. Possible categories of students in general chemistry classes. (Nakhleh, 1993, p. 53)

The author proposed three initial hypotheses: 1) The remedial course would have the highest concentration of conceptual thinkers. 2) The honors students would demonstrate both types of thinking. 3) The engineering/science majors course would be made up of mostly algorithmic thinkers, as well as some conceptual thinkers.
The author claimed that, by inspection, the data indicated many of the subjects could answer an algorithmic question correctly, but could not answer a conceptual problem correctly. Eleven of the comparisons were found to be statistically significant for a difference in performance on the paired questions. Comparing results on the gas law problems with the results found by Nurrenbern and Pickering (1987), the author found similar frequencies and significance levels in both studies.

The author noted and attempted to explain three interesting findings in the results. The first, that there was little difference in results on the topic of equations for the remedial subjects when compared to the other groups. This result was explained as being due to the professor's incorporation of conceptual ideas in both the lectures and exams. The second finding was that chemistry majors had no significant differences on limiting reagents. This result was explained by the fact that the students were chemistry majors and might be more willing to construct their chemistry knowledge in a particulate nature. The third result was that except for the remedial class there were no significant differences for the density questions. This result was explained by the assumption that all of the students had studied density many times in high school and had developed adequate conceptual and algorithmic knowledge of density.

Nakhleh (1993) compared the results across courses for the pairs, comparing results for gas laws, equations, and density because there was a complete set of data for these topics. Significant differences were found for gas laws ($p=0.016$), equations (no $p$ given), and density ($p=0.006$). The comparison of means for each class showed that the score on the algorithmic questions was higher than for conceptual questions for all three categories.

All responses were counted and the responses fell in the categories as follows: 49% in high algorithmic/high conceptual (A1C1), 31% in high algorithmic/low conceptual (A1C0), 10% in low algorithmic/high conceptual (A0C1), and 10% in low algorithmic/low conceptual (A0C0). The author cited the 31% in A1C0 as a cause for concern since many
students were able to answer traditional problems without the important conceptual knowledge at the end of a year of chemistry instruction.

The author reported that Hypothesis 1 was not supported by the data, as the remedial course had the same trend of more algorithmic success. The data did support Hypothesis 2, with the honors students performing better on both algorithmic and conceptual problems. Hypothesis 3 was also supported according to the author, though the data was based on three of the five areas, and not all five. The original purpose of this research, to devise a way to identify second tier students in chemistry, was not mentioned after the introduction, so it may have been dropped or been deemed unsuccessful.

Zoller, Lubezky, Nakhleh, Tessier, and Dori (1995) attempted to examine the differences between students' performance on algorithmic, lower order cognitive skills (LOCS), and conceptual exam questions. They further studied the differences between university chemistry students in the United States and Israel.

This study was a comparative study that focused on the differences in students' performance on algorithmic, LOCS, and conceptual exam questions across populations. The goal of the authors was to determine student performance on these three categories, explore correlations between them, and to find possible reasons for any differences. They wished to translate their research into appropriate instructional strategies.

For this study, Zoller et al. (1995) constructed eight questions and designated them as testing algorithmic, LOCS, conceptual, and HOCS understanding. The definitions of algorithmic and conceptual questions were similar to those used in earlier research (Nakhleh, 1993; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering, 1987). The definitions for LOCS and HOCS were simplified to: LOCS questions are those that require simple recall, or application of familiar knowledge or algorithms; and HOCS questions are those that require students to apply knowledge to unfamiliar situations or to make connections or evaluations. The eight questions were placed on the midterm or final at both Israeli universities, but only questions 1-3 were used at Purdue University. No
reason for this omission was given, but based on the omission, the authors reported only the results from questions 1-3. Question 2 was the steel-tank problem taken from Nurrenbern and Pickering (1987) (see Figure 1). The three questions were from each of the three categories tested: algorithmic, LOCS, and conceptual. The authors mentioned that a future report would examine the HOCS questions and the data from those questions and from interviews of the Israeli students.

The results showed that for all three groups of students the highest score was for the algorithmic question, with the LOCS question next, and the conceptual question with the lowest score. The authors felt it interesting that the general pattern of means was maintained even when the students were chemistry or science and engineering majors at Technion in Israel or Purdue. Zoller et al. (1995) based two conclusions on the consistent results: 1) algorithmic success on exams does not imply conceptual success; and, 2) algorithmic success does not imply LOCS success.

The authors' analysis further pointed out that, despite their prediction otherwise, students were able to solve algorithmic problems without using LOCS reasoning. The authors predicted that the algorithmic and LOCS problems would correlate closely because most chemistry students were taught algorithms to solve the problems and they felt that the students would have memorized them. Zoller et al. (1995) found this result disconcerting and asked: "Does this suggest that traditional algorithmic questions – the ones most commonly found on chemistry tests – constitute a separate class/category where success requires mainly memorization and technical skills, often with little or no understanding so that even LOCS are more conceptual?" (p. 989).

The authors identified the difference in means between Israeli and American students as possibly the most significant finding of the study. The means for the two sets of Israeli students were consistently higher than for the Purdue students. The authors presented possible factors for this result, which were the different class size and instructional styles used. Classes in Israel were smaller and the teaching style was more
interactive and HOCS oriented than that at Purdue. No observational evidence for this ranking was given. "The two factors are conducive to the students' understanding of fundamental concepts and are more likely to help students develop HOCS" (Zoller et al., 1995, p. 989). The authors felt that if their hypothesis were true it would be a significant finding.

Factors Affecting Problem-Solving Ability

The previous studies found that there was a gap between the algorithmic understanding of students and their conceptual understanding. The reasons for this discrepancy were not necessarily explored. The following studies probed further in the students' understanding and the factors that affect problem-solving ability. It is an interesting fact that the majority of these studies preceded the previously reviewed studies, and studied high school rather than college chemistry students.

Gabel, Sherwood, and Enochs (1984) examined high school chemistry students' problem solving behavior as they solved chemistry problems in think-aloud interviews. The purpose of the study was to examine the differences in processes used by successful and unsuccessful problem solvers. Gabel et al. designed a study to further investigate the findings of Nurrenbern (1979) and to overcome the limitations that they felt were in that report. The authors listed three limitations of Nurrenbern's study: 1) a small sample (n=22) from only two high schools, 2) only one topic, stoichiometry, was studied, and 3) the limiting reagent problems used were so difficult that only a few of students were able to successfully solve them.

This study was one part of an aptitude by treatment interaction study conducted in 1979-1980 (Gabel, 1981), and the questions from that study led to research questions for this study. The authors examined whether there were differences in problem-solving strategies used: 1) by students with different proportional reasoning abilities, 2) by
students who had been taught problem-solving strategies, and 3) by students who were successful in solving problems in interviews versus those that were unsuccessful.

The sample for this study consisted of 266 high school chemistry students selected from a population of 609 students in classes taught by 10 teachers from eight high schools. The high schools were located in central and south central Indiana in inner city areas, suburbs, moderate-size cities, and small towns/rural areas. The subjects were all volunteers who were further screened according to availability during interview times, scores on a proportional reasoning test and a unit test, and the problem-solving strategy taught to the student.

The study was constructed in three parts: proportional reasoning assessment, problem-solving instruction, and interview. A proportional reasoning skill aptitude test was administered during the beginning of the school year. About half of the subjects were classified as having high proportional reasoning ability, with the other half having low proportional reasoning ability. A unit test was given for each topic to rate success in problem solving. Each test consisted of 10 items with two or three transfer items, which required the transfer of knowledge to a situation not seen before.

The treatment consisted of one of four strategies for learning to solve problems: factor label, use of analogies, use of diagrams, and proportionality. No descriptions of these methods were included in this report, but could be found in another report (Gabel & Sherwood, 1983). In each classroom students used booklets that were prepared to teach chemistry problems by the strategy assigned to the student and for the topic on which they would be interviewed.

Interviews were conducted two to four weeks after the unit test on the topic was given. The interviews lasted 30-45 minutes and consisted of three parts. The first part of the interview consisted of a think-aloud warm-up period. In the question section, the subjects were asked chemistry concept questions to determine the subjects' knowledge of essential chemistry concepts. If the subject answered a problem incorrectly he or she was
provided with the correct information. The third section was the problem section, which consisted of three problems of increasing difficulty being presented to the subject. The final problem was a transfer problem requiring original thinking to solve correctly. The interviews were tape recorded and later coded according to a scheme adapted from the scheme used by Nurrenbern (1979).

Gabel et al. (1984) stated that due to the complexity of the study, data were too numerous to report as means and standard deviations, but were available in the full National Science Foundation report (Gabel, 1981). The authors synthesized the results for the four questions for each area of chemistry investigated.

The first research question examined whether students, when classified according to degree of success on their unit test, showed different chemistry problem-solving strategies. According to the authors, the results indicated that there were some differences. Students who used systematic procedures in the interview, especially on mole and stoichiometry problems, tended to be more successful in solving problems. The less successful subjects on the unit tests tended to use a non-systematic approach in the interviews. Other results noted by the authors included the use of algorithms with reasoning rather than just algorithms, unsuccessful problem solvers made most comments about the solutions, and those successful on the test were successful in the interview. An interesting result was that there were no significant differences between the abilities of successful and unsuccessful students to answer content questions on the gas law and molarity units. The authors attributed this result to either poor instruction on those units or "perhaps students memorized formulas rather than gaining a conceptual understanding of the content" (Gabel et al., 1984, p. 227).

The authors found that some strategies differ when students with high proportional reasoning ability are compared with those with low proportional reasoning ability. Gabel et al. (1984) found similar trends for students with high proportional reasoning ability as for students who were successful problem solvers: they used
algorithms with reasoning more frequently, were more successful on problems and questions, and used systematic approaches for the mole and stoichiometry problems. The authors expected these results, and also noted that the low proportional reasoning ability students tended to make more comments.

The third area of examination determined if students would differ in their strategies based on the problem-solving strategy they were taught. The statistical results showed a difference, but the authors cautioned that the results were misleading. They assumed that the results were misleading because it was easier for the coders to recognize when the factor label and proportionality methods were used, and the difficulty in recognizing the use of the analogy and diagram methods.

The final question for examination concerned the difference in strategies used by students who solved a problem correctly and those who did not. The authors found that the strategies were different, but that most differences were expected. A systematic approach aided in getting correct solutions except for gas law problems, since the gas law problems could be solved more easily with formulas. The authors found that students who used algorithms with reasoning were more likely to solve the problems correctly than those who did not. Gabel et al. (1984) noticed another trend that they had not expected to find "large numbers of students depended only on algorithmic procedures and gave no evidence of reasoning out problems" (p. 230). They found that more than half of the subjects did not use any observable reasoning on any of the problems, and none of these were able to solve the transfer problems. The authors also found that correct solutions depended on whether the subject could answer the content questions without prompting, especially on the mole and stoichiometry problems that could not be solved with a formula.

The authors felt that their findings "confirmed" the finding by Nurrenbern (1979) that students use algorithms without conceptual understanding. "This study shows that when chemistry students solve problems of varying difficulty in a variety of topics (moles,
stoichiometry, gas laws, and molarity) few students used recall techniques, and the majority of students, successful or unsuccessful, high or low proportional reasoning, relied on strictly algorithmic techniques rather than using reasoning skills" (Gabel et al., 1984, p. 230). Another interpretation of the results by the authors suggested that difficulties on the transfer problems, and failure to answer content questions correctly while solving problems, indicated that the subjects were relying on algorithms as a substitute for conceptual understanding.

Yarroch (1985) studied high school chemistry students and their ability and knowledge of balancing chemical equations. The purpose of the study was to determine how students that were successful in their ability to balance simple equations differed in their approach to balancing equations and to determine what the students knew about the methods and rules of balancing chemical equations.

To accomplish this, the author recruited 14 high-school chemistry students from two different high schools for individual interviews. The subjects were volunteers selected by their teachers from a group of students that agreed to be interviewed. The teachers selected two students from each class that were confident in their ability to balance chemical equations. These subjects were selected so that the author could "determine what the students knew beyond their ability to obtain correct answers" (Yarroch, 1985, p. 450). The subjects were all in their fourth quarter of first-year chemistry, and had been taught balancing chemical equations earlier in the year.

Each subject was interviewed in a 30-minute tape-recorded interview. Four simple chemical equations, representing three synthesis reactions and one decomposition reaction were used for the interviews. The reactions were: a) \( \text{N}_2 + \text{H}_2 \rightarrow \text{NH}_3 \); b) \( \text{F} + \text{Xe} \rightarrow \text{XeF}_4 \); c) \( \text{HI} \rightarrow \text{H}_2 + \text{I}_2 \); and d) \( \text{I}_2 + \text{Br}_2 \rightarrow \text{IBr} \). Each subject was given an equation to read aloud and then balance, with the interviewer performing the written work under the command of the subject. This method was used to slow down the solution process so that it would be clear how the subject was approaching the problem. After each equation
was balanced the interviewer probed for understanding of the various symbols used in the equation and for the subjects' knowledge of the two rules that govern chemical equations of this type. The first rule is derived from the Law of Conservation of Matter and requires that the same number of a symbol (representing an atom of some element) appear on both sides of the equation. The second rule is derived from the empirical Law of Definite Proportions and requires that in balancing the equation the subscripts for each symbol representing a molecule must not be changed. For example, the subscript three in NH$_3$ (ammonia) must not be changed. This process was then repeated for the other three equations.

The subjects were then asked to draw diagrams illustrating the reactions described in the last two balanced equations. If the drawing was unclear the subject was asked to label the drawing. Of the 14 students, 12 produced drawings, while the remaining two were unwilling or unable to produce the requested drawing. Throughout the interviews, the interviewer used only those chemistry terms introduced by the subject and asked for clarification if the use of the term was unclear. Any relevant chemistry terms that were not used by the subject were introduced at the end of the interview by the interviewer.

All 14 subjects interviewed were able to correctly balance all four of the chemical equations given to them, as was expected by the researcher. "However, there were differences in what the students in this sample understood about the problems they solved, especially with the relationships between the mathematical aspects of those problems and the empirical and theoretical chemistry those problems were meant to represent" (Yarroch, 1985, p. 453). All of the subjects followed a similar process to balance the equations, represented schematically in Figure 3. The process is two-tiered, with the first tier assigning coefficients to satisfy the first rule and the second tier checking the results. The process could be repeated if necessary.

Based primarily upon the drawings, the subjects were divided into two groups. Group 1 contained five students whose diagrams represented a valid chemical
Figure 3. Procedural representation of the process used by all students to balance each of the interview questions (Yarroch, 1985, p. 452).
interpretation of the reactions the equations represented. Group 2 contained seven subjects whose drawings did not reflect an accurate representation of the reactions represented in the equations and the two subjects who failed to produce a drawing.

The subjects in Group 1 shared similarly correct knowledge of chemical coefficients and subscripts. Two of the subjects did appear to have difficulty drawing representations of polyatomic products, like ammonia (NH₃), first attempting to represent ammonia without breaking the diatomic bonds of the reactants (i.e.: H-H bonds in H₂).

Subjects in this group shared similar understandings of the chemical reaction symbol (→), stating that it was similar to the mathematical equal sign (=) for purposes of Conservation of Matter, but that it was different from an equal sign because both sides of a chemical equation are not equivalent. Their knowledge of the Conservation of Matter reflected the understanding that symbols, elements, or particles were conserved in the equation balancing process, but they failed to mention mass. Members of this group recognized violations of the Law of Definite Proportions when they observed the interviewer violate this rule in examples, but their reasons for this rule were brief and not fully elaborated. The author felt the knowledge shown by this group "was not too different from that knowledge present in good instruction and in the chemistry text books" (Yarroch, 1985, p. 455).

The drawings from members of Group 2 who produced drawings represented the total number of each element (typically represented by labeled circles), but did not reflect the coefficients and subscripts in the balanced equations. The products of the ammonia reaction were typically represented as six hydrogen atoms (H) and two nitrogen atoms (N) joined in a linear molecule (i.e.: 0-0-0-0-0-0) rather than two polyatomic ammonia molecules (NH₃). These subjects showed little knowledge of chemical coefficients though they were able to successfully balance the chemical equations. To these students the coefficients and subscripts were only distinguishable by their location, each having the same meanings, and the chemical equation symbol was equivalent to the mathematical
equal sign. The knowledge of the Law of Conservation of Matter was similar to that in Group 1, though they focused more on conserving symbols rather than particles. The subjects knowledge of the Law of Definite Proportions was weaker than for Group 1, with two subjects stating that it was acceptable to violate this rule and the other five arguing that their teachers preferred that they not violate the rule. The final two subjects, who were unable or unwilling to draw the reactions were placed in Group 2 because they allowed the interviewer to violate the Law of Definite Proportions. The knowledge of Group 2 students was sufficient to balance all four of the chemical equations, but was fragmented and lacked depth.

Yarroch (1985) speculated that the results showed at least two distinct levels of understanding used by the subjects to solve the problems. The higher level of understanding utilized the necessary abstract aspects of chemistry and "the lower level could be described as an efficient, mathematical manipulation of symbols" (Yarroch, p. 458). The author pointed out that though the Group 2 students had little trouble balancing the simple equations posed, the holes in their conceptual knowledge would make the solution of other chemical problems difficult or unsolvable. The author gave as a possible reason for the lack of knowledge beyond the mechanical manipulation of symbols that this level of understanding is all that is needed to succeed on course assessments.

Anamuah-Mensah (1986) designed a study to determine strategies used by chemistry students when solving volumetric analysis problems and to identify conceptual difficulties of students while solving these problems. The subjects for this study were 47 grade-12 chemistry students from eight high schools in the lower mainland of British Columbia, Canada. The students were grouped into high, medium, and low achievement groups based upon their scores on a 14-item Volumetric Analysis Test written by the author.
The goal for the individual, 50-minute interview was for the subject to calculate the concentration of hydrochloric acid (HCl) when given the concentration of sodium hydroxide (NaOH) used in a titration. The subjects were asked to speak aloud their strategy and method as they solved a practice problem. Each subject was then provided with the necessary apparatus and solutions to titrate 25 mL of 0.1 M NaOH and determine the volume of HCl needed to neutralize the base. Based upon the data from this titration the subjects were asked how they would determine the concentration of the acid used. They solved the problems on paper provided while verbalizing their thought process. The investigator intervened only when the subject failed to speak aloud for more than 10 seconds.

To further probe the subjects understanding, they were asked to use their data to predict the concentration of acid in three situations where the mole ratio was other than 1:1. The three situations were:

1. If the acid reacted with the base in a mole ratio of 2:1, respectively, what would be the concentration of the acid?
2. If you used H₂SO₄ in the titration instead of HCl, what would be the concentration of the H₂SO₄?
3. If instead of sodium hydroxide you had used sodium carbonate to titrate hydrochloric acid, what would have been the concentration of the hydrochloric acid? (Anamuah-Mensah, 1986, p. 761)

Each subject was then asked to explain his or her prediction. Each interview was audiotaped.

The analysis of data consisted of isolating the steps used by the subjects from both the transcripts and the subjects' written solutions. Anamuah-Mensah (1986) found that the subjects used one of two strategies or their variants to solve the problem given. The two strategies were the Formula Approach and the Proportional Approach. In the Formula Approach, the subjects attempted to use a formula from the text or class to solve the problem. No attempt was made to demonstrate an understanding of the relationships among the variables. As the author described, "qualitative understanding of the problem
appeared to be lacking" (Anamuah-Mensah, p. 762). The Proportional Approach utilized a ratio or proportion to determine the number of moles of acid or concentration of the acid without explicit use of a formula. These subjects seemingly demonstrated recognition of a relationship between the variables.

The majority of the subjects used the Formula Approach in their problem solving. Though it appeared that most of those using the Formula Approach were in the medium and high achievement groups, the author did not find a significant relationship between the types of strategy used and the subject's achievement level. The majority of the subjects (78.7%) correctly solved the problem for the concentration of the HCl solution, with most of these using the Formula Approach. The high and medium achievement groups were more successful than the low achievement group.

The author felt that the low achievement group would rely more on the Formula Approach because it was less conceptually demanding, but did not find this result. He also expected the high achievement group to more often use the Proportional Approach because it required a greater conceptual understanding, again he did not find this result. He attributed some of the results as follows:

perhaps because the students in the high and medium achievement groups although capable of solving the problem using either the Formula Approach or the Proportional Approach tended to use the Formula Approach because it offers an easier and less conceptually demanding route to the solution of the problem. (Anamuah-Mensah, 1986, p. 763)

The author attributed the low achievement groups' strategy choices to their lack of ability to remember the formulas and so they resorted to procedures not well understood.

In the prediction situations the subjects encountered several difficulties even though they employed the same strategies. Only 21.7% of the subjects correctly predicted all three situations. The difficulty encountered most often was incorrectly using the mole ratio when there was a 2:1 or 1:2 ratio between moles of acid and base. The subjects frequently reversed the ratio, if they recognized the different ratios. This reversal showed
a deficient understanding of the relationships between the variables, according to the author.

The author concluded that the prevalent use of the Formula Approach might be due to teaching strategies that the subjects encountered. The author emphasized the number of subjects that failed to obtain correct solutions using the Formula Approach, and suggested that "blind emphasis on formulas without ensuring the understanding of the relationship implied may lead students nowhere and hence must be guarded against" (Anamuah-Mensah, 1986, p. 768).

Anamuah-Mensah, Erickson, and Gaskell (1987) attempted to study the interrelationships between proportional reasoning, content knowledge, and performance on volumetric analysis calculations. In this study the authors wanted to explore how structure and content influence the performance of students in two distinct groups: those who use algorithms with understanding, and those who use algorithms without understanding. The research objectives were:

1. To develop an integrated path analytic model to hypothesize an explanation of students' achievement on volumetric analysis problems.
2. To examine the fit of the model to the observational data for students using algorithms with understanding and those using algorithms without understanding. (Anamuah-Mensah et al., p. 724)

Anamuah-Mensah et al. used explanatory observational studies methodology to develop the model.

The initial sample consisted of 402 students from the lower mainland of British Columbia enrolled in Chemistry-12 in 17 classes in 10 schools. Ability to answer volumetric analysis problems was assessed on a 15-item Volumetric Analysis Test (VAT). No information was given as to the origin of the VAT.

The causal model used for the path analysis was developed from previous research reported in the literature relating to students' understanding of chemical concepts. The proposed model hypothesized a direct linkage from Subsumed Concepts to performance in
solving volumetric analysis problems (Performance), direct proportional reasoning (Direct) to inverse proportional reasoning (Inverse) and Subsumed Concepts, and from Inverse to Performance and Subsumed Concepts. Two residual variables were added to the model to account for variables not measured, such as prior experience.

The authors analyzed the steps used on the VAT to differentiate the two groups. Those who used a 1:1 ratio in two or more instances where it was inappropriate were placed in the algorithms without understanding group, and all others were placed in the algorithms with understanding group. The sample was divided into 105 students who used algorithms with understanding and 160 students who used algorithms without understanding.

For the subjects in the use of algorithms without understanding group, three of the paths were found to be statistically significant at the 0.05 level. The relationships from Subsumed Concepts to Performance, from Inverse to Subsumed Concepts and from Direct to Inverse were all found to be statistically significant. The model fit was tested with a chi-square goodness-of-fit test and it was found "that the model cannot be distinguished statistically from the saturated model" (Anamuah-Mensah et al., 1987, p. 730). The authors claimed that this result suggested that the model offered a plausible explanation of the data for this group. The relationship between Inverse and Performance, and for Direct to Subsumed Concepts were found not to be statistically significant. These two paths were dropped from the model to test a more parsimonious model dubbed the Z-model (it forms a z-shape). This model was analyzed and was also found to represent a plausible representation of the data. The estimates changed slightly for the paths, with all three remaining statistically significant at the 0.05 level. The authors rejected the proposed integrated model in favor of the Z-model for those who used algorithms without understanding.

For the subjects who used algorithms with understanding, the proposed integrated model showed closer correspondence with the data. Only the path coefficient between
Direct and Subsumed Concepts (estimate of 0.12) was not statistically significant. The authors dropped the Direct to Subsumed Concepts path and formed a model for this group. The model was also found to adequately explain the data. The effects analysis for this data showed that there was still a significant effect between Direct and Subsumed Concepts that needed to be accounted for, so the original model was retained for subjects who used algorithms with understanding and labeled the P-model.

Anamuah-Mensah et al. (1987) explained their results by surmising that the subjects who used algorithms without understanding did not see or understand the structural relations inherent in the problems and so did not use them in their solutions. The subjects who used algorithms with understanding did show understanding of the structure and used it to their advantage.

Categorizing Problem Solvers

The following studies attempted to categorize the types of problem solvers in college chemistry courses. Whether it was one student (Herron & Greenbowe, 1986), or a large group of introductory chemistry students (Mason, 1995; Mason, Shell, & Crawley, 1997; Nakhleh & Mitchell, 1993), the studies tried to identify successful students with a lack of conceptual knowledge. The final three reports (Mason; Mason et al.; Nakhleh & Mitchell) categorized students based on the categories proposed by Nakhleh (1993) and attempted to identify the second-tier students of Tobias (1990).

Herron and Greenbowe (1986) examined the problem solving of one successful student, "Sue." This case study was intended to show how a student could clear the hurdles of the educational system without developing skills necessary to solve problems in the real world. Sue was originally one of 31 subjects in Greenbowe's (1983) doctoral research. She was a college freshman at Purdue University enrolled in beginning chemistry.
In the earlier study (Greenbowe, 1983), the participants were given several written tests to assess basic mathematics competence, chemical understanding related to the study, and general level of intellectual functioning based on the work of Jean Piaget. After the preliminary tests were given, the subjects solved stoichiometric questions of varying difficulty in a talk-aloud approach.

The authors chose to further investigate the difficulties of one subject, Sue. Sue was a pre-veterinary science major, who had taken two years of chemistry, four years of mathematics (algebra I and II, geometry, and calculus), and one year of physics in high school. Besides beginning chemistry, she was enrolled in advanced calculus at the time of this study.

Herron and Greenbowe (1986) found that despite her chemistry background, Sue's understanding of several chemistry facts was not adequate. She failed to write the correct formula of a compound when given the chemical name, and the error in writing formulas led to incorrect answers for the stoichiometry problems. As Herron and Greenbowe observed, "Although her procedure for solving the limited reagent problem was correct, she arrived at the incorrect answer because her chemical facts were wrong" (p. 528). In other parts of the interview, the authors saw that Sue had mastered algorithms for applying facts; for example, she was able to correctly determine the oxidation state of an unknown metal, M, from the formula of its chloride, MCl₃, a problem many others had difficulty with.

Besides the examples of failure to correctly apply chemical facts, Sue at times provided a correct answer, but not the answer asked for in the problem. Sue, as well as others, reported intermediate answers as the final answer and failed to verify their answer. A further difficulty for Sue was tied to her failure to verify her answers because she had difficulty representing word problems in terms consistent with the "physical reality" present in the problem.
The authors attributed Sue's difficulties to 1) poor understanding of mathematical representations and 2) failure to check the representations of the problem against other knowledge to check its accuracy. Elsewhere in the report, the authors listed the important areas of problem solving in which they felt Sue had a weakness:

1) Successful problem solvers have a good command of basic facts and principles.
2) Successful problem solvers construct appropriate representations of problems.
3) Successful problem solvers have general reasoning strategies that permit logical connections among elements of the problem.
4) Successful problem solvers apply a number of verification strategies to ensure that
   a) the representation of the problem is consistent with the facts given[,] 
   b) the solution is logically sound,
   c) the computations are error free and,
   d) the problem solved is the problem presented. (Herron & Greenbowe, 1986, p. 528)

In their discussion of the case study, the authors characterized Sue as a "rule learner." They clarified this classification by saying:

Sue views her primary task in the educational system as memorizing rules and algorithms.... When she is presented with problems, such as those used in this study, she looks for clues in the problem statement to identify the rule that she must apply to solve the problem. (Herron & Greenbowe, 1986, p. 530)

The authors compared Sue to successful problem solvers from the study and identified the difference between them as the failure to check solutions, not the application of rules. The authors pointed out that Sue's difficulty came when she attempted to solve problems that were unfamiliar or novel. The familiar rules did not necessarily apply, but Sue used them to come up with an incorrect solution. Her ability to solve problems that required the application of a rule led to success on many problems on the stoichiometry quiz, but when that rule was inappropriate, Sue failed to see that. They felt that her work suggested that she did not equate the mathematical and chemical symbols used with real objects and events.
According to the authors, the major concern raised in this case study was that Sue was not atypical of beginning chemistry students. She was typical of many students in the study and of science students passing science courses everywhere. And the problem of these students was not in the amount of science they studied but in the amount of science applied.

Nakhleh and Mitchell (1993) further investigated the trends found in previous studies (Nakhleh, 1993; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990) with the objective of finding out what students think about when they solve conceptual and algorithmic problems. They also wished to determine if there were differences and/or preferences in the students' approach to each type of problem.

A group of 60 freshmen chemistry students, all of whom were declared chemistry majors, were studied. The study was conducted in two parts with paired questions used to identify and classify subjects for personal interviews.

Part 1 of the study was completed by placing two paired multiple-choice gas law questions, one algorithmic and one conceptual, on the third exam in a course where gas laws were studied. The gas law questions were taken from Nakhleh (1993) with the conceptual problem the steel-tank problem adapted from Nurrenbern and Pickering (1987). Success or failure on the problems were recorded and each student was grouped in one of four categories, similar to those suggested by Nakhleh (1993): High Algorithmic/High Conceptual (both problems answered correctly); High Algorithmic/Low Conceptual (conceptual problem incorrect); Low Algorithmic/High Conceptual (algorithmic problem incorrect); and Low Algorithmic/Low Conceptual (both problems answered incorrectly). The results for Part One were: High Algorithmic/High Conceptual 43.3%, High Algorithmic/Low Conceptual 41.7%, Low Algorithmic/High Conceptual 5%, and Low Algorithmic/Low Conceptual 10%.

Part Two consisted of an individual interview. Six of the chemistry students were selected for interviews with two subjects selected from three of the four groups. No
subjects were interviewed from the Low Algorithmic/High Conceptual group as the authors claimed that none were available due to the small number in this category (3).

In each 50-minute interview, the subject was asked to work through the two problems from the exam and a pair of stoichiometry problems, with the conceptual problem again taken from Nurrenbern and Pickering (1987). The subjects were asked to solve the problems using think-aloud protocols that were demonstrated by the interviewer. After completing the problems, the subjects were asked to compare the conceptual and algorithmic problems as to perceived difficulty and to express a preference. All interviews took place within a four-day period following the course final. The final course grades were also recorded. The authors' analysis of the data focused on several results. In Part One, more than 50% of the students failed to correctly answer the conceptual question. Given that the subjects were chemistry majors, that result was disappointing. Nakhleh and Mitchell (1993) stated their opinion that "they [students] do not demonstrate understanding of the chemistry concepts, or, cannot apply those concepts" (p. 191).

The interviews produced results that the authors found interesting, the first being that all six interview subjects answered the gas law conceptual problem correctly, as well as the algorithmic problem. This trend could be due to the subjects seeing the gas problems for a second time, as the authors suggested. The authors' focus was on how the questions were solved, and half of the subjects used an algorithm (applying a gas law equation) to solve the gas law conceptual problem. Two other students used a test-taking strategy by eliminating the clearly wrong answers and deciding between the remaining choices, which the authors classified as algorithmic responses. The remaining student, categorized as High Algorithmic/High Conceptual, clearly demonstrated conceptual understanding when solving the problem. All of the students categorized as high algorithmic learners used algorithms on at least one conceptual problem. The authors attributed this finding to the fact that the subjects had probably solved hundreds of
traditional problems and so were more comfortable with their algorithmic skills and did not trust their conceptual abilities.

The preferences for question types given by the subjects were evenly split between algorithmic and conceptual, but the subjects added stipulations to their preferences. The authors indicated that the students frequently preferred the conceptual problems for homework or practice problems, but not for exams. The authors suggested that this preference might be due to the students' frame of reference of an exam with many algorithmic problems and their fear of an exam of similar length with conceptual problems requiring more thought.

Mason, Shell, and Crawley (1997) attempted to determine "whether problem-solving schema used by students differ as their ability to solve problems in introductory chemistry improve" (p. 905). They identified several missing pieces in the chemical education literature, which were: identifying where difficulties in problem-solving schema arise, identification of differences between expert and novice problem-solvers in chemistry, and whether problem-solving practice over a short time helps novice problem solvers develop schema similar to experts. This research was reported earlier as a paper presented at an annual meeting (Mason & Crawley, 1994); because the research was presented in different forms, there was some information that was presented in one report, but not the other, or was presented more clearly in one report. The following review will examine both reports with an emphasis on that reported in Mason et al. (1997). An effort was made to note information included in only one report with a citation; it can be assumed that information not specifically referenced was contained in both reports.

The purpose of the research was to find the similarities and differences in the ways students solve chemical algorithmic and conceptual problems. Based on prior research, it was known that there were different types of problem solvers and the authors hoped to document how the schema differed for these types.
For this study the authors chose four topics in chemistry to study: density, stoichiometry, bonding, and gas laws. The authors also chose to categorize the novice subjects according to the scheme proposed by Nakhleh (1993) (see Figure 2).

The research questions were: 1) What strategies do expert and student problem solvers use to answer algorithmic and conceptual problems, and are there differences based on the type of student? 2) How do the problem-solving procedures used by experts and different types of students compare?

The student subjects for this study were selected from a first semester chemistry course for non-science majors at a large southwestern research university, the University of Texas at Austin. Twenty students (10 male and 10 female) were selected by stratified random sampling from the original class of 180. The subjects were randomly selected as a stratified sample based on the percentage of students in each major represented in the course. Care was then taken to represent the gender breakdown of each major. Two professors who taught introductory level chemistry courses were chosen as expert problem solvers. It was not made clear if the experts were researchers or other faculty members.

Prior to the interviews all students in the course were asked to complete 13 in-class assignments made up of paired algorithmic and conceptual problems on selected topics. These assignments were collected to document the attendance and problem-solving ability of the students and to ensure that they were novice problem solvers (Mason & Crawley, 1994) and had some prior knowledge of the subject matter (Mason et al., 1997). The authors also pointed out that these assignments allowed the novice subjects to experience these types of paired questions.

The 22 subjects (20 novices and 2 experts) were interviewed in a think-aloud protocol as they solved four paired algorithmic and conceptual problems, one pair for each topic area. All questions except for the bonding questions came from the study by

As the subjects solved the problems, the interviewer graphed their problem-solving schema using an incident identification tool. The tool used was modified from that developed by Schoenfeld (1980). In this graphical method the abscissa was time and the ordinate was divided into five aspects of problem solving: read, define, set up, solve, and check. The heuristic used was based on the problem-solving literature. The episodic events were coded according to the following guide: 1) read was the time needed to determine the intent of the problem or any time needed in dealing with specific wording of the problem; 2) define was the time needed to sort out the required information from the problem, or to make references to specific content definitions; 3) setup was the time needed to select concept(s) for conceptual problems or equation(s) for algorithmic problems; 4) solve was the time needed to develop an answer or conclusion to a problem; 5) check was the time needed to review the completed problem or partially completed problem (Mason et al., 1997). As the subject solved the problem aloud, the interviewer followed the time axis marking the aspect of problem solving being utilized. The interviews were also tape recorded and transcribed to verify the accuracy of the episodic graphs. Three variables from the graphs were evaluated: time needed to complete a solution, the number of transitions between aspects, and the rate of transitions over time of solution.

The number of correct answers were determined and this information was used to determine the placement of the novice subjects in one of the four categories devised by Nakhleh (1993) (see Figure 2). The categories and the number in each category were: High Algorithmic/High Conceptual (2), High Algorithmic/Low Conceptual (13), Low Algorithmic/High Conceptual (0), and Low Algorithmic/Low Conceptual (5). The criteria was based upon the number of correct answers in each category, three or four of the problems correct (either algorithmic or conceptual) was classified as "high", and two or
fewer correct in a category was classified as "low" in that category. All subjects interviewed correctly solved at least one problem in each mode (Mason et al., 1997). No subjects that qualified for the Low Algorithmic/High Conceptual group were in the stratified sample. The authors did not find this result surprising as only 4.5% or eight of the 180 students in the class fit into this group.

The data from the novice subjects were analyzed based upon majors and showed that for all majors the number of algorithmic problems answered correctly exceeded that of conceptual problems answered correctly. For each of the four subject groups studied, the time of solution, number of episodic transitions, and transitions over time were recorded and typical episodic graphs were devised.

The composite incident identification graphs for each group and each problem type were compared for similarities and differences. The Expert group graphs showed little effort and few transitions while those of the Low Conceptual groups show a large number of transitions, jumping from one aspect to another. The HA/HC subjects graphs showed similarities to those of the Experts. The authors noted that the rate of transitions had very little difference between the groups (1.7 to 2.2), but they noted that the trend for the rate of transitions for the groups seemed to follow a pattern based upon conceptual ability. For the High Conceptual groups (Experts and HA/HC) the transition rates were higher for the algorithmic problems, while for the Low Conceptual groups (HA/LC, and LA/LC) the transition rates were higher for conceptual problems than for algorithmic problems.

For the other two measures, time and number of transitions, a trend was seen with the value increasing from Expert to HA/HC to HA/LA to LA/LC. "In most instances, as problem-solving ability improved, the times required and number of transitions needed to complete a problem decreased" (Mason & Crawley, 1994, p. 22; Mason et al., 1997, p. 919). The algorithmic problems did have more transitions and took longer for all groups. This result was explained by the theory that conceptual problems often need specific knowledge, and that algorithmic problems can sometimes be solved by trial-and-error.
The authors compared typical problem-solving episodes by graphing the different aspects versus the average time for each aspect, for each type of problem and for each group. The graphs for each group appeared to follow similar paths with the expert group taking less time in each aspect and the LA/LC group taking longer.

The authors found that their results were similar to those found by Nakhleh and Mitchell (1993), though in this study 75% of the students were classified as Low Conceptual. They found that 68.4% of the students were classified as High Algorithmic, which they claimed went along with reports from studies by Nakhleh (1993) that introductory chemistry students usually have better success with algorithmic problems. "These results serve to demonstrate that the majority of the students enrolled in introductory chemistry courses do not understand or fail to apply chemistry concepts correctly; they have learned to 'crunch' numbers to arrive at correct mathematical solutions" (Mason et al., 1997, p. 921).

Mason (1995) used the data gathered for a previous study (Mason & Crawley, 1994) to investigate how different types of novice problem solvers approached paired algorithmic and conceptual problems. The research question was devised to further dissect the information from the previous study. The research question was: What are the differences and similarities between the approaches used by experts and different categories of novice problem solvers to solve paired algorithmic and conceptual problems on the topic of stoichiometry? The question had two hypotheses, that there would be a difference in the algorithmic mode and that there would be a difference in the conceptual mode.

Mason (1995) reexamined the data from the prior study (Mason & Crawley, 1994) and determined that of the four topics (gas laws, stoichiometry, bonding, and density), stoichiometry was the most difficult for both experts and novices to solve. The data used were the number of correct answers and the incident identification graphs discussed in the earlier study. The design, many of the results, and the population of this study were
discussed previously (see discussion of Mason et al., 1997). Data that were not proffered in the earlier report were presented in this report. The data included a breakdown of the data for each topic studied and the typical identification graphs for the stoichiometric problems for each group. Mason (1995) claimed that "the data collected from all paired questions support that this topic [stoichiometry] is far more difficult for both experts and novices than any of the other three topics" (p. 3).

Mason (1995) went back to the transcripts of the think-aloud interviews from the earlier study (Mason & Crawley, 1994). Only three subjects failed to correctly answer the algorithmic stoichiometry problem, so Mason focused on the conceptual problem. On the conceptual problem, 16 of the 22 subjects failed to answer the problem correctly. The subjects who failed to answer correctly came from the following groups (percentage of group in parenthesis): one Expert (50%), ten from High Algorithmic/Low Conceptual (77%), and five from Low Algorithmic/Low Conceptual (100%).

The incident identification graphs for both modes of the stoichiometric problems for the Low Conceptual subjects showed a large number of transitions that did not follow a discernable pattern. "An implication of this observation is that there must have been confusion among the members of this category of novices as they solved the algorithmic and conceptual-mode stoichiometric problems" (Mason, 1995, p. 17).

The author found many of the same trends for each of the subject areas that were seen for the averaged data reported earlier (Mason & Crawley, 1994). The algorithmic problems took more time and transitions, but were solved correctly more often than the conceptual problems, though actual data on number of solutions were not given. Time and transitions increased as the problem-solving ability decreased.

Mason (1995) did point out an implication that was not reported in other similar studies, that since a large majority (85%) of the subjects were able to answer the algorithmic problem correctly "we can assume that lack of mathematical ability may only play a small role in overall student success in introductory chemistry" (p. 18). She added
that the lack of student success in chemistry problem solving might be attributed to lack of conceptual understanding.

Students' Perceptions

Few of the reports in this review have looked at the students' perceptions of their chemistry learning, and assessment of that learning. Besides the three following reports (Beall & Prescott, 1994; Lin, Kirsch, & Turner, 1996; Phelps, 1996), only the studies by Nakhleh and Mitchell (Nakhleh, Lowrey, & Mitchell, 1996; Nakhleh & Mitchell, 1993) have looked at student perceptions. By examining student perceptions, other information was gathered that could prove useful.

Beall and Prescott (1994) expressed concern with the chemical education literature that seemed to show the weakness of chemistry students' conceptual knowledge. The authors said that the fear of educators was that students were viewing chemistry as a list of equations, and that chemical educators had brought that upon themselves by their educational and assessment strategies.

While the authors agreed that there was a tension between "calculational" and "conceptual" chemistry, they expressed doubt that researchers and educators had correctly judged conceptual learning. "What conceptual knowledge is, how to teach it, and how to test for it are much more difficult to define" (Beall & Prescott, 1994, p. 111). Based on their doubts about chemistry educators' ability to gauge conceptual knowledge, Beall and Prescott criticized the "celebrated" work of Nurrenbern and Pickering (1987). The authors disagreed with the use of problems containing graphical representations to test for conceptual knowledge. The authors acknowledged that Sawrey (1990) and Pickering (1990) used the same problems and obtained similar results, but were concerned that the same graphical problems were used in these studies. Beall and Prescott's major concern was that "A central, critical and, we believe debatable assumption of these studies is that a visually posed problem is a conceptual problem" (p. 111). The authors argued that a
conceptual problem is one that is expressed in grammatical language rather than in numbers, symbols, and equations.

The study conducted for this report contained two sections – student performance and student perceptions. The study took place at Worcester Polytechnic Institute (WPI) where the authors taught. The research was conducted over three years to explore the notion of testing conceptual knowledge of chemistry with questions with answers in words. The subjects for this study were students in general chemistry at WPI and were primarily Engineering majors.

Ten key chemistry topics were identified for each examination and one calculational and one conceptual problem were included on the exam for each topic. All of the problems were multiple choice with three distracters, and the conceptual problems were composed of words. The authors gathered data on the number of right and wrong answers for individual questions and for overall results in two classes of more than 300 students each. The data were gathered on six exams each semester.

It was mentioned that relative abilities on calculational and conceptual problems were difficult to determine because of the problem of determining if the paired questions were at the same difficulty level. Beall and Prescott (1994) dismissed this difficulty by assuming that, by chance, the relative difficulty would be greater for about half of the computational problems and greater for about half of the conceptual problems in each pair. Despite this difficulty, the authors determined that there were a similar number of errors made on the two categories of questions. On the examinations, 54% of the errors made were on conceptual problems and 46% were made on calculational problems. They arguably decided that with the uncertainty of difficulty level, the similar results were "essentially an even split" (Beall & Prescott, p. 112). When correct answers were compared, 64% of conceptual questions were answered correctly and 70% percent of the calculational questions were answered correctly.
In the second part of the study, the students' reaction to the two types of questions was gathered on a survey. This survey was administered at the end of the first semester of the course given in the second year of the study. On the surveys, 80.8% of the students agreed with the statement, "The calculational exam questions are easier than the conceptual questions." On other questions, 82.2% of the students felt that they generally got the calculational problems correct, and 13.3% felt that they generally got the conceptual questions correct. The authors pointed out that it was clear that students perceived a difference in the difficulty of calculational and conceptual questions despite evidence to the contrary. Beall and Prescott (1994) stated that "they [students] feel they are strikingly inferior at the conceptual questions even though the results in the examination definitely indicate otherwise" (p. 112).

The authors attributed the phenomena of difference in perceptions and performance to errors in perception. The students believed that they generally chose a correct algorithm, but failed to check their answers, thus incorrectly feeling that they had correctly solved the calculational problem. They also became defensive when solving a conceptual problem and assumed that they had answered incorrectly. The authors suggested that it might aid students' perceptions if they reviewed their exams to see that calculational problems were more complex and conceptual problems were less so.

Phelps (1996) made an attempt to bridge the gap between algorithmic and conceptual problem solving in chemistry. She justified the importance of this endeavor on the findings of Nurrenbern and Pickering (1987), Sawrey (1990), Pickering (1990), and Nakhleh (1993). Phelps attributed the gap between algorithmic problem solving and conceptual understanding to instructors who allow their students to hide their lack of conceptual understanding by assuming correct numerical answers show conceptual understanding. She asserted that "chemistry teachers must find a way to communicate the importance of conceptual problem solving to their students just as they have communicated the importance of using the correct formula and obtaining the correct
numerical answer" (Phelps, p. 301). Citing Tobias (1990), Phelps suggested that focusing on concepts might attract students that are turned off by an algorithmic focus.

This study attempted to close the gap between algorithmic problem solving and conceptual understanding by changing methods of instruction in two general chemistry courses. The courses included one course designed for science majors and one designed for non-science majors such as nursing and liberal arts. The two courses were offered concurrently during the period 1991-1993. The classes were lecture sections of introductory chemistry offered at a medium-sized university in the South. The class sizes ranged from 150 to 200 students.

The study followed a qualitative design with the teacher as researcher. Data were collected as classroom observations, tapes, student interviews, and sample student work. The author used a constant comparison technique to analyze the data. Phelps (1996) grouped the data into "assertions that summarized the lessons that came from the students' responses to the new approach to chemistry" (p. 301).

The changes in instruction involved beginning each unit with the qualitative understanding of the concepts and with deemphasis on the numerical aspects. The problems used for each new topic were initially conceptual problems, often presented as a demonstration or a real-world problem. Conceptual problems were also included on exams. After the majority of the class was comfortable with the concepts, the numerical aspects of the topic were introduced. Students worked together on in-class problems, were encouraged to form out-of-class study groups, and encouraged to interact in the class.

Phelps (1996) used many of the same demonstrations and teaching questions for both the science majors and non-science majors classes. She noticed a difference between the responses in each class, the science majors were less willing to interact in class than the non-science majors. Though reluctant in class, the science majors developed more willingness to ask questions and discuss concepts outside of class as the year progressed.
The science majors focused on the numerical aspects of chemistry, but showed reluctance to solve problems in class, fearing that they might get them wrong. The nonscience majors interacted more with each other and with the instructor. They also freely used class time to discuss concepts and shared ideas and questions. They were initially reluctant to share in class, but became more interactive as they learned that being wrong was all right in chemistry.

Phelps (1996) expressed the results from this study as three assertions. Each assertion was discussed and defended with quotations from the data. Assertion 1: "Nonscience majors engage in socialization in other courses where their opinions and ideas are valued and they are expected to share them" (Phelps, p. 302). In supporting this assertion, the author added that an interactive approach helped to alleviate some of the nonscience majors fear of chemistry. Assertion 2: "Science majors believe that there is a right answer to all questions and that they should know it" (Phelps, p. 302). The author also suggested that the science majors were less confident when instruction focused on the concepts and that the competitive atmosphere of some science classes and programs encouraged this feeling. Assertion 3: "Science majors are comfortable with the protocol of hiding behind the numbers, and they know the dangers of asking 'Why?'" (Phelps, p. 303). Phelps suggested that students pursuing a major in science had already succeeded in a system that they are comfortable with, and that system rewarded algorithmic problem solving and did not demand conceptual understanding. The science majors often knew of the gaps in their conceptual knowledge but understood that their success was based on answering the professor's questions in a timely fashion.

The conclusions drawn by Phelps (1996) cited benefits for both groups of students included in this study. The nonscience majors showed more interest and enthusiasm for the course and were confident that they could do chemistry. Their interest in the concepts spilled over into willingness to tackle numerical problems that arose. The science majors were at first uncomfortable because the course did not fit their preconceived notion of
what constituted chemistry. As the course progressed, Phelps noticed that it was the women and minority men that were the first to become interactive with each other and the instructor. Once all students realized that learning concepts was important to success, they were willing to work at understanding them. Phelps made a statement that should be explored further: "Most science majors know that they do not understand concepts fully, and many of them move through the course work anxiously waiting to be found out" (p. 303).

Phelps (1996) identified two liabilities for a more interactive-conceptual approach, coverage of material and impact on students' future learning. The author was not able to cover as much material using this approach as in past courses, but argued "merely covering material without regard for understanding is not a lofty goal" (Phelps, p. 303). Another probable liability identified was that in future courses intent on material coverage, the students might feel frustrated in their desire for conceptual understanding.

The strongest argument in favor of Phelps' (1996) variation was that the interactive-conceptual approach gave the students an opportunity to learn chemistry using the processes used by scientists. Phelps suggested that the focus on algorithmic problem solving discouraged some of those who had the correct skills to succeed as scientists and who were unwilling to "put those skills on hold while they endure the necessary undergraduate science courses" (p. 304).

Lin, Kirsch, and Turner (1996) wished to examine how the gap between concept learning and problem solving might differ at a minority institution. Lin et al. pointed out that most reports from studies investigating this phenomenon came from institutions with primarily nonminority populations of students. The authors specifically mentioned works by Nurrenbern and Pickering (1987), Sawrey (1990), Pickering (1990), Nakhleh (1993), and Nakhleh and Mitchell (1993).

The purpose of the study was to conduct a study of algorithmic and conceptual problem solving at Florida A&M University (FAMU), a predominantly minority
institution. The authors hoped that this study would provide useful information for those considering implementing a more concept-based instructional strategy. Lin et al. (1996) offered a further motivation for this study based on their teaching experiences at minority and nonminority institutions: "the authors have observed that a large proportion of minority students are more interested in concepts than in algorithmic aspects of chemistry problems" (p. 1003). The authors hypothesized that they would find a relatively larger percentage of conceptual students than algorithmic students at FAMU.

In this study, Lin et al. (1996) utilized questions from Nakhleh (1993) to identify second-tier students and test student performance on conceptual and algorithmic questions. The questions consisted of 10 paired algorithmic and conceptual problems on the following topics: gas laws, equations, limiting reactants, empirical formulas, and density. The questions were incorporated as part of an hour exam in the courses studied. Along with the questions, students were asked for their preference between algorithmic and conceptual questions. The students also took the American Chemical Society (ACS) standardized test. The authors also obtained the students' standard test scores, in this case Scholastic Aptitude Test (SAT) scores, from FAMU's Research Council.

The sample for this study consisted of 270 students enrolled in four sections of general chemistry at FAMU. Two sections were taught by a biochemist seeking a law degree, who the authors felt emphasized conceptual thinking in the course. One section was taught by a physical chemist who the authors believed may have emphasized mathematical manipulation. An organic chemist whose emphasis fell between the other instructors taught the final section.

The number of student responses that fit into the following categories were given: correct algorithmic questions (A1), incorrect algorithmic question (A0), correct conceptual question (C1), and incorrect conceptual question (C0). The responses were also categorized according to the scheme from Nakhleh (1993). One surprising result was that the total number of algorithmic and conceptual questions answered correctly were
essentially equal, 382 and 383 respectively. Also surprising were the number of responses that fit into the A0C1 (conceptual correct and algorithmic incorrect) category, which accounted for 22% of the responses.

In the analysis of the data, several comparisons were made within the group and between this study and previous studies. Lin et al. (1996) noted that the proportion of correct answers in this study were not high. For this group of students there appeared to be no distinguishable difference between performance on most of the problem pairs. Lin et al. observed that these results were different from those found by Nakhleh (1993) on the same set of questions. The authors also compared the results found on the gas laws problems with those found by Nurrenbern and Pickering (1987) and Nakhleh (1993). The conceptual gas law problem was the same for all three studies, with the exception of a fourth distracter added by Nakhleh (1993) and used in this study. Lin et al. also compared the frequency of responses on the five pairs of questions and the average of the responses between the FAMU students and students from Purdue (presumably from Nakhleh, 1993). For each set of problems the percent correct on the algorithmic problem (A1) and the conceptual problem (C1) were given as well as the percentage of responses falling into the categories of A1C0 and A0C1. The ratios A1/C1 and A0C1/A1C0 were calculated. Not surprisingly, the overwhelming majority of the A1/C1 ratios were greater than 1 for both schools, indicating greater success on the algorithmic problems than on the conceptual problems. The authors chose to use the ratio, A0C1/A1C0, as "a measure of the relative numbers of conceptual thinkers and math-oriented problem solvers" (Lin et al., p. 1004). The higher the ratio the greater the relative number of conceptual thinkers compared to algorithmic thinkers in that group. For the averaged results a ratio of 1.02 was found for the FAMU students and 0.36 for the Purdue students. These ratios were the results expected by the authors.

The students were asked for their preferences between algorithmic and conceptual problems. These preferences were correlated with the performance of the students and
showed some interesting results. Those students who expressed a preference tended to do better on that type of question than on the other type. There were a large number that expressed no preference.

Lin et al. (1996) examined the results on the ACS standardized test by comparing the test means for each grouping of students (i.e. A1C0) on each question pair and for the overall result. According to the authors: "These data suggest that there may be no significant differences between performance on the conceptual and algorithmic questions for FAMU students" (Lin et al., p. 1005).

The authors compared the four classes taught by the three instructors. The averages on the ACS standardized test showed significant differences. The two courses taught by the biochemist who emphasized conceptual thinking had averages that were higher than the other two courses. The course taught by the organic chemist had an average that was not significantly different from the lower score for the first two courses. The fourth course, taught by the physical chemist who emphasized mathematical manipulation, had an average that was significantly lower than the other three. Lin et al. (1996) used these results to "suggest that incorporating more conceptual teaching into the course does improve students' performance" (p. 1005).

History and Philosophy of Science

Recently, there has been a call to incorporate the history and philosophy of science into science teaching (Jensen, 1998a, 1998b, 1998c; Matthews, 1994). The following articles examined the gap between algorithmic and conceptual understanding in light of the history and philosophy of science. Niaz and Robinson (1992a, 1993) or Niaz (1995b, 1995c, 1998a) conducted most of the studies in this section. All incorporated the history and philosophy of science except for Niaz and Robinson (1993) included as further evidence of the theories of these researchers.
Niaz and Robinson (1992a) attempted to incorporate the history and nature of science into the question of algorithmic and conceptual understanding of the behavior of gases. Citing studies from Gabel et al. (1984) and Niaz and Robinson (1991), the authors suggested that "algorithmic and conceptual problems may require different cognitive abilities" (Niaz & Robinson, 1992a, p. 54).

The authors used work from the history and philosophy of science to track the development of theories on gas behavior and compared the two research paths followed to reach these theories with students' paths to understanding gas behavior. Boyle, Charles, and Gay-Lussac developed numerical laws that described bulk gas properties, but did not explain why these laws proved useful for ideal gases. The laws can be combined into the Ideal Gas Law (PV=nRT), which quantifies the relationship between pressure (P), volume (V), temperature (T), and number of particles (n) for an ideal gas with a conversion factor (R) included. According to the authors, the Ideal Gas Law (and its predecessors) was developed inductively. Solving problems based on the Ideal Gas Law require manipulation of the variables in the equation and were characterized by the authors as the 'algorithmic mode.' The properties quantified by the Ideal Gas Law were explained 200 years later by the Kinetic Molecular Theory of Maxwell and Boltzmann. The Kinetic Molecular Theory was developed in a hypothetico-deductive (H-D) system, where the H-D system went from hypothesis to observation. According to Niaz and Robinson (1992a), the Kinetic Molecular Theory required understanding a pattern to make sense of data that they termed a "conceptual gestalt." As the authors surmised, "If the nature and methods of science influence the history of science (cf. the development of the Ideal Gas Law) then it seems that this epistemological perspective has instructional significance" (Niaz & Robinson, 1992a, p. 55). The authors hypothesized that an individual student's path to understanding the behavior of gases may follow a similar path to that of the history of science – from inductive to H-D or algorithmic to conceptual. This theory prompted the authors' research question: "if the transition in the understanding of gases was facilitated
by the sequence: enumeration of particulars (induction) – H-D system, then it is pertinent to ask, what makes the same transition difficult for our students?" (Niaz & Robinson, 1992a, p. 55). The authors' research hypothesis was used to develop the research question, but it was not adequately explained why it would be logical for an individual student to follow a transition similar to that of the scientific community.

The authors had two objectives: 1) compare student performance on gas law questions requiring either 'algorithmic mode' or 'conceptual gestalt'; and 2) investigate the effect of variables such as disembedding ability, mental capacity, and developmental level on student performance on these problems. The sample consisted of 82 students enrolled in a preparatory chemistry course for science and engineering students at a large university in the US.

To determine the cognitive variables of interest the authors administered the following tests to all subjects: the Group Assessment of Logical Thinking (GALT), the Figural Intersection Test (FIT), and the Group Embedded Figures Test (GEFT). Developmental level was assessed by a shortened version of the Group Assessment of Logical Thinking (GALT), the mental capacity of the subjects was measured by use of the Figural Intersection Test (FIT), and the Group Embedded Figures Test (GEFT) was used to measure the degree of field dependence/field independence.

All students were given eight questions on gas behavior on two regular exams. Five questions were included on an exam given during the 15th week of the semester and three were included on the course final during the 17th week. The questions were part of the regular assessment of the students and were not created for this study. Six of the eight questions were designated as testing 'algorithmic mode' and two (one on each test) measured 'conceptual gestalt.' The conceptual question included on the final (Question 8) was the steel-tank problem used by Nurrenbern and Pickering (1987).

The authors pointed out that the performance on the two 'conceptual gestalt' questions was poor. They also pointed out that during the semester 13 questions were
used to assess knowledge of gas behavior and only two questions were conceptual questions. This fact indicated that the emphasis in the course had been on algorithmic learning.

The results from all eight study questions and the three variables were correlated with each other and gave 19 statistically significant results. Multiple regression tests were run for all questions versus the three variables. In three of the algorithmic questions the GALT explained a significant amount of the variance (4.9%, 5.3%, and 10.0%), but neither of the other tests explained a significant amount of the variance. For the conceptual questions the FIT accounted for a significant portion of the variance (7.6% and 4.8%). The authors interpreted this data to mean that in the conceptual questions "the information processing demand of the problems appear to be an important constraint" (Niaz & Robinson, 1992a, p. 61). A further regression analysis was run with performance on a conceptual question (Question 7) entered along with the three cognitive predictor variables as independent variables and the other conceptual question (Question 8) remained as a dependent variable. Question 7 explained 10.8% of the variance, with the FIT 2.3%, the GEFT 0.5%, and the GALT 0.3%. In this analysis the FIT explained a significant amount of the variation (5.6%) on the performance on Question 8. Niaz and Robinson (1992a) concluded: "These results provide support for the two distinct approaches to solving problems based on the behavior of gases, viz. the 'algorithmic mode' and problems requiring 'conceptual gestalt'" (p. 62).

The authors reached several conclusions: 1) 'Algorithmic mode' problems required a degree of formal operational reasoning; 2) Information processing ability was an important predictor of success on 'conceptual gestalt' problems; and, 3) based on the history of the Ideal Gas Law and the Kinetic Molecular Theory, Niaz and Robinson (1992a) said "ontogenetically it seems that solving gas problems based on 'conceptual gestalt' would be more conducive to learning, i.e. quantitative precedes qualitative" (p.
The authors pointed out a problem with this final conclusion, that chemistry students were already showing a quantitative proficiency.

Niaz and Robinson (1993) examined the cognitive demands of both algorithmic and conceptual problems. The authors' main purpose was to investigate the way in which cognitive variables, such as developmental level, mental capacity, and disembedding ability, explained student performance on algorithmic and conceptual problems. This study was first reported as a paper presented at an annual meeting (Niaz & Robinson, 1991) and was most often cited in the literature in that form, this review will focus on the later journal article (Niaz & Robinson, 1993) reporting this study.

Niaz and Robinson (1993) posited that the figurative format of the conceptual questions used by Nurrenbern and Pickering (1987) may have an effect on the results. The questions used in this study were all multiple-choice, but the authors speculated that their cognitive demand would vary with inclusion of the figurative aspects that would require more disembedding and information processing.

The sample for this study consisted of 62 students enrolled in a preparatory chemistry course (Chemistry 100) for science and engineering students at Purdue University. The authors reported that the course was taught with an interactive and participatory approach rather than the traditional expository method.

To measure the cognitive variables of interest, the authors administered the following tests to all subjects: the Group Assessment of Logical Thinking (GALT), the Figural Intersection Test (FIT), and the Group Embedded Figures Test (GEFT). Developmental level was assessed by a shortened version of the Group Assessment of Logical Thinking (GALT), the mental capacity or M-capacity of the subjects was measured by use of the Figural Intersection Test (FIT), and the Group Embedded Figures Test (GEFT) was used to measure the degree of field dependence/field independence.

The three experiments used in this study were each made up of two or three multiple-choice questions included on the course final given during the 17th week of the
semester. In every experiment, one question was a conceptual problem and the remaining questions were algorithmic problems. All conceptual problems contained figurative aspects. Experiment 1 consisted of three problems on gas laws. The conceptual problem was the steel-tank problem from Nurrenbern and Pickering (1987). Experiment 2 consisted of two stoichiometry questions and experiment 3 consisted of two limiting reagent problems. The conceptual problems for experiments 2 and 3 were stoichiometry problems from Nurrenbern and Pickering. For all three experiments the students showed greater success on the algorithmic problem, when compared to the conceptual problems.

The conclusions from Niaz and Robinson (1993) emphasized that the GALT was consistently the greatest predictor of success on the algorithmic problems, and that the results for the conceptual problems showed a different predictor for each problem. The authors pointed out that though the conceptual problems all had figurative aspects in common, a different cognitive variable was the best predictor of success for each. The authors stated that a major contribution of this study was to identify the mental processes necessary for successful conceptual problem solving. The authors (Niaz & Robinson, 1993) further stated that "this study provides explicit empirical evidence against one of the unquestioned axioms of freshman chemistry, viz. teaching students to solve computational problems facilitates conceptual understanding" (p. 415).

Niaz (1995b) attempted to explain the gap between algorithmic and conceptual problem-solving ability as a transition similar to the "problemshifts" proposed by Lakatos (1970). By embracing the work of Lakatos, Niaz (1995b) incorporated the history and philosophy of science into the examination of this issue. The author expressed that despite the increased awareness among science educators of the gap between conceptual understanding and algorithmic ability, more work needed to be done to investigate the psychological and epistemological basis of the gap. This study was reported previously (Niaz, 1994) as a paper presented at a national meeting.
The objective of this study was to build models based on students' strategies for solving chemistry problems and show how these models form sequences similar to the progressive problemshifts proposed by Lakatos (1970). Each model should increase the explanatory power of the model and should show a progressive transition of varying degrees from algorithmic to conceptual understanding.

The sample for this study consisted of 83 freshmen Chemistry I students at the Universidad de Oriente in Venezuela. The chemistry course was designed for science majors. Through the semester the students were given four sets of questions labeled as Experiment 1 through Experiment 4. The problems were part of the regular monthly exams given throughout the semester and the students were encouraged and given credit for giving justification for the answer they selected or calculated. The experiments included from two to four items and contained at least one problem requiring conceptual understanding and at least one problem that could be solved with an algorithm. The topics covered by these experiments included mole calculations, gas laws, solutions, and the photoelectric effect.

The author used the following definitions in deciding if an item required conceptual understanding: a) the problem required greater conceptual understanding relative to another problem; b) an algorithmic problem was based on mathematical transformations and was well rehearsed in class; c) the degree of conceptual or algorithmic classification was dependent on the previous experience of the students; and d) the difference between the two was not dichotomous.

The results presented by Niaz (1995b) were in the form of numbers of students answering each of the problems correctly, partially correct, or incorrectly. The author used this data to develop a model of transitions similar to the problemshifts of Lakatos (1970).

In Experiment 1, there was clearly a greater level of success on the algorithmic problem (1A) than on the conceptual problem (1B). In his analysis of Experiment 1, the
author suggested that the results showed that the number of students answering the conceptual problem correctly using a one-step strategy showed that they were able to "chunk" the information or process the information more efficiently. Niaz (1995b) also stated "These results suggest that Ss [students] progressively construct models (based on strategies) that require greater conceptual understanding" (p. 27). The author felt that based on the results from Experiment 1, it was reasonable to suggest that students "go through a process of progressive transitions and build models that facilitate different degrees of conceptual understanding" (Niaz, 1995b, p. 27) similar to progressive problemshifts. The author then proposed a series of five models with the numbers of students that fit into each model. The models followed an orderly progression from answering the algorithmic problem with a partially correct answer to answering the conceptual problem using the one-step strategy.

For Experiment 2, 52 students solved the algorithmic problem (2A) correctly, and 8 incorrectly. Only four students solved the conceptual problem (2B) correctly, 13 were partially correct, and 43 were incorrect. All four students that correctly solved the conceptual problem correctly solved the algorithmic problem correctly. Niaz (1995b) attributed this result to students' failure to fully conceptualize the problem and felt that this lack of conceptualization clearly showed how students memorized equations and looked for numbers to plug in. The results for Experiment 3 were quite different, as the students had difficulty with both the algorithmic and conceptual problems. For these problems, the author claimed that the students were not taught an algorithmic prop, and the lack led to poor performance on these problems. The author claimed that the results for this experiment showed support for the hypothesis that conceptual understanding as shown in Item 3C, was helpful in solving the algorithmic problems. As with Experiments 1 and 2, the author developed a series of five models showing the students' transitions from purely algorithmic to conceptual understanding. In Experiment 4, the usual pattern of results of greater success on the algorithmic problems was seen. The six models and their
transitions devised by Niaz (1995b) offered a more thorough description of the problem shift than the previous three sets of models. The first three models showed progression leading to greater algorithmic understanding, and the beginning of conceptual understanding. The last three showed a greater integration of conceptual understanding.

In discussing the conclusion, Niaz (1995b) pointed out that this study added support to many previous studies' findings that there was considerable difference between performance on conceptual and algorithmic problems. The author pointed out that this study also supported the contention from other chemical educators that the ability to solve algorithmic problems was not necessarily helpful in solving conceptual problems, but that conceptual understanding was helpful in solving algorithmic problems.

The main conclusion by Niaz (1995b) was that:

In general, the difference between student performance on algorithmic and conceptual problems can be interpreted as a process of progressive transitions (models) that facilitate different degrees of explanatory/heuristic power to student conceptual understanding, similar to what Lakatos (1970) has referred to as the rational reconstruction of scientific research programs. (p. 32)

Niaz (1995c) investigated the relationship between conceptual and computational performance on chemical equilibrium problems with Venezuelan college chemistry students. The purpose of the study was to: 1) Gauge the students' understanding of chemical equilibrium; 2) Compare student performance on conceptual and algorithmic problems; and, 3) compare students' development of knowledge with scientists' development of theories.

The sample for this study consisted of 78 freshmen students at the Universidad de Oriente in Venezuela. All students were enrolled in one of two sections of Chemistry II for science majors. The students were asked to solve 11 problems dealing with different conceptual and computational aspects of chemical equilibrium. The problems were included on regular exams and the students were required to give an adequate reason for
their answer to receive full credit. Three problems were included on Exam 1 during the sixth week, two problems were included on Exam 2 during the eighth week, and six problems were included on Exam 3 during the tenth week. Six questions had from three to six subsections, while the other five were either multiple-choice or work-out problems. Seven problems and two subsections were classified as conceptual problems, while three problems and one subsection were classified as computational problems. The problems were also categorized by the understanding of chemical equilibrium that they tested. The categories were taken from prior research and were: 1) approach to equilibrium, 2) changing equilibrium, and 3) characteristics of chemical equilibrium. The categories were not equally represented in this study, with category 1 having 2 questions, category 2 having four questions, and category 3 having five questions.

Niaz (1995c) defined conceptual questions for this study as problems that could not be solved with memorized algorithms or formulae. The author admitted that students in this study had difficulty with the conceptual questions because of their type and because they had not generally seen that type of problem in class. Most of the conceptual problems used consisted of "a series of related and probing questions that help to construct student understanding of equilibrium" (Niaz, 1995c, p. 345). Niaz (1995c) defined the computational questions as problems that required "mathematical transformations that are well rehearsed in class, and in most cases can be solved by memorized algorithms" (p. 345).

The results of this study were presented in several ways. The number and percentage of correct answers for each subsection of each problem was given, including its categorizations according to the type of reasoning tested (conceptual or computational) and equilibrium category. Niaz (1995c) also compared performance on certain conceptual and computational problems. The problems were chosen because the students' performance on the problems was neither too high nor too low.
Based on the results of question 2, Niaz (1995c) proposed: "It is suggested that the closely related probing questions utilized in this study may have helped the students understand (perhaps on second thoughts) the underlying concepts better" (p. 346). A finding by Niaz (1995c) that appeared quite interesting was that when the number of correct answers on the items of certain conceptual questions were compared to performance on two computational problems, it appeared to be a directly proportional relationship. In other words, the more conceptual items that the students answered correctly, the greater the percentage of students who answered the computational question correctly. When examined in the other direction, from computational to conceptual, the relationship broke down. Niaz (1995c) suggested that: "These results indicate that success on conceptual items is more conducive to resolution of computational items than vice versa" (p. 350).

The author compared the results for subjects who answered all parts of the computational problem correctly but failed to answer all parts of the conceptual problem with those subjects who answered all parts of the conceptual problem but failed to answer all parts of the computational problem correctly. For all eight comparisons the number of subjects with more success on the computational problem was higher than those with more success on the conceptual problem. The author believed that these results suggested that by solving computational problems only, students may not develop an understanding of equilibrium that leads to conceptual understanding or the "conceptual framework" suggested by Camacho and Good (1989).

The conclusions offered by Niaz (1995c) seemed to follow his ideas rather than the results. The author pointed out that the results provided "evidence against the widely prevalent idea that the ability to solve computational (numerical) problems leads to conceptual understanding" (Niaz, 1995c, p. 352). The author made a questionable suggestion: "It is suggested that solving computational problems before solving problems that require conceptual understanding would be more conducive to learning, that is, the
quantitative precedes the qualitative" (Niaz, 1995c, p. 352). This obscure statement was said to be consistent with the data, and with an earlier study from the author (Niaz & Robinson, 1992a) and the history of science theories of Hanson (1958). The final finding by Niaz (1995c) went well beyond the data with the statement:

Another important finding of this study is that given an opportunity, and after having been exposed to closely related, alternative probing questions, students give up a certain mode of thinking, at least partially. Furthermore, students adopt an alternative view that apparently contradicts their previous thinking. (p. 352)

The author never presented any evidence that the questions in each item were substantially related to the other items, so to state that the students were changing their modes of thinking and views is much beyond the data presented here.

Niaz (1998a) attempted to develop a teaching strategy to facilitate students' conceptual understanding of chemical equilibrium. Building on the result of earlier studies (Niaz, 1995b, 1995c), the author sought to create a teaching strategy that utilized the nature of science theories of Lakatos (1970) to promote a shift from algorithmic to conceptual understanding of chemical equilibrium.

The main objective of the study was to develop a teaching strategy that would aid in conceptual change in students' understanding of chemical equilibrium. The teaching strategy was based on seven basic assumptions: 1) emphasis on key points to facilitate a "chain reaction" leading to conceptual understanding; 2) students will abandon misconceptions if exposed to closely related probing questions; 3) students must be provided with views that contradict their views; 4) the new framework must appear acceptable to the students; 5) the student should be able to change some assumptions without contradicting hard-core beliefs (Lakatos, 1970); 6) disequilibrium must come from the student; and 7) the teaching strategy must be interactive. The hypothesis of the study was that the students' participation in the study would facilitate their conceptual understanding of chemical equilibrium.
The sample was made up of two sections of Chemistry II at the Universidad de Oriente in Venezuela. One section was randomly chosen as the treatment group with the other as the control group. The treatment group was exposed to two teaching experiments during the fourth and fifth week of the semester. The experiments consisted of the presentation of the equilibrium relationship: $2 \text{NO}(g) + \text{Cl}_2(g) \rightleftharpoons 2 \text{NOCI}(g)$ ($\Delta H < 0$). Four questions were then asked concerning the equilibrium reaction rates. The treatment group discussed these questions in class. Other than the two experiments, the classroom experiences of both groups were held constant.

The author then included equilibrium problems similar to the experiments in five post-test questions given at a three week interval and at an eight week interval. The post-tests were included in regularly scheduled exams. Niaz (1998a) found that the treatment group performed better than the control group. Only two statistically significant differences ($p < 0.05$) were found on the 17 exam questions. The magnitude of the difference lessened on the eight week post-tests. This result led Niaz (1998a) to conclude that "even relatively short periods of appropriate experiences can facilitate understanding of chemical equilibrium" (p. 121).


The study incorporated three chemistry teachers and five classes of eighth-graders ($N=220$) from a Taiwanese urban high school that the author described as typical. The teachers in the study were recommended by the school principal because of their teaching practices and experience. Two of the three were randomly selected for the treatment. The treatment consisted of a half-day workshop where two chemistry historical cases, atmospheric pressure and development of atomic theory, were incorporated into the
supplementary material. Lin (1998) developed the supplemental material, which included a hands-on experiment, discussion material, and historical information. The material and the theoretical background of the treatment were presented to the two teachers, and the materials were discussed with the teachers until they were comfortable with its implementation.

One class from each treatment teacher was randomly selected for the historical approach (N=88) and the other class served as a control group (N=89) taught in the regular manner. One class from the non-treatment teacher was randomly selected as a comparison group (N=43). The author reported that the groups were equivalent when ranked for academic achievement by the school's administration.

Lin (1998) measured the outcome of this study using a researcher-developed four-item conceptual problem-solving test. The test measured the students' ability to synthesize information in problem solving. The test items covered the concepts of atom, atomic weight, the law of definite proportions in volume, and the law of conservation of mass. The problems required explanations as well as answers and each problem was worth six points for a total of 24 points.

The scores on the Conceptual Problem-Solving Test for the three groups were compared, with the Experiment group achieving the highest median score (8.97), followed by the Control group (7.64), and the Comparison group (5.36). An ANCOVA using an earlier physical science exam as a covariate showed a significant effect (p < 0.05) for the new instructional approach. The author also examined whether there was a different effect for high achievers and low achievers. The students were placed in high and low achiever groups based on the last semester's physical science achievement. For the high achievers, the experiment group had the highest achievement (12.32) followed by the Control group (10.97) and the Comparison group (8.29). The ANCOVA showed a significant difference between the three groups, but post-hoc comparisons showed no significant difference between the Experiment and Control groups. For the low achievers,
similar results were found with the Experiment group (5.61) achieving highest, then the Control group (4.10), and the Comparison group (2.56). The ANCOVA showed a significant difference for the experimental group. The author claimed "comparing the results of the high and low achievers suggests that the low achievers were more affected by the historical approach" (Lin, 1998, p. 1329).

To further examine whether the students in the experimental group benefited from the history-of-science method, Lin (1998) randomly selected one student from the high-achievement, medium-achievement, and low-achievement groups in each class for an interview. The 15 students were each asked an atmospheric pressure question that the author had used in a previous study. Not all of the experimental students showed complete understanding of the question, but none of their answers reflected a "nature abhors a vacuum" argument. More than half of the control and comparison students answered based on the "vacuum" argument.

Instructional Strategies

After determining that a problem exists, chemistry educators attempted to determine methods for alleviating the problems. The following studies examined programs that might have a positive impact. Along with Phelps (1996), the programs showed promise.

Lythcott (1990) examined the relationship between problem-solving approaches and chemical knowledge. The author believed that the problem with many problem-solving strategies was that the rules of the strategies allowed problems to be solved with "no confrontation with the chemistry of why they work" (Lythcott, p. 248).

Lythcott's (1990) research hypothesis was that "if students understood problem solving as a search after meaning, not the following of prescribed rules, then both their chemistry knowledge and problem-solving performance would improve" (p. 248). The author studied chemistry students enrolled in two classes of a first-year regular chemistry
course at a suburban high school. The chemistry program at this school was reported to have an excellent reputation. The study employed problems about mass in chemical reactions. The two classes were taught different strategies for solving chemistry problems. The first class was given the factor-label method, essentially a set of rules for solving mass-mass problems, and practice in using those rules. The second class was taught the learning strategy called qualitative redescription (Reif, 1983). The strategy consisted of: 1) determining what the problem was about, 2) describing in basic English what the substances look like and what would be seen, 3) developing an expectation of the final answer, and 4) searching for a means to determine the answer. The class studied came up with the factor-label method using this approach. Four days of instruction on mass-mass relationships were given and the treatment class solved many fewer problems during instruction than the control class.

After instruction the students were interviewed twice using a think-aloud process. In the first interview, the students were asked to solve two simple mass-mass problems. The tape-recorded interviews took place during the four days following instruction. The next part of the study consisted of another tape-recorded interview to determine the requisite chemistry knowledge of the subjects. The interview lasted approximately 50 minutes, and the subjects were told that the purpose of the interview was to elicit their chemistry knowledge. The interview began with conversation about mass in chemical reactions. As the subject used the term mole, they were asked to answer questions about its meaning and uses.

The rest of the interview was made up of three tasks for the students to complete. The first task involved a balanced equation from the problem-solving task in the earlier interview. The equation showed the reaction of potassium with water to form potassium hydroxide and hydrogen gas. The subjects were asked if the coefficient for water was changed how that would affect the coefficient for hydrogen. The purpose was to determine if the subjects understood that the coefficients represented a proportion
between water and hydrogen. The second task asked the subjects to explain what the \(2H_2O\) meant in the earlier balanced equation. The subject responses were probed to determine their understanding of molecules as discrete particles. The third task was used to elicit the subjects' knowledge of the meaning of a balanced equation in terms of particles. The terms atom and molecule were used instead of particle after the subject used them. The subjects were asked to represent the reaction with labeled circles representing atoms. This task was used by Yarroch (1985). The task was utilized to determine the students' understanding of polyatomic molecules and a further test of their understanding of the meaning represented in the coefficients of the balanced equation. The interviewer verbally interpreted the drawing to ensure that the meaning was clear.

The treatment group had the same percentage of completely correct answers, but had a smaller percentage of inadequate solutions than the control group. Lythcott (1990) discussed the results from only 13 of the subjects in this report. The 13 were chosen because they were the subjects who correctly solved or made only one minor error in solving both mass-mass problems in the problem-solving interview. Of the 13 subjects discussed, eight were from the control group and five were from the treatment class. Prior to the study, the regular teachers classified each student based on their chemistry performance to that point. The students were classified as very successful (VS), successful (S), average (Av), or unsuccessful (Un). Of the 13 subjects, one was categorized as unsuccessful, two were average, six were successful, and four were very successful. The eight students for the control group contained one unsuccessful, five successful, and two very successful students. The five students from the treatment group were made up of two average, one successful, and two very successful students.

Lythcott (1990) noted that of the 13 subjects examined, all of whom had answered the problems correctly,

only two had a clear notion of the proportionality of coefficients, only five expressed complete confidence in the existence of particles of water, only
five were able to represent adequately the balanced chemical equation by drawing (i.e., models) of atoms, and only six described a mole in chemically acceptable terms. (p. 251)

The author concluded that the subjects showed chemistry knowledge that was inadequate though they all answered the problems correctly. The author felt that this student inadequacy was especially true of the control group subjects.

Lythcott (1990) discussed the results from this study by offering four possible interpretations of the data. The first interpretation was that this phenomenon was only present in this sample. The author cited the findings of Yarroch (1985) and Gabel and Sherwood (1983) to support the claim that results were not isolated to this population. The second interpretation was that this phenomenon was due to a lack of cognitive development at the formal operational level for the students. Lythcott cited the findings of Nurrenbern (1979) and Gabel and Sherwood (1983) that found that formal operational students showed the same phenomena to negate this argument. The third interpretation was that chemistry was so difficult to understand that some students must rely on "this mindless rule following" (Lythcott, p. 251). Lythcott argued that this interpretation was faulty because all but one of these 13 subjects were classified as average or better students, and the author would not accept that chemistry was so hard that only a small group of bright students could understand it. "Another possibility is that many students could understand the basic chemistry if given the opportunity" (Lythcott, p. 251). The fourth interpretation was that there was a fault with the problems used. Lythcott argued that: "If a student can solve the problem, get the grade, and pass the test by assiduously following rules without struggling to understand, predictably this is what will happen. Why would students expend more energy on a task than it requires?" (pp. 251-252).

Bunce, Gabel, and Samuel (1991) conducted an exploratory study to examine the effect of problem-solving instruction employing the explicit method of problem solving (EMPS) (Bunce & Heikkinen, 1986). The authors wished to determine if providing practice in problem categorization for chemistry problem solving improved student
achievement. Bunce et al. defined problem categorization in chemistry as "the process of assigning a description to a chemistry problem according to the major concept(s) involved" (p. 507). The problems would be placed into categories such as stoichiometry. A second purpose of the study was to determine if problem categorization could be taught in the limited specific instruction provided.

The subjects of the study were 24 female students in a college chemistry course for health-care professionals. The course was offered at a private university in the southeast. The students were expected to attend the course lectures and a four-hour per week laboratory. In the lecture, both control and treatment groups were encouraged to use the EMPS on tests and were directed to use it on homework. The students were randomly assigned to two laboratory sections, one control and one treatment.

The EMPS was described as an organized approach to problem solving. The approach was modified from an approach studied in the first author's dissertation. The EMPS consisted of the following steps: Given, Asked For, Recall, Overall Plan, Mathematics, and Review. The definition of each step was given. The treatment emphasized the Recall step which was defined as: "Rule, equation, or principle that is involved in the problem's solution" (Bunce et al., 1991, p. 508).

On three occasions when the tests were returned, both groups spent 30-40 minutes reviewing the problems in the pre-laboratory lecture. In the control group the achievement test questions were solved on the overhead by the instructor using the EMPS. To provide equal problem-solving time, two similar problems were solved, and discussion was not encouraged. In the treatment group, instead of showing problem solutions, the problems were shown on an overhead transparency and the students were asked to categorize each problem. The discussion focused on students' categorization of each problem by identifying the relevant clues and elimination of extraneous information. The discussion was confined to problem categorization and correct use of EMPS was assumed. The students were explicitly shown how problem categorization was part of the
Recall step. Effort was made to encourage the students to use broad categories such as gas laws rather than narrower categories such as pressure-volume.

The authors administered a series of 16 tests throughout the semester to measure achievement and categorization ability. The first test administered was the Logical Mathematical Reasoning Test given during the first lecture. The test measured students' ability to perform several mental manipulations prior to solving a problem.

Bunce et al. (1991) administered a pre-test and post-test, each consisting of six problems to be categorized, before and after treatment to determine any difference due to instruction and treatment. As well as categorizing the problems, the tests asked the students to group similar problems together with as many categories as they wished. The students were also told to write a one-sentence justification for their categorization. The pre-test and post-test each contained different problems and took approximately 15 minutes to complete. A second post-test consisting of the same problems as the pre-test was administered prior to the final achievement test.

The authors also administered three single-concept tests (C) requiring students to categorize and solve five, six, and six problems on these tests, respectively. The tests were given immediately following instruction on the three topics studied: stoichiometry, gas laws, and molarity/neutralization. The test scores were used as part of the students' grades. The tests were administered to determine the effectiveness of treatment and the categorizing sophistication of the students.

Three cumulative tests (D) were also administered. These tests consisted of subtests of problems on the topics of the study. The students were not required to categorize the problems on these tests. Bunce et al. (1991) justified the inclusion of these tests because they hypothesized that the treatment might show more effect on tests that contained more types of problems than the single concept tests. Two tests were given at regularly scheduled times, and the third (U2) was given as an unannounced test after instruction on the three topics was completed. The authors justified the inclusion of an
unannounced test because the first author had found significant differences from an unannounced test in her unpublished dissertation.

The tests, instruction, and treatment were completed in the following order: Logical Mathematical Reasoning Test, pre-test, first instruction, C₁, Treatment 1, second instruction, C₂, Treatment 2, U₁, third instruction, C₃, Treatment 3, U₂, post-test(s), U₃. The length of the study was not given.

The data were analyzed by summing the items on each test or subtest on the achievement tests (C and U) to give a score or subscore for each test or subtest. The authors tested the effectiveness of the treatment on achievement test scores and combinations of achievement test scores, which were: compilation of all achievement tests (C and U), combination problems (a subset of C and U), cumulative tests (U), and the unannounced test (U₂). The unit of analysis was the group.

The means and standard deviations for both groups on all achievement tests were reported. The means for the treatment group were higher for all tests, but only two statistically significant ($p < 0.05$) differences were found between the means on the tests by an F-test. Significant differences were found on the first one-topic test (C₁) and the unannounced cumulative test (U₂). The differences between scores on the total of the cumulative tests (U₁, U₂, and U₃) were tested and were found not to be statistically significant. The differences between scores on the sum of single topic tests (C₁, C₂, and C₃) were also found not to be significant.

To determine if the treatment would be more effective in more complex situations, the authors ran analysis of covariance (ANCOVA) tests for all combination problems and for all single-concept problems. The ANCOVA showed a statistically significant difference between the groups for the scores on the combination problems ($p = 0.01$), but not for the single-concept problems.

To answer the research question whether students could be taught to categorize chemistry problems through the treatment provided, Bunce et al. (1991) originally planned
to examine the students' categorization sheets from the pre-test, post-test, and achievement tests. The authors decided early in the study to abandon this method because "A lack of consistency in the terminology used by students makes the interpretation of their categorization skill ambiguous" (Bunce et al., p. 514). The authors chose instead to interview the subjects to examine this question. Twelve of the 24 subjects were chosen to be interviewed. The subjects were chosen based on the scores on the Logical Mathematical Reasoning Test and on C₁, with six subjects selected from both the treatment and control groups. An attempt was made to interview a subject from the treatment and control groups who had high, medium, and low scores on the two tests.

The interviews consisted of two parts and lasted 30-40 minutes. In part one, the subjects were given four index cards in random order, each of which contained a problem similar to those on the achievement tests. The subject was asked to categorize each problem and then to group problems that could be solved in a similar fashion. The interviewer elicited explanations for the categorization and groupings of the problems from the subject. The second part of the interview had the subjects solve the same problem from amongst the four prior problems. The students were provided with paper, pencil and a calculator, and were given a periodic table, and the value of the gas law constant (R) if requested. This portion of the interview was done with a think-aloud protocol and the interviewer prompted verbalization if necessary. In the interview, the subjects were asked about their use of the EMPS.

In their discussion of the results, Bunce et al. (1991) acknowledged that few differences between achievement scores for treatment and control groups were found statistically significant, but that the means for the treatment group were consistently higher. The first significant result was for the difference between group means for the combination problems. Bunce et al. suggested that this result signified that giving students specific instruction in categorization improved their achievement scores when more than one chemical concept was required in the solution. The second significant finding was for
the unannounced test (U2). The authors attributed this result to the students' preparation for announced tests, and the treatment students being able to rely on the categorization strategy on the unannounced test, while the control group students "who have approached problem solving in a more automatic fashion without analyzing the problem-solving process, will forget much of what they have learned once the expected testing situation is over" (Bunce et al., p. 515).

Bunce et al. (1991) offered three possible reasons for the lack of significant differences: 1) small sample size, 2) the control students were also taught the EMPS, and 3) the duration of treatment. After discussing the possible reasons for the lack of significant results, the authors argued that "the significant findings on the combination problems and on the unannounced quiz provide indications that having students practice categorization of problems enhances achievement on more complex problems and in situations where students do not specifically prepare for an exam" (Bunce et al., p. 516).

From the interviews the authors found that the majority of students in both groups grouped problems according to units such as gram or liter. The remaining students categorized the problems based on the equation used to solve the problem. Bunce et al. (1991) determined that many students used what they called a "Rolodex approach" to problem solving.

The Rolodex approach involves putting each formula or rule learned in a chemistry course on a different mental file card. When a chemistry problem is read, the student identifies the units given and asked for in the problem and then flips through a mental file of formulas until the units of the problem match the units of the formula. (Bunce et al., p. 517)

The authors asked half of the interviewed students about their conceptual knowledge and found that all of the students had some conceptual knowledge, but that they admitted they did not need/use the knowledge when solving formula-driven problems.

Bunce et al. (1991) stated that this study supported the findings of Gabel et al. (1984) and Nurrenbern (1979), that even with the use of the EMPS the students failed to
incorporate physical entities into their problem solving. This study showed that the students had conceptual knowledge but failed to use it in problem solving. "One might argue that teaching students to use a systematic approach to problem solving such as the EMPS promotes this type of behavior because students do not find it necessary to make the conceptual linkage to achieve a level of success in problem solving that is expected of them by instructors" (Bunce et al., p. 519).

Nakhleh, Lowrey, and Mitchell (1996) reported the results from an NSF supported study to change the manner in which chemistry instruction was presented. The authors reported the results of Project REMODEL, the purpose of which was to "narrow the gap between conceptual and algorithmic understanding in freshman chemistry" (Nakhleh et al., p. 758). The authors incorporated innovations in lecture, laboratory, and student assessment in an introductory chemistry sequence for chemistry majors and evaluated those innovations to provide information on these reforms and barriers to reform to the chemical education community. This report focused on the lecture and assessment innovations incorporated in the second semester of the sequence during the spring of 1994.

The authors, in collaboration with the course instructor, designed weekly sessions where students had the opportunity to cooperatively work on conceptual problems and report their solutions to the class. The authors also worked with the professor to develop four exams made up of a mix of traditional problem-solving questions and conceptual questions. They believed that these special sessions and conceptual exam questions would "force students to 'plug the holes' in their conceptual understanding in a way that solving algorithms does not" (Nakhleh et al., 1996, p. 758).

The study was based on the action research model, which the authors believed was appropriate for this type of study because the action research model allowed the authors to continually refine the model based on the data collected. The researchers had seven research questions that guided the study: 1) How were students' attitudes and motivation
affected by the innovations? 2) What misconceptions did the students have about the chemistry topics in the course? 3) Were the misconceptions addressed by the strategies? 4) How did students use multiple representations of chemistry concepts? 5) How did the multiple representations affect students' understanding of the chemistry concepts? 6) How did the faculty, staff, and teaching assistants react to the changes? And, 7) what barriers to implementing the changes were there? Many of these questions were not addressed in this report which the authors did not explain.

Nakhleh et al. (1996) collected data in several ways during this study. Data on the students' attitudes toward the changes were gathered from initial and final surveys of the students, interviews with selected students, and interviews with the instructor and the two teaching assistants. The group reports presented in the special sessions were analyzed to gather data on the students' conceptual understanding. Students' conceptual understanding was also gauged by the conceptual questions on exams. Data on obstacles to change were gathered from field notes and observations from the first two authors and interviews of students and staff.

Demographic information and information of preferred ways of learning were gathered in an initial survey given at the beginning of the course. The final survey was used to gather information on the students' reactions to the special sessions, the conceptual exam questions, and V-diagrams of the laboratory. The V-diagrams were not discussed elsewhere in this report. The initial and final surveys asked a different set of questions. Also included on the final survey were free-response questions concerning the innovations.

The course where the innovations were introduced was CHM 126, which was the second semester of a general chemistry sequence for chemistry majors. The class traditionally consisted of three 50-minute lectures, a three-hour lab, and a 50-minute recitation per week. The professor for the course had taught the course for five years, and had typically emphasized numerical problem solving with little emphasis on conceptual
problems. A typical lecture consisted of 20 minutes in developing the theory and 30 minutes on various types of problems where the topic was applied, usually emphasizing calculations. The exams were composed of numerical free-response questions.

In this study, the first author attempted to improve the conceptual problem solving of the students by replacing one lecture per week with a 50-minute period devoted to conceptual problem-solving. Six conceptual questions related to the lecture material were prepared before each special session by the first author, and handouts with the questions were prepared for the students. In the session, the students were divided into six groups of about the same size, based on where the students were seated, and each group was assigned one problem. The students took the first 25 minutes of the class to solve the problem and prepare to present their solution. The last half of the period consisted of group presentations of the solutions. The special sessions covered colligative properties, equilibrium, acid-base equilibria, electrochemistry, kinetics, and thermodynamics.

The four exams for the course contained a nearly equal mixture of conceptual and computational free-response questions. The exams were developed collaboratively between the instructor and the first author and averaged 11 questions per exam. The conceptual questions were related to lectures and the special sessions, but were not repeats of those used in the special sessions. The exams were given in the evening and students were allowed up to an extra hour to finish the exam. The first exam covered colligative properties, phase diagrams, gas phase equilibria, and acid-base equilibria. The second exam covered buffers, pH, and solubility. The third exam covered redox and electrochemistry and the final exam covered kinetics and thermodynamics.

Nakhleh et al. (1996) presented the results of this study in four sections: special sessions, exams, performance on conceptual and algorithmic problems, and impressions of the professor. According to the authors, the special sessions were viewed as "a very worthwhile part of the course" (Nakhleh et al., p. 760) by the students. The authors
highlighted two ways in which the special sessions proved beneficial: allowing a deeper level of discussion, and pointing out students' weak areas of conceptual understanding.

The exams for the course were different from standard practice because of inclusion of conceptual questions. According to Nakhleh et al. (1996) students reported initial difficulty with conceptual questions because "they had never had to think of chemistry in that way" (p. 761). By the second exam the students were intent on understanding conceptual problems as well as they did computational problems because they knew they would be tested on the concepts. The students learned that they needed to understand the concepts discussed in the special sessions and asked the professor to post solutions to problem session questions as well as homework solutions. Students also reported that the conceptual questions were challenging.

On the exams, Nakhleh et al. (1996) examined the difference in student success on conceptual and algorithmic questions on all four exams. A statistically significant difference (p < 0.05) was found between means on conceptual and algorithmic problems for Exam I and Exam III, but not for the other two exams. On Exam I, a 21% difference was found between averages on algorithmic (11.03) and conceptual (7.91) problems. Nakhleh et al. (1996) attributed this result to the students' "lack of practice with conceptual reasoning" (p. 761). Exam II did not show a significant difference, which the authors interpreted as due to the practice in conceptual reasoning done in the special sessions. Exam III again showed a significant difference. This difference was attributed to the fewer special sessions offered for the material on Exam III because of professional commitments of the authors and the professor. On the final exam the differences were again not found to be significant, which was attributed to the reinstitution of the special sessions.

Nakhleh et al. (1996) interviewed the course professor about the innovations and he was very enthusiastic about the implemented changes. The professor noted the following points about the course with the changes: 1) students were more interested and
alert; 2) he had sufficient time to cover the material even with two lectures instead of three; and 3) this experience was his best in 12 years of teaching. The professor supported the special sessions and conceptual questions as informative in assessing the students' thinking. "He also reported that teaching in this new way demands the ability to think on your feet, to take advantage of students' comments during special sessions to extend the discussion of the material, and to bring in real world applications of interest to the students" (Nakhleh et al., p. 762). The authors also highlighted the necessity of providing support for professors while implementing innovations. The authors stated that their next step was to adapt Project REMODEL for large lecture groups ($N > 200$).

Noh and Scharmann (1997) examined the conceptual and algorithmic understanding of Korean high school chemistry students. The authors wished to see if a pictorial representation of matter in a chemistry course would help students to develop a better conceptual understanding and a lesser reliance on algorithmic problem-solving strategies. The authors felt that previous studies had focused on promoting problem solving or conceptual change, but not both, and they wished to design a study to promote both.

The authors implemented suggestions from prior research to develop this study. The study featured two main aspects, the introduction of pictorial representation of matter prior to quantitative relationships and an emphasis on molecular representations in chemistry problem solving. The authors emphasized that the instructional strategy that was implemented did not incorporate all teaching strategies that were consistent with current learning theories, but focused on "understanding the problem" in problem solving and emphasized a scientific conception of matter.

Noh and Scharmann (1997) conducted this study at a Korean academic high school and made efforts to test the generalizability of previous studies across cultures. To do this, the authors replicated studies that compared students' ability to solve conceptual and algorithmic problems which had all been conducted with American college and
university students (Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz & Robinson, 1991; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990). The authors' purposes were: 1) to investigate the influence of an emphasis on matter at the molecular level on students' conceptions of matter and physical changes and on their ability to solve pictorial and algorithmic problems; 2) replication of previous studies on solving pictorial and algorithmic problems with Korean high school students; and 3) "to study relationships between logical reasoning ability, conceptions, pictorial problem-solving ability, and algorithmic problem-solving ability" (Noh & Scharmann, p. 202). The hypotheses tested in this study were: 1) There would be a significant difference on the post-test scores for the treatment and control groups when the Group Assessment of Logical Thinking (GALT) was included as a covariate; 2) there would be a significant difference for the scores on the post-test Chemistry Conceptions Test (CCT) subtest on the dissolution concept for the treatment and control groups; and, 3) there would be a significant relationship between the scores on the GALT and the scores on the post-tests.

The sample for this study consisted of two intact classes of eleventh-grade men with declared science majors at a Korean coeducational academic high school in Seoul. The chemistry course was taught twice weekly with a laboratory and lecture component. The same teacher, who had nine years of teaching experience, taught both sections.

The treatment consisted of 13 weeks of instruction emphasizing matter at the molecular level with pictorial representations. The teacher used the visuals when new concepts were introduced, qualitative aspects were explained, equations were introduced, or problems were solved. The instruction for the control group consisted of traditional expository teaching. The topics covered during the study were chemical equations, gases, liquids and solids, and solutions.

The authors selected the target concepts for the tests in this study from a textbook used in Korea and from students' misconceptions literature. Four target concepts were
selected for this study, which include the particulate nature of matter (Particle), states of matter (State), diffusion (Diffusion), and dissolution (Dissolution).

Noh and Scharmann (1997) used the GALT to assess the logical reasoning ability of the students. The Chemistry Concepts Test (CCT) was developed for this study to assess the conceptual knowledge of the students. A second test, the Chemistry Problem-Solving Test (CPST), was also developed for this study to assess problem-solving ability. The CPST consisted of ten pairs of algorithmic and pictorial problems with three pairs of questions on stoichiometry, five on gases, and two on solutions.

In analyzing the results, Noh and Scharmann (1997) included information concerning all three tests and classroom observations. In the classroom observations, the researcher noted that the teacher mentioned pictures or tables in the text for the control group (7) more than for the treatment group (3), and that the teacher drew more molecular pictures for the treatment group (17) than for the control group (11). After instruction, the information concerning the textbook pictures was discussed with the teacher, who speculated that this difference in picture use was because pictorial materials were available for the treatment group.

The results for the gas law and stoichiometry questions on the CPST were analyzed and compared to results from research by Sawrey (1990), Nakhleh (1993), Nakhleh and Mitchell (1993), Nurrenbern and Pickering (1987), Pickering (1990), and Niaz and Robinson (1991). As was done in the Sawrey report, the results for the upper and lower 27% of the classes were also given. On the stoichiometry problem pairs, the subjects' performance on the traditional or algorithmic questions (54.5) was better than that for the pictorial or conceptual questions (36.6), which was similar to the earlier studies cited. For the upper 27% of the classes in this study, the trend remained in the same direction, but was considerably smaller (55.6 conceptual versus 59.3 algorithmic). The trend was more pronounced for the lower 27% of the subjects (28.6 conceptual versus 50.0 algorithmic). On the gas law problem pairs the subjects of this study
performed better on the conceptual problems than algorithmic problems which was a result different than the comparative studies. This result may be due to lower performance on traditional problems when compared to prior studies, but Noh and Scharmann (1997) felt that the instruction was successful in developing conceptual understanding.

If the difficulty with the pictorial problems is due to the lack of some factual knowledge about the particulate nature of matter rather than some special ability, as Pickering (1990) suggested, both instructional types in this study, including traditional expository teaching, appeared to emphasize greater conceptual understanding. (p. 212)

The authors believed that the low algorithmic scores, and the higher success rate than the American college students on the pictorial problems was evidence of the instructional success.

In analyzing the results for the CCT, the authors believed that the data suggested the treatment was more effective than traditional instruction at improving students' conceptual understanding of chemistry, but that the treatment efficiency could not be taken for granted. The treatment group outperformed the control group, but only two (Diffusion and Dissolution) of those results were statistically significant. The authors suggested that the lack of significance may reflect the fact that many aspects of the nonsignificant concepts, Particle and State, were introduced in Korean schools as early as fifth grade, and some aspects of the concept that showed the greatest significance, Dissolution, were not introduced until 11th grade. Given that fact and the low scores on that concept led Noh and Scharmann (1997) to state: "This may suggest that the treatment was most effective in students' learning of a new or difficult concept compared to traditional instruction: the treatment appeared to emphasize conceptual understanding more adequately" (p. 213).

The authors believed that the treatment was equally effective in promoting algorithmic success. Since the treatment students were not explicitly taught problem-
solving skills except "understanding the problem", the authors felt that the algorithmic results were reasonable.

Because the treatment group outperformed the control group on the CCT, the authors expected better performance from the treatment group on the pictorial half of the CPST, which was not seen. The authors suggested that this unexpected result might be due to the different questioning strategies employed on the two tests, open-ended on the CCT, and multiple choice on the CPST.

Noh and Scharmann (1997) gave several implications of this research, the most useful of which might be support for greater use of pictorial representations in instruction. Based on the results they suggested that pictorial representations should especially be used when introducing new concepts. The authors also raised the question of whether pictorial questions truly test conceptual knowledge and stated "some doubts of the validity of the pictorial questions used previously were raised from the findings of this study" (Noh & Scharmann, p. 214).

Major Findings of the Research

After reviewing the relevant literature, several aspects of college and high school chemistry seemed apparent. The aspects found concerning student learning and problem solving are discussed below.


2. Success on computational problems in chemistry is not a valid indicator of conceptual knowledge in chemistry (Mason, 1995; Mason et al., 1997; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz, 1995b, 1995c; Niaz & Robinson, 1992a, 1993;


5. Instruction that emphasizes conceptual understanding in chemistry improves conceptual understanding, provided students are made aware of the importance of conceptual understanding (Lin, 1998; Lin et al., 1996; Lythcott, 1990; Mason, 1995; Mason et al., 1997; Nakhleh et al., 1996; Niaz, 1998a; Phelps, 1996).

6. An effective method of stressing the importance of conceptual knowledge in chemistry is the inclusion of conceptual problems in the assessment of chemistry students (Beall & Prescott, 1994; Mason et al., 1997; Nakhleh et al., 1996; Niaz, 1995b, 1995c, 1998a; Niaz & Robinson, 1992a, 1993; Phelps, 1996).

7. The failure to correctly apply conceptual knowledge is due to lack of knowledge rather than lack of ability (Bunce et al., 1991; Herron & Greenbowe, 1986; Noh & Scharmann, 1997; Pickering, 1990).

Summary of the Literature

The studies examined in this literature review took several forms and employed many research techniques. The samples ranged from one college freshman (Herron & Greenbowe, 1986) to several hundred high-school students (Anamuah-Mensah et al., 1987; Gabel et al., 1984; Lin, 1998). All but one study (Mason, 1995) were published in
the science education literature, though several were first presented at annual meetings (Mason, 1995; Mason & Crawley, 1994; Niaz, 1994; Niaz & Robinson, 1991) and others began as doctoral dissertations (Anamuah-Mensah, 1986; Herron & Greenbowe, 1986; Noh & Scharmann, 1997).

The majority of the studies utilized a quantitative methodology to answer the research questions, with 17 of the 26 studies using quantitative methods exclusively and six (Bunce et al., 1991; Lin, 1998; Lythcott, 1990; Nakhleh et al., 1996; Nakhleh & Mitchell, 1993; Niaz, 1998a) using a combination of quantitative and qualitative methods. The final three studies (Anamuah-Mensah, 1986; Phelps, 1996; Yarroch, 1985) used a qualitative method exclusively.

Many studies (Beall & Prescott, 1994; Lin et al., 1996; Mason, 1995; Mason et al., 1997; Nakhleh, 1993, Nakhleh & Mitchell, 1993; Niaz & Robinson, 1993; Noh & Scharmann, 1997; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990) used a variation of the paired algorithmic and conceptual questions originally used by Nurrenbern and Pickering. The paired questions often showed a gap between performance on algorithmic or computational problems, and conceptual problems. Many of the studies (Anamuah-Mensah, 1986; Bunce et al., 1991; Gabel et al., 1984; Herron & Greenbowe, 1986; Lin, 1998; Lythcott, 1990; Mason, 1995; Mason et al., 1997; Nakhleh & Mitchell, 1993; Yarroch, 1985) used a version of the think-aloud protocol to determine problem-solving strategies, methods, or difficulties. White and Tisher (1986) called this method a very practical method for studying problem solving. The data gathered in these interviews was used in widely different ways, from strictly coded quantitative methods (Gabel et al.; Mason; Mason et al.) to detection of patterns in methods and strategies (Anamuah-Mensah; Bunce et al.; Lythcott; Yarroch). The think-aloud protocol showed its usefulness and flexibility in these studies.

The chemistry topics examined in the studies were topics typically covered in general chemistry at the high school and college levels (see Taft, 1997) and so were
representative, but not comprehensive. Gas laws, stoichiometry, and moles were the most prevalent topics studied and are important for the study of chemistry. There was little evidence that the phenomenon found with these topics would not also be found with other chemistry topics.

The most common trend seen in the literature reviewed was that chemistry students at all levels performed better on computational chemistry problems than they did on conceptual chemistry problems. This phenomenon was primarily studied in college chemistry students (Beall & Prescott, 1994; Lin et al., 1996; Mason, 1995; Mason et al., 1997; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz, 1995b, 1995c, 1998a; Niaz & Robinson, 1992a, 1993; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990; Zoller et al., 1995) though it was also examined in Korean high-school students (Noh & Scharmann, 1997). Three studies reviewed (Beall & Prescott; Lin et al.; Noh & Scharmann) showed essentially equal performance on conceptual and algorithmic problems, but in all three studies, the success on computational problems was 50% or less so it might be more correct to state that the lack of success on the two types of problems was equal.

Bunce et al. (1991) noted that the students failed to apply the chemistry knowledge they possessed when solving problems that might be solved with an algorithm. Herron and Greenbowe (1986) saw the same phenomenon with "Sue," a successful chemistry student. In 1991, Niaz and Robinson reported findings that quantified the lack of relationship between computational success and conceptual understanding that others (Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990) described but had not critically examined.

Niaz (1995c) showed that conceptual knowledge seemed to be a predictor of computational success. Other studies showed this trend as well, though they did not state their results as such. Anamuh-Mensah (1986) saw that students had less success on volumetric problems with ratios other than one-to-one, but with application of conceptual
knowledge success was greater. A follow-up study (Anamuah-Mensah et al., 1987) found that students who used algorithms with understanding showed different correlations in problem solving. Mason et al. (1997) saw that high conceptual students performed like the experts studied. Phelps (1996) saw greater computational success with the non-science majors as they became more comfortable with the concepts. Gabel et al. (1984) emphasized that those students who applied algorithms with understanding proved more successful on the novel problems, a result that was likely due to conceptual knowledge.

Several of the studies examined students' problem solving closely enough to find strategies employed and found that students primarily applied algorithmic understanding. Phelps (1996) noted this especially with science majors. Bunce et al. (1991) coined the term "Rolodex method" to describe the mental process of choosing a formula to fit the problem, and the same process was referred to as the Formula Approach by Anamuah-Mensah (1986). Herron and Greenbowe (1986) classified their subject, who used a similar approach, as a "rule learner." Nakhleh and Mitchell (1993) noted that the majority of the students attempted to solve the conceptual problems with a formula or algorithm. Yarroch (1985) saw correct balancing of chemical equations without an understanding of what coefficients and subscripts meant and what equations said about the molecular interactions.

Some of the studies attempted to focus more on conceptual instruction or examined more conceptual instruction (Lin, 1998; Lin et al., 1996; Lythcott, 1990; Mason, 1995; Mason et al., 1997; Nakhleh et al., 1996; Niaz, 1998a; Phelps, 1996). Lin et al. saw a small significant difference in performance on a standardized test for chemistry students taught with more conceptual emphasis than those taught with a more computational approach. Nakhleh et al. and Phelps found increased conceptual understanding with conceptual instruction. Both studies pointed out the need to not only teach the concepts, but to make their importance explicit to the students. In both studies (Nakhleh et al.; Phelps) asking for conceptual knowledge on examinations emphasized the

Many of the studies included conceptual problems on the course exams, but only a portion of the studies (Beall & Prescott, 1994; Mason et al., 1997; Nakhleh et al., 1996; Niaz, 1995b, 1995c; Niaz & Robinson, 1993; Phelps, 1996) stated that it was a regular practice. Nakhleh and Mitchell (1993) found that many of the subjects saw the conceptual questions as interesting and more fun than the computational problems, but were apprehensive about having them on exams. Phelps also found this apprehension for science majors, but felt the feeling was a result of previous instruction. Beall and Prescott found that students' perceptions of their performance on conceptual questions was typically lower than their actual performance while their perceptions of performance on computational questions was higher than actual performance. After it was known that conceptual knowledge was expected, the students studied by Phelps and Nakhleh et al. became more successful on conceptual problems. Nakhleh et al. described the results as "By the second hourly exam (out of four) they were as intent on understanding the conceptual problems as well as the mathematical problems because they were convinced that the problems would appear on the exams" (p. 760).

Several researchers examined other aspects of learning that were theorized to be correlated with chemistry problem-solving success. Proportional reasoning (Anamuah-Mensah et al., 1987; Gabel et al., 1984), deductive and inductive reasoning (Anamuah-Mensah et al.), developmental level (Niaz & Robinson, 1992a, 1993; Noh & Scharmann, 1997), field dependence/independence, and mental capacity (M-capacity) (Niaz & Robinson, 1992a, 1993) were all examined in the studies reviewed. Gabel et al. found that successful problems-solvers tended to have higher proportional reasoning ability. Anamuah-Mensah et al. found that students who used algorithms with understanding differed from those who used algorithms without understanding by connections between
direct proportionality with the concepts and indirect proportionality with volume analysis tasks. Those who used algorithms without understanding lacked the two links in the path analytical model proposed by Anamuah-Mensah et al. Noh and Scharmann and Niaz and Robinson (1992a, 1993) used the Group Assessment of Logical Thinking (GALT) to determine the subjects developmental level based on Piaget's model of cognitive development. The results in these three studies were tainted by the low reliability of the results on the GALT. Niaz and Robinson (1992a, 1993) found that algorithmic success generally correlated with formal operational level as assessed by the GALT. Niaz and Robinson (1993) also found that each of the three conceptual or figurative problems examined significantly correlated with a different cognitive variable, either mental capacity as measured by the Figural Intersections Test (FIT), field dependence/independence as measured by the Group Embedded Figures Test (GEFT), or logical structure measured by the GALT. The final results may indicate one of the difficulties with conceptual questions – they rely on different methods for successful solution.

Pickering (1990) found that the lack of success on conceptual problems was due to a lack of knowledge rather than a lack of ability. Noh and Scharmann (1997) supported this finding, though Bunce et al. (1991) saw it as a lack of application of conceptual knowledge possessed by the students.

Limitations of the Findings

The literature reviewed highlighted several aspects of the relationship between algorithmic and conceptual understanding in chemistry, but the studies also had some limitations. Some limitations, such as lack of validity and reliability information were common to most studies, while some other limitations were specific to certain studies.

The studies that utilized paired algorithmic and conceptual questions (Beall & Prescott, 1994; Lin et al., 1996; Mason, 1995; Mason et al., 1997; Nakhleh, 1993, Nakhleh & Mitchell, 1993; Niaz & Robinson, 1993; Noh & Scharmann, 1997; Nurrenbern
& Pickering, 1987; Pickering, 1990; Sawrey, 1990) had several limitations with the method that were not generally discussed in the studies: validity of the questions, and relative difficulty of the question pairs. The steel-tank problem of Nurrenbern and Pickering was used in all but the Beall and Prescott studies mentioned above, yet little mention of its validity was made. The same is true of the other questions used. Most of the question pairs used came from Nurrenbern and Pickering and Nakhleh (1993), but only Noh and Scharmann mentioned attempting to validate the questions, while several studies (Mason, 1995; Mason et al.; Nakhleh, 1993; Nakhleh & Mitchell) implied that the questions' previous use were evidence of validity. While the use of the problems in several circumstances may show the consistency of the results, only Noh and Scharmann truly reported any gauging of validity. Beall and Prescott, Noh and Scharmann, and Niaz and Robinson (1993) questioned the validity of the pictorial questions used to measure conceptual knowledge. Noh and Scharmann produced some data to support their claims, while the other researchers relied on their own experience and background in questioning the validity. Beall and Prescott and Niaz and Robinson (1992a, 1993) brought up the difficulty of gauging the relative difficulty of the problems used. Due to this difficulty, it is possible that in some cases the gap between performance on conceptual and algorithmic questions may be confounded by relative difficulties of the questions in each pair. Beall and Prescott dismissed this difficulty by assuming that, by chance, the relative difficulty would be greater for about half of the computational problems and greater for about half of the conceptual problems in each pair.

Another difficulty with many of the studies (Beall & Prescott, 1994; Bunce et al., 1991; Lin, 1998; Lin et al., 1996; Mason, 1995; Mason et al., 1997; Nakhleh, 1993, Nakhleh & Mitchell, 1993; Nakhleh et al., 1996; Niaz, 1995b, 1995c, 1998a; Niaz & Robinson, 1992a, 1993; Noh & Scharmann, 1997; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990; Zoller et al., 1995) was the use of the questions on regular exams. Though this is a common method of measuring knowledge and ability, some of
the studies (Lin, 1998; Lin et al., 1996; Nakhleh, 1993, Nakhleh & Mitchell, 1993; Niaz, 1995b, 1995c; Niaz & Robinson, 1992a, 1993; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990; Zoller et al., 1995) may not have used similar questions in instruction as were used on exams, thus causing a problem with the novelty of the questions (Gronlund, 1985). This potential problem was highlighted in Nakhleh and Mitchell where nearly all of the subjects interviewed were able to solve the conceptual problems correctly in the interviews though they were not able to on the exams.

A further limitation of the studies was the lack of qualitative studies that examined students' problem solving. Yarroch (1985), Anamuah-Mensah (1986), Herron & Greenbowe (1986), Lythcott (1990) and Bunce et al. (1991) all examined problem solving from a qualitative protocol and found information that may not have been found in a quantitative study. Focusing on a correct or incorrect response, as many of the studies did, neglects the why and how of the problem solving. As with Yarroch, it is often informative to examine how successful problem-solvers might be getting the right answers for the wrong reasons.

In the majority of the studies little demographic information concerning the sample was given. In qualitative studies, demographic information can be used to determine if there is a logical generalization that can be drawn between the sample and another group (LeCompte & Preissle, 1993), while in quantitative studies the information can be used to determine if a statistical generalization can be drawn (Borg & Gall, 1989). The lack of demographic information in the majority of the studies lessens their usefulness to other chemical educators.

Implications for Future Research

Future study of the relationship between algorithmic and conceptual understanding in chemistry is warranted. Though some recent studies (Nakhleh et al., 1996; Phelps, 1996) have shown some success in narrowing the gap between computational and
conceptual understanding, the students in those studies resisted the changes and the 
Nakhleh et al. study utilized more personnel than are generally available for instruction. 
Changing instruction takes energy and commitment, so more research should help 
convince educators that conceptual knowledge is lacking and that changes are necessary.

Qualitative studies such as those done by Yarroch (1985), Anamuah-Mensah 
(1986), Lythcott (1990) and Bunce et al. (1991) should be repeated to determine 
strategies that may hinder conceptual learning. Understanding the problem-solving 
strategies of chemistry students may help determine instructional changes that would be 
embraced by the learners and instructors. It is also possible that instructional strategies 
could be developed that would attract students who are capable of succeeding in 
chemistry, but who avoid it, such as Tobias' (1990) second-tier students. As Phelps 
(1996) stated:

Perhaps, we are discouraging people from pursuing science who have the 
extact set of skills necessary to be a good scientist but who are not willing 
to put those skills on hold while they endure the necessary undergraduate 
science courses. (p. 304)

Innovations such as those implemented by Nakhleh et al. (1996) and Phelps need to be 
implemented elsewhere and developed further.

Pickering (1990) attempted a longitudinal study by following beginning chemistry 
students into an organic chemistry course during the next year. Mortality was a problem 
with this study as it would be with almost any longitudinal study, but Pickering's (1990) 
study was the only study to follow students longer than a year. Following a group of 
students from general chemistry through their college career could prove beneficial.

A longitudinal study could also examine more closely the theory of Niaz (1995b, 
1998a) and Niaz and Robinson (1992a) that students follow a transition from 
computational to conceptual understanding. The transition may follow the form described 
by Kuhn (1970a):
Exposure to a series of exemplary problem-solutions teaches them to see different physical situations as like each other; they are, if you will, seen in a Newtonian gestalt. Once students have acquired the ability to see a number of problem-situations in that way, they can write down ad lib the symbolic forms demanded by other such situations as they arise. Before that acquisition, however, Newton's Second Law was to them little or no more than a string of uninterpreted symbols. Though they shared it, they did not know what it meant and it therefore told them little about nature. What they had yet to learn was not, however, embodied in additional symbolic formulations. Rather it was gained by a process like ostension, the direct exposure to a series of situations each of which, they were told, were Newtonian. (p. 273)

Examining changes over time may give educators further insight into how to teach at the beginning chemistry level.

The work of Carter (1987) was discussed by Bodner (1991) and Herron (1990, 1996) and showed some interesting areas for further exploration. Carter interviewed general chemistry students and asked about their view of the nature of chemistry, their attitudes toward chemistry, the role of instructors, and tested their problem-solving ability. Carter's results showed a possible connection between students' understanding of the nature of chemistry and view of education and their problem-solving strategies. According to Carter, the students' views of chemistry correlated with their methods for solving problems and applying conceptual knowledge. Those students who believed that chemistry was a way of understanding our world related problems to the concepts and previous knowledge, while students who believed chemistry to be abstract and alien saw "The way to succeed is to work the same problems over and over until they are memorized" (Herron, 1996, p.76). It might prove useful to follow up this work.

Another area for further investigation is the teaching of chemistry. None of the research reviewed made a thorough study of the teaching, relying instead on a short categorization of instruction. The studies focused on student outcomes, which are important, but it may prove useful to do an instructor case study similar to that of Larson
(1997) to determine what instructional strategies may positively affect students' conceptual understanding.

There are many areas for further investigation of the relationship between algorithmic and conceptual understanding in chemistry and it is important that chemistry educators examine content and instruction so that understanding of the chemistry concepts is developed in students. As Bunce et al. (1991) and Friedel, Gabel, and Samuel (1990) suggested, teaching strategies for chemistry problem solving may only teach algorithms without requiring understanding.

Chemistry educators have at times been guilty of teaching students how to arrive at a correct answer instead of developing an understanding of the science of chemistry, focusing on the mathematics ignores many of the concepts, and hence the beauty of chemistry.
CHAPTER 3: DESIGN AND METHOD

Introduction

Previous research (Gabel et al., 1984; Lin et al., 1996; Mason, 1995; Mason et al., 1997; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz, 1995b, 1995c; Niaz & Robinson, 1992a, 1993) on the relationship between computational and conceptual understanding has focused on the number of students who fit into different categories of learners, but failed to examine the causes for the disparity between computational and conceptual knowledge in chemistry. This study focused on student understanding of the particulate nature of matter that may lead to poor conceptual performance by chemistry students. This study was accomplished through in-depth interviews with students enrolled in a general chemistry course at Oregon State University. The interviews explored the students' knowledge of computational and conceptual aspects of stoichiometry as well as their ideas about the learning of chemistry.

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 conceptual structure of stoichiometry?

The subjects of this study were taken from a general chemistry course taught at Oregon State University. During the interviews, students demonstrated their view of the nature of matter through drawings of reactions, and they performed a card sort activity to examine their personal structure of stoichiometry. In the second part of the interview the students were asked to solve computational and conceptual problems that covered stoichiometry and enthalpy. The students' answers were probed for the logic and method behind their solution method.
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. According to Taft (1997), 94% of the institutions studied covered the significance of balanced chemical equations. 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) has 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). Taft (1997) found that 94% of colleges and universities studied taught the computational aspects of stoichiometry, with the majority reporting that the concepts were studied extensively. Taft also found that 94% of the institutions taught the conceptual nature of stoichiometry as the significance of balanced equations, but with less coverage. 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 et al., 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. Stoichiometry was the topic for the card sort task, and the topic of the problems used in the problem-solving task.

Data gathered from interviews were analyzed using a constant comparison method (LeCompte & Preissle, 1993) looking for patterns to shed light on the conceptual/computational pattern seen in earlier studies. The students' responses were also used to determine the feasibility of classifying students as done by Nakhleh (1993).

Data gathered from interviews, classroom observations, instructional materials, and analysis of instructional resources were used to identify patterns of students' success or lack of success on computational and conceptual problems in chemistry. These factors were examined for their correlation with students' learning.

Research Subjects

The subjects of this study were students enrolled in a general chemistry course at a comprehensive university, Oregon State University (OSU), 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 OSU.

Subjects

The subjects were volunteers enrolled in the course examined. The course is described later in the chapter. 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. At that time, preliminary Informed Consent forms (see Appendix B) were collected with contact information for scheduling interviews. 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 (OSU, 1998). 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. A laboratory experience was added in the second course of the sequence. A support room for individual or small group assistance was also available. The lectures were taught by a chemistry professor who was responsible for administration of the course as well as assessment and assigning grades. 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. During some quarters two professors could divide the quarter and each teach part of the course. The professors have doctoral degrees in chemistry and typically were also responsible for research and other courses (graduate and undergraduate) during the year. 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. The teaching assistants were typically assigned four sections of approximately 24 students each per quarter. The teaching assistants were also required to serve in the chemistry support room, tutoring walk-in students for one hour per week. Besides their teaching responsibilities, teaching assistants traditionally were responsible for course-work and their own research.

Procedures and Methods of Data Analysis

As discussed previously, 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.
**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 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. Many previous studies suggested that course instruction encouraged reliance on computational knowledge, and several studies (Lin et al., 1996; Nakhleh et al., 1996; Phelps, 1996) found links between instruction and conceptual understanding. Classroom instruction was observed to help answer the research question concerning factors that affect students' conceptual structure of chemistry. Course instruction was
observed with a focus on how concepts are presented. In the classroom observations, special attention was paid to the proportion of computational and conceptual problems demonstrated or discussed in class. A further focus was how often and in what proportions the instructor discussed chemistry concepts versus the computational aspects of those concepts. Conceptual aspects of the topics are typically the qualitative portions of theories that explain the measurable or observable aspects. For example, atomic theory shows rearrangement of atoms in molecules, which leads to stoichiometric calculations. The computational aspects are the traditional stoichiometric calculations, such as gram-mole calculations used to predict or determine measurable aspects of stoichiometry. Another area of focus was 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 commentaries (Gillespie, 1997; Jensen, 1998a, 1998b, 1998c), and may have a significant impact on students. Textbooks may assist students to develop connections between the molecular level and the macroscopic level by being explicit in drawing these connections (Jensen, 1998a), textbooks and other resources may also perpetuate the lack of conceptual understanding by focusing on the computational aspects of the content (DeBerg). 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. The resource materials were analyzed in the following manner: 1) The pertinent sections of the textbook and tutorial were read with a focus on how topics were organized; 2) general trends for the presentation of new material in the text were identified, such as a tendency to present computational aspects before conceptual aspects or vice versa; 3) the tutorial was reviewed for the ways in which it supported the textbook presentation; 4) the next examination of the textbook and tutorial focused on how computational aspects of chemistry were presented, how the particulate nature of matter was presented, and how bulk properties of chemicals were tied to molecular properties; and, 5) end of chapter problems and sample problems in the text, and quiz and example problems in the tutorial were examined for focus on computational and conceptual problems. How the resources presented computational problems was examined for ties to conceptual information. How the problems focused, or failed to focus, on the particulate nature of matter, was another area of concern.

The course was taught by an instructor with several years of instructional experience. To gather information on the instructors' philosophy of chemistry and philosophy of education, the instructor was interviewed about his views. The instructor filled out an informed consent form at that time (see Appendix A). 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 card sort task associated with stoichiometry. 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 (Chapters 3 & 5 in Hill & Petrucci, 1996). Since a scheduled exam closely followed instruction, the interviews were delayed until after the exam. This delay was employed to avoid an added stressor prior to the students' exams. 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. At the beginning of the interview, the subject completed an informed consent form to ensure that they have been informed of their rights and the purpose of the study (see Appendix B). The subjects also had the opportunity to ask the interviewer questions. The subjects were then 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 (see Appendix B). To ensure face validity of this questionnaire, two science educators reviewed the questionnaire. The reviewers examined the questionnaire for confusing or misleading questions, and inappropriate
wording. 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; Scholz, 1996), 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 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 C.

**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 D. To ensure content validity five educators (two science educators, and three chemistry educators not involved in the study) reviewed the questions. For the Balancing Task, which entailed balancing of chemical equations, the reviewers were asked the following questions for each equation: 1) Is the level of the equation appropriate for a general chemistry student? 2) Is the question clear and understandable? If the reviewer answered no to any of the questions for any equation they were directed to reject that equation and offer suggestions, if appropriate, for addressing the concerns to make it acceptable. For the stoichiometry problems, the reviewers were asked the following questions for each problem: 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 problem clear and understandable? If the reviewer answered "No" to any of the questions for any problem they were directed to reject that problem and offer suggestions, if appropriate, for addressing the concerns to make it acceptable. 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. This task was used by Yarroch and Lythcott (1990). 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. It was assumed that the subjects of this study would be more successful at this task than the high-school chemistry students studied by Yarroch and Lythcott, but the views of the particulate nature of matter elicited in this task were assumed to be enlightening.

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, 1995c), 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**

**Overview**

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 limitation 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 below. The researcher's card sort structure is included in Appendix E.

A description of the researcher's card sort structure was written to aid in forming a basis for evaluating the analysis of the participants' card sort structures. The researcher constructed his structure (see Appendix E) in five interconnected sections utilizing all of the concepts contained on the cards. The overall structure was generally rectangular with four of the groups as the vertices of the rectangle and the fifth group placed in the center of the rectangle. The central group contained cards that described the main areas of stoichiometry with a general chemical equation (Card # 12), a diagram showing a method for solving stoichiometry problems (Card # 15), an example calculation (Card # 21), and a generic stoichiometric word problem (Card #22). The upper left corner contained cards dealing with the mole concept, including molecular weight and Avogadro's Number. The upper right corner contained the enthalpy cards (Cards # 28-32) arranged in pairs with the endothermic cards on the right and the exothermic cards on the left. The lower right corner contained three cards representing limiting reactant reactions. The lower left group represented reactions without a limiting reactant. The four corner groups were connected by double-headed arrows to the center group, which represented the central concepts.
The corner groups represented concepts that were a part of the concepts included in the center group.

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: 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 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. The constant comparison method was used to identify possible trends in instruction that might be present. 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: 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 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.

The students' backgrounds were first compared and trends in their backgrounds were examined. Gender was examined in this comparison, but it was not expected to be significant because previous studies (see Gabel & Bunce, 1994) had not found gender as a factor in problem solving ability.
The next analysis examined the card sort structures. Similarities and differences between the structures were examined and described. Each subjects' structure was assigned to a category developed through a constant comparison method.

The Balancing Task results were then examined for trends. The results of the Drawing Task were examined using a constant comparison method, and similar drawings were assigned to the same category.

The Problem-Solving Task data were coded based on the methods of solution. Each problem was coded separately from the other problems. The problem solutions were placed into categories using a constant comparison method.

The results from the Perceptions Task were the last data to be examined. The answers to the questions in this part of the interviews, plus appropriate data from other parts of the interviews were examined for trends that offered insight into the students' views of chemistry and the study of chemistry.

The data were examined for trends that could explain the categorization of students on tasks and for similarities and differences between students. The students were then assigned to Nakhleh's (1993) scheme (see Figure 2, p. 18) based on their performance on the Problem-Solving Task. The feasibility of using this scheme was examined.

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. The resource materials available and the data were compared to see if students reflected the presentation seen in the resources or held structures different than in the resources.
Together the analyses develop a profile of what influenced the chemistry understanding of the subjects.
CHAPTER 4: RESULTS

Introduction

The study was constructed to answer the following questions: 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?

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. Together, course instruction, textbook, and tutorial presented a picture of the instructional factors that might influence the students interviewed.
Instructor's Card Sort Task

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. The cards (see Appendix C) for the Card Sort Task were all concepts, definitions, and equations dealing with stoichiometry and enthalpy change. 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 organized the concepts into topics to be presented as part of the course. Due to

Figure 4. Dr. Dalton's card sort structure (lines added for clarity)
the researcher's illness, the interview took place after instruction on the topics, and concurrently with student interviews. It is assumed that this did not affect the results. The first topic presented by Dr. Dalton was thermochemistry (see Figure 4). Since entropy is not discussed until the final third of the text and the third quarter in the sequence, the cards and the instructor's discussion focused on enthalpy change and especially on exothermic and endothermic reactions. The instructor admitted that he had not presented thermochemistry prior to stoichiometry but he speculated how students would react to presentation of the topics in that order.

**Dr. Dalton:** I'm not sure why chemistry textbooks are arranged this way, but it seems to me that it would be very interesting to see how students take to the concept of thermodynamics before we start muddling things up with mole calculations.

Dr. Dalton's structure began with a generic chemical reaction that contained the change in enthalpy (Card #12) which was the overlying concept for the graphical, equation, and verbal descriptions of exothermic and endothermic reactions (Cards #27-32). The next grouping of concepts represented microscopic representations of chemical reactions placed in increasing order of complexity. The instructor suggested that the cards could also allow for a non-numerical discussion of limiting reagent reactions. From there he moved to the mole concept, introducing moles as a link between the microscopic and macroscopic levels. From the mole concept, he suggested that instruction would move to atomic masses, then molar masses, and stoichiometric calculations. In the structure, limiting reactant concepts were placed in a separate grouping, but were discussed throughout. The final concept, which was not represented by a separate card, as pointed out by the instructor, was a limiting reactant stoichiometric calculation. Connections between groupings were not drawn or made through explicit lines, but were described verbally through the instructor's description of the structure.

Conceptual and computational representations were related in the structure as providing information for the other. Conceptual representations were often presented first
as microscopic representations. Dr. Dalton suggested using the overall concept of thermochemistry as an introduction to chemical processes that the students would be familiar with and which would not require the discussion of numbers. In the case of going from microscopic to macroscopic, Dr. Dalton used the mole concept. The mole concept also served as a direct connection from conceptual to computational as he went from microscopic descriptions of chemical processes to atomic masses, molecular weights, molar masses, and then stoichiometric calculations. In his discussion he said:

\textbf{Dr. Dalton:} I would go ahead and ask them how I could put a sample of sodium chloride on a scale I have and find out how many atoms are present? How can we possibly do this? I talk about the fact we need a relationship between the microscopic and macroscopic world.

The structure constructed by Dr. Dalton contained no lines or other drawn connections, but the overall structure was articulated verbally. Dr. Dalton was asked to build his structure in a way that made sense to him and he chose an overall outline of how the material would be presented in a chemistry course. The structure was generally linear with concepts building upon each other to computational stoichiometric problems, and finally to a limiting reactant stoichiometric problem. There were connections that backtracked to earlier concepts, but these were few. The major organization went from the macroscopic concept of thermochemistry, to the microscopic representation of chemical processes, to the mole concept as a tie between microscopic and macroscopic, and then to macroscopic stoichiometric calculations.

The final card sort evaluation question concerning how the concepts were incorporated has been answered in the previous questions. The one card that was left out was card #7, which came from the textbook (Hill & Petrucci, 1996) and attempted to describe the macroscopic reaction between carbon black and oxygen to form carbon dioxide. The instructor felt that the representation presented too many concepts in one graphic (reactions, conservation of mass, gases, and solids) and would cause confusion for the students. He seemed surprised that the representation came from the textbook.
The card sort task showed that the instructor thought in terms of pedagogy. The general structure was hierarchical, building from qualitative or microscopic concepts to computational applications. It was apparent that the instructor showed concern for students' understanding because of remarks made during the Card Sort Task where he discussed how to present aspects of stoichiometry so students would better understand the concepts.

Class Observations

Instruction in the course was traditional with example problems, demonstrations, and discussions with students. Dr. Dalton was an energetic 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.

Dr. Dalton displayed good rapport with his students by joking and sharing stories with them. Some of the stories were self-deprecating or poked fun at imagined or real people such as his brother. He also encouraged students to ask questions and discuss their understandings of the concepts. The instructor also told chemically based stories and encouraged students to be a part of the stories by asking them to add to the stories or asking if they had experienced similar phenomena.

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). In the first class meeting, the instructor referred to the tutorial more than five times, and he often referred to it during subsequent lectures. In the first class meeting he told the students that the points awarded for completing and turning in the tutorial assignments were "free points," that they could get the points without great effort, and do themselves an academic favor. Dr. Dalton often referred the students to tables, graphs and sample problems in the
textbook. On several occasions he also used the textbook as a reference during his lectures, looking up values or formulas while presenting a problem or concept.

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. Before each exam, the instructor held a review session during the scheduled class time where he discussed the objectives for the exam. For each objective he solved example problems, gave suggestions for material to focus on, and gave hints about what information might be useful on the students' notecards. The notecards were 3" x 5" index cards that the students could take into the exam; each student was allowed one card that could include anything the students felt would be useful, such as definitions, equations, and worked out problems, as long as it was in their own handwriting. During these review sessions, Dr. Dalton told students what material would and would not be covered on the exam, and several times mentioned the number of specific types of questions that would be on the exam. The instructor also used this time to answer questions and clear up confusion among the students. Previous exams were also available on the course web page to allow students to see examples of questions they might see. The instructor also made expectations clear during his lectures by telling the students the level of understanding of topics he expected, and the level of difficulty of problems to expect. Twice during the course observations he told the students what the topic of their recitation quizzes would be. He also pointed out problem-solving strategies, short cuts, and thought processes to aid the students in solving problems.

Dr. Dalton performed a chemical demonstration during almost every lecture observed. Many of the demonstrations, such as the thermite reaction and the acetylene cannon, were discussed as part of the concept being presented, while a few demonstrations, such as the combustion of a Pop-Tart, appeared to be for entertainment purposes only, as they were not incorporated into discussions of the lecture topics. The acetylene cannon is a two-step reaction that was used to illustrate balancing equations and
limiting reactants. The instructor began by pouring a pre-weighed sample of calcium carbide, CaC₂, and an excess amount of water into the "cannon" to react and form acetylene, C₂H₂, and calcium oxide, CaO. He then ignited the acetylene and atmospheric oxygen to "fire" the cannon and propel Styrofoam balls out of the cannon. He wrote unbalanced equations on the board for the two reactions and asked the students to help balance the equations. He then performed the stoichiometric calculations necessary to determine how much acetylene was formed from the calcium carbide and water in the first reaction. While doing this demonstration he discussed on a qualitative level that the calcium carbide was the limiting reactant in the first reaction, since he had added water in excess.

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. For example, when discussing the photoelectric effect, Dr. Dalton reviewed the structure of an atom, that the electrons formed the outer portion of an atom. He then discussed how atomic structure and the photoelectric effect together were responsible for the light sensor/customer chime at a local convenience store. He explained that as a light beam hit a metal target across the doorway, photons caused electrons in the metal atoms to be ejected, thus causing a flow of electrons. If a customer entering the store blocked the light beam, electrons were no longer released from the metal target signaling the bell to chime, and thus indicating that a customer had entered. So he tied previous concepts and real-world examples together to present a new topic. 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. On several occasions when balancing equations, such as with the acetylene cannon demonstration, he used ball-and-stick molecular models to illustrate the rearrangement of atoms occurring in the reaction. The instructor also
foreshadowed concepts that would be covered in the future, such as mentioning that molality would be useful when discussing colligative properties.

Dr. Dalton frequently discussed the conceptual aspects of topics before presenting the computational aspects. For example, in the acetylene cannon demonstration, the molecular depiction of the reaction was covered before the computational stoichiometric calculations. 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. No computer animations or drawings were seen being used in instruction, but chalk drawings of atoms, molecules, and subatomic particles were frequently used. Ball-and-stick models were used on several occasions to depict reactions and structures. Though the particulate nature of matter was not as heavily emphasized in instruction as in previous research (Noh & Scharmann, 1997) the connections between the microscopic level and measurable macroscopic phenomena were made explicit for some concepts.

Dr. Dalton attempted to involve students in instruction by frequently calling for answers to questions posed in class. He would ask the students to give him values, such as molar masses, or ask for the next step in a problem. It was clear in the observations that the instructor expected student interaction. If he did not receive answers to his questions, he would stop and encourage a response or ask if the students had a question. The instructor's questions were posed to the entire class and all were expected to answer; he did not call on individual students to answer questions. His expectations of student involvement were made clear by an inadvertent slip by the researcher. In an informal
conversation outside of the classroom, the researcher mentioned a conversation overheard during class; two students were confused by an example and tried to clear up the confusion among themselves, but did not ask the instructor. During the next lecture, Dr. Dalton mentioned that he had heard about the incident and encouraged the students to ask if they were confused or uncertain.

Overall, instruction was traditional with an emphasis on computational chemistry as the goal of chemistry. It was also non-traditional, as there was emphasis on conceptual understanding and the particulate nature of matter.

Assessment in the course was primarily done through examinations with additional evaluations based on recitation quizzes and completion of tutorial assignments. 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 grading scale for the course is given in Table 1. There were three midterm exams each worth 100 points, and a comprehensive final exam worth 165 points. The lowest midterm exam score was dropped when determining the final course grades; for a total of 365 points, or 81% of possible points, for exams. There were 25 assignments of sections of the software tutorial, with each section worth two points, for a total of 50 points possible for completing tutorial assignments. The tutorial assignments are discussed in the Resource section. There were also eight five-point recitation quizzes, with the lowest quiz score dropped; the quiz scores accounted for 35 points. The quizzes usually had two problems and were given in the weekly recitations by the Teaching Assistants. The problems on the quizzes were taken from problem sets or were similar to problem set problems. Because the quiz problems were taken from problems assigned as part of problem sets taken from the textbook, those problems are discussed in the Resource section of this chapter.
Table 1: Grading Scale for Introductory Chemistry Course

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<tr>
<th>Grade</th>
<th>Minimum Score Needed</th>
<th>Corresponding Percentage</th>
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<tr>
<td>A</td>
<td>391 Points</td>
<td>~87%</td>
</tr>
<tr>
<td>A-</td>
<td>382 Points</td>
<td>~85%</td>
</tr>
<tr>
<td>B+</td>
<td>373 Points</td>
<td>~83%</td>
</tr>
<tr>
<td>B</td>
<td>346 Points</td>
<td>~77%</td>
</tr>
<tr>
<td>B-</td>
<td>337 Points</td>
<td>~75%</td>
</tr>
<tr>
<td>C+</td>
<td>328 Points</td>
<td>~73%</td>
</tr>
<tr>
<td>C</td>
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<td>~67%</td>
</tr>
<tr>
<td>C-</td>
<td>292 Points</td>
<td>~65%</td>
</tr>
<tr>
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<td>~63%</td>
</tr>
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</tbody>
</table>

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. Most questions were worth five points, with more involved computational problems worth 10 points. Students took the midterm exams during scheduled evening exam times. Each midterm exam was scheduled for one hour and 20 minutes, though the instructor announced that the exams should take approximately one hour. 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.

Often in general chemistry the first part of the course focuses on foundational aspects such as definitions, units, and elementary chemistry, such as the naming of simple compounds. The first exam covered this material and more than half of the exam was made up of elementary conceptual problems, such as identifying a metal in a list of elements. The computational problems required the application of simple algebraic or
arithmetic tools to answer questions involving unit conversions, density, or the determination of the number of neutrons in an isotope.

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, which appeared to be the most difficult problem on that exam based on the number of calculations necessary to solve.

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:

\[ 2 \text{Li (s)} + \text{H}_2\text{O (l)} \rightarrow \text{Li}_2\text{O (aq)} + \text{H}_2 (\text{g}) \].

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.

There was a minor concern with this problem in that the reaction of lithium and water produces lithium hydroxide, LiOH, and hydrogen gas, rather than lithium oxide, Li₂O. 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.

Exam 3 covered quantum chemistry, a concept that has a computational component considered beyond the level of this course. The exam reflected this issue with
the majority of problems being conceptual, and dealing with the energy levels of electrons in atoms. A few computational problems asking about properties of light were also included. The final exam had a mixture of computational and conceptual problems. Most of the problems were similar to the corresponding problems on the midterm exams, with several of the computational problems differing only by the numbers used in the problems.

After inspecting the exams, several points about the exams 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. Two examples are the following questions taken from the final exam.

<table>
<thead>
<tr>
<th>Discuss Quantum Numbers and Atomic Orbitals</th>
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<tbody>
<tr>
<td>[4 Questions – 5 Points Each]</td>
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</table>

19. When \( n = 4 \) and \( l = 0 \), there:

(a) are 0 values for \( m_r \)
(b) is 1 value for \( m_r \)
(c) are 2 values for \( m_r \)
(d) are 3 values for \( m_r \)
(e) are 4 values for \( m_r \)
Discuss Metals, Nonmetals, and Noble Gases

[1 Question – 5 Points]

26. The least reactive element is:
   (a) Lithium.
   (b) Copper.
   (c) Aluminum.
   (d) Fluorine.
   (e) Helium.

The level of the questions may have been due to the objectives being assessed, but there were resources (Ellis et al., 1998; Robinson & Nurrenbern, 1998) available that provide multiple choice conceptual questions of several cognitive levels. 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.

The instructor appeared to view the conceptual and computational aspects of chemistry as tied together and important to the understanding of chemistry. Conceptual understanding of chemistry appeared to be the ultimate goal of instruction, while also understanding the applications of computations. When discussing the skills that students needed to succeed in a general chemistry course, Dr. Dalton said:

To have a student come in who cannot rearrange the density expression, that student will be at a disadvantage because they will be learning the algebra while trying to understand the concepts of chemistry, that’s gotta be tough. The purpose of this course isn't to teach them algebra, it's to understand the concepts, but we use algebra to solve mathematical relationships.
The computational aspects were presented as important for the applications of chemistry and not as an end in themselves. The instructor suggested several topics, such as thermodynamics (enthalpy), stoichiometry, and quantum mechanics, that should be presented conceptually first followed by an introduction of numbers when they became useful.

**Dr. Dalton:** Because the concepts here are more fundamental than actual calculations of grams-to-mole, that is that some processes are exothermic and some are endothermic. This [enthalpy] pretty much can act completely independent of all of this [stoichiometry] and then what would be nice after you talk about an actual reaction occurring we could bring this back into the picture and say "Look, we've examined a process in detail, let's do it again and find out if in fact we have something going on with thermochemistry." We can try changing the masses to see if more energy is given off. Less, also.

He also made several comments similar to: "I would honestly make this one of the very last stoichiometry problems, so that students don't get lost in the numbers and lose the concept."

Dr. Dalton discussed several limitations for students in learning chemistry, with the major issues such as the lack of computational skills, lack of study time, and the hierarchical structure of the concepts. As discussed previously, the instructor felt that a major limitation for some students was their inability to use the mathematical tools necessary to solve computational problems. The skills needed included algebraic manipulation of equations, and thinking about concepts in terms of mathematical relationships. Another computational limitation was the students' difficulty in understanding the role of the mole concept and Avogadro's Number as a link between the microscopic and macroscopic levels. The instructor spoke at length about students' success being limited by their lack of practice.

**Dr. Dalton:** I honestly believe that at this time that it's probably, for most students, just a time factor. Not putting in the time to read the supporting
materials, do the problems, and really just think about how these things are working.

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.

**Dr. Dalton:** It seems to me that when we hit stoichiometry and limiting reagent problems if the student has not spent the time reading and examining the true nature of the problem that the problem seems so vast for them that "I can't do it." And it seems as though the first three or four chapters of any basic chemistry textbook build upon each other and by the time we're ready to do a limiting reagent problem they're really required to do things like stoichiometry, moles-to-grams calculations. If they don't have those fundamentals down you ask them to understand the big picture and it's not going to happen.

The students' ability to visualize the particulate nature of matter was not discussed at length, but Dr. Dalton made his views clear. The instructor felt that the students had difficulty with the microscopic level because atoms and molecules could not be seen and so were difficult to visualize. He discussed ways to combat this difficulty including focusing on chemical applications as an introduction to concepts, and the use of models. Again the "jump" from microscopic to macroscopic was an issue primarily due to the size of Avogadro's Number, which students have a difficult time comprehending.

**Dr. Dalton:** The stoichiometry on the atomic level is really quite simple; it's playing with gumdrops and sticks. You introduce that tough concept of a big number [Avogadro's Number] relating the macroscopic to microscopic world and you've got hurdles to jump over. The explanations to this, I think, are quite clear, the demonstrations in lecture, the use of models for the visual learner, talking your way through a reaction, hopefully simpler than this one. I mean these are the methods that we use, I think that they're effective.

Near the end of the interview, the instructor added a comment that further illuminated his teaching philosophy.
Interviewer: That is one of the things that I am interested in, how do we help students make those connections?
Dr. Dalton: I think the answer is simple. We need to teach by example. I think we should be demonstrating a key concept, the principle science, and then investigating it.

For the course examined, Dr. Dalton liked to focus on applications of the chemistry to aid students in understanding the concepts. The applications included demonstrations and real-world applications when beginning instruction on a new topic.

Interviewer: When you present a new topic, how do you generally start presenting the new topic?
Dr. Dalton: Demonstration of it, some kind of a visual, then that leads into a discussion. Hopefully, what we're doing is sucking the students into a discovery activity. Doing something and then asking why, question what they actually saw.

Interviewer: What aspects of a new topic do you focus on in the early presentation?
Dr. Dalton: Applications. How does this affect our world? It is difficult to go ahead and start talking about the excitement of a dynamic reaction at the microscopic level. We don't see it, we don't have a good understanding of what that is, but tools that industry uses or a concept that you can see commonly and don't quite understand, those are more interesting. They are to me, and in asking students they seem to be to them also.

When closing instruction of a topic, the instructor talked of making certain of the students' understanding and their ability to meet the objectives.

Dr. Dalton: Certainly student understanding comes to mind. And so I'm constantly questioning for that and just the ability to meet the objectives, and those are usually, "Can you discuss the concept that we just examined?" And if it's a mathematical problem, "Can you solve a problem related to that, on a quantitative basis?" And I'm pretty good about closure and reiterating why we examined this problem.

The instructor did not explicitly discuss how his views on how students learn and his instructional methods were related, but his answers to the instructional questions showed that he had thought about what obstacles his students encountered and ways in which his instruction could lessen the obstacle's impact. He also discussed the general perceptions of chemistry courses and the methods that he used to dispel the myths associated with studying chemistry.
Dr. Dalton: I certainly understand an anxiety attached with coming into a chemistry class. There is no doubt about it. I would like to think that we do not make the topic or the course structure intimidating, but in itself we probably do. Any student that goes home after purchasing their textbook before the course starts and starts thumbing through the pages that has not been exposed to general chemistry in high school previously, is going to be thinking "What is this? I see all these drawings of molecules and charts that I don't understand. And I have never seen an exponential decay. Well, what am I getting into?" I understand that. Honestly, I would like to think that with the open forum in my class that I take some of that away. I don't mean to patronize the students when I say that you can be successful in this class if you apply yourself and spend time. And I think that is true for most students, I think most students can really successfully get an A and B in class. There really is a mystique about it, probably more so in physics than chemistry, in cases where we are dealing with something "so scientific that I can't understand something like that." I sincerely hope that students have changed that impression by the time the term is over.

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.

The instructor also added his views about the order in which topics are presented in a typical chemistry course, and in the textbooks used. Some of his ideas were discussed earlier when evaluating the card sort, but he elaborated.

Dr. Dalton: Quite frankly, I think we start off on the wrong foot in general chemistry. We start off talking about some very difficult topics, and we don't seem to be very descriptive. We're recommending for our upper-division students to expose them to more descriptive chemistry and concepts involved, why do we not do that for general chemistry.

Based on the interview it appeared that Dr. Dalton is a conscientious instructor who had thought about how students learn, and their limitations. He also reflected on issues in chemistry education such as the particulate nature of matter, microscopic/macroscopic ties, and ties between conceptual and computational aspects of chemistry.
Instructional Profile

In analyzing the class observations, course exams, and the instructor interview it appeared that Dr. Dalton's instruction generally followed the philosophy he discussed in the interview. He showed concern for students' mathematical ability getting in the way of their conceptual understanding and so often approached new material with a conceptual or descriptive method before introducing the computational aspects. The instructor stated that the goal was to teach the concepts and so a good proportion of time was spent on understanding the concepts. Dr. Dalton mentioned in the interview that he believed that if students put in the requisite time practicing solving problems and understanding the concepts then they should be able to get an A or B in the course. He emphasized and encouraged the use of the resources that could assist students in succeeding and pointed out the resources such as practice exams, textbook problems, and the tutorial software. The grading scheme for the course also reflected this concern as students could earn 50 points for completing assignments using ChemSkill Builder (Spain & Peters, 1997). The points for these assignments accounted for more than 10% of the 450 points possible.

The instructor's philosophy was also reflected in the course grading. The lowest midterm exam score was dropped for each student thus giving him or her an opportunity to do poorly on an exam and not be overly penalized. The course grades were also assigned based on a criterion-referenced rather than a norm-referenced scale, allowing all students to reach their own level of success and not compete with their classmates. Dr. Dalton mentioned in the first class meeting that each student could earn an A, and that in one small course more than 90% of his students earned A's.

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 appeared that Dr. Dalton believed that ability to solve computational problems demonstrated conceptual understanding. As seen in the literature review, many studies (Mason, 1995; Mason et al., 1997; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz, 1995b, 1995c; Niaz & Robinson, 1992a, 1993; Nurrenbem & Pickering, 1987; Phelps, 1996; Pickering, 1990; Sawrey, 1990; Zoller et al., 1995) have shown that ability to solve computational problems does not indicate conceptual understanding. It appeared that the instructor believed as Nurrenbem and Pickering stated: "Chemistry teachers have assumed implicitly that being able to solve problems is equivalent to understanding of molecular concepts" (p. 508).

In the overall picture of instruction it appeared that the instructor was knowledgeable, interested, and capable. His instruction was definitely far from the "sink or swim" mentality that appears in many college courses and Dr. Dalton attempted to relieve the fears of his students about chemistry. It could also be seen from the exams and presentation of limiting reactants how students could develop or reinforce the belief that chemistry was primarily interested in solving numerical problems, even though conceptual understanding was emphasized in the lectures.

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 used for this course was one that had been used for several years and was intended for introductory chemistry courses. It consisted of 23 chapters with six appendices, which included data tables, a glossary, answers to selected problems, some information on background topics (mathematical operations and physical concepts), and
further information on the naming of organic compounds. Interspersed through the text were short essays on topics of interest, generally real-world applications of chemistry. The book was organized in a manner similar to other general chemistry texts with the early chapters covering material that would be review for many students, including an introduction to the language and symbolism of chemistry. Atomic theory was introduced in the second chapter along with the concepts of chemical formulas and some basic means of classifying chemicals – acids and bases, ionic compounds, and organic compounds. Stoichiometry was introduced and covered in chapter three. Chapter three discussed molecular and formula weights, the mole and Avogadro's Number, mass percents, chemical equations, stoichiometry of reactions, limiting reactants, percent yield, and solution stoichiometry. The fourth chapter, on gases, was not covered during this course, but during the subsequent course. Thermochemistry was covered in Chapter 5. Atomic structure was discussed in chapter six, electron configurations in chapter seven, and the s-block elements in chapter eight. The remainder of the book was covered in the following two courses.

In the book's preface the authors (Hill & Petrucci, 1996) discussed the types of problems that were included in the text and the justification for their inclusion.

It is not enough, however, just to be able to plug numbers into an equation and get an answer. We hope to help you develop judgement about whether or not the answer is reasonable; we do this through worked out estimation examples followed by estimation exercises. You also need to develop some insight into the chemical concepts on which problems are based. We provided guided conceptual examples, followed by conceptual exercises, to foster this process. (p. xii)

The authors (Hill & Petrucci) also stated that they used "drawings, computer graphics, and photographs" (p. xvii) to help the students visualize chemical phenomena at the microscopic and macroscopic levels.
In the textbook, as indicated in the Preface, there were many examples and sample problems (called Exercises) as well as one or two estimation examples and conceptual examples. Almost all of the Examples and Exercises were computational. The few conceptual examples and exercises included were appropriate for the material covered but based on the description in the Preface it could be argued that there should have been more conceptual examples. The solving of problems was rarely discussed in the body of the text but was left for the Example/Exercise boxes. This splitting of the content may not be an effective method of presenting the material as the students may skip the Example/Exercise boxes or read only the boxes. At the end of each chapter were Review Questions, Problems, and Additional Problems. The Review Questions were primarily conceptual questions asking for a definition or an explanation. Some of the questions asked for simple definitions and others asked for more meaningful explanations. An example of a more involved question was:

11. Explain the meaning of the equation
   \[ \text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} \]
   at the molecular level. Interpret the equation in terms of moles.
   State the mass relationships conveyed by the equation. (Hill & Petrucci, 1996, p. 102)

The presentation of the concepts in the chapters examined (1-3, & 5) followed a logical progression. When appropriate, the authors linked the concept being discussed with sections later in the book where the topic would be discussed in more depth. For example, when discussing reactions, the text points out that reversible reactions would be discussed in Chapter 16. There did not appear to be examples of explicit references to previous content. Though the authors stated in the Preface that they would use different representations to help students visualize chemical phenomena; they rarely tied the levels together. A rare example was in the discussion of the mole concept, where the authors implicitly tied the molecular and macroscopic levels together in their discussion, showing
Avogadro's Number as the tie between the two. They also used a diagram to illustrate their point showing a molecular and macroscopic view of the reaction between carbon and oxygen to form carbon dioxide (See Figure 5).

Stoichiometry is presented in the text primarily as a computational aspect of chemistry with few ties between the conceptual and computational models. Except for three diagrams/pictures, the text did not make explicit connections between concepts and the computational models that came from them while discussing stoichiometry. The authors used analogies to help present the material, using dozens, gross, and reams as analogies for the mole and using an analogy of putting together airline lunches to illustrate limiting reactants. The Examples and Exercises for stoichiometry were almost all computational and were primarily solved by an algorithm or the factor-label method.

![Figure 5. Illustration from text (Hill & Petrucci, 1996, p. 72)](image)

The Preface informed the students that several different pictorial methods would be used to assist them in visualizing chemical phenomena at both the molecular and visual levels. In the chapter on stoichiometry, four representations were used in the 11 sections of the chapter. In chapter two, on the language of chemistry, only six representations
were used, unless structural formulas of organic chemicals were counted. It appeared that the comments in the Preface overstated their use.

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's introduction emphasized practice in problem solving as an important ingredient in learning chemistry. 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. The tutorial also provided an advantage for the instructor because the program scored each student's attempts for each section and the results could be uploaded to a class grade book program. 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.

Each section began with a short tutorial on the topic and showed some worked out example problems that students could skip if desired. The examples were interactive, asking students to supply answers to the example problems. An example of the tutorial for balancing equations was:
Now, let's look at a few balanced chemical reactions.

\[ N_2 + 3 \text{H}_2 \rightarrow 2 \text{NH}_3 \]

This says that one nitrogen molecule reacts with 3 hydrogen molecules to make two ammonia molecules. But, it also says that one MOLE of nitrogen molecules react with 3 MOLES of hydrogen to give two MOLES of ammonia.

How many moles of hydrogen would be needed to react with 2 moles of nitrogen according to the equation? (Spain & Peters, 1997)

After the tutorial the student was automatically moved onto the exercises. Each question was displayed on the screen with an answer box where the student typed in an answer with appropriate units. If needed, the student could access a periodic table, conversion table, formula list, or calculator through the program by pressing a button on the command bar. The tutorial continually encouraged the students to use their own calculator rather than the one provided on the screen to gain practice with their personal calculator. After the answer was entered, the program informed the student that they were correct with an encouraging statement or asked them to try again. If the student failed to answer correctly on the second try the program provided a method and solution. The program provided a running score for the student as a percent of possible points. Each major section also provided a scorecard giving the highest score received by the student for each subsection. The student could check a results table that gave each subsection's score, the average for each section, time spent on each section, and the date when the score was uploaded by the instructor.

A review of the stoichiometry section of the ChemSkill Builder (Spain & Peters, 1997) showed that: 1) The tutorial presented solving limiting reactant problems by the use of ratios, which was different from the method demonstrated by the text and the instructor. An example problem illustrated the tutorial's method.
If 3 moles of $\text{C}_2\text{H}_4$ were allowed to react with 10 moles of $\text{O}_2$ according to the equation:

$$\text{C}_2\text{H}_4 + 3 \text{ O}_2 \rightarrow 2 \text{ CO}_2 + 2 \text{ H}_2\text{O}$$

What is the LIMITING REACTANT?

$\text{C}_2\text{H}_4$ $\text{O}_2$ Neither [Answers were chosen by use of the mouse.]

[If solution was incorrect.]

\[
\begin{align*}
\text{Needed:} & \quad \text{Available:} \\
\text{mol O}_2 & = 3 = 3.0 & \text{mol O}_2 & = 10 = 3.33 \\
\text{mol C}_2\text{H}_4 & = 1 & \text{mol C}_2\text{H}_4 & = 3 \\
\end{align*}
\]

There is more than enough $\text{O}_2$ available. Hence: $\text{C}_2\text{H}_4$ is limiting. (Spain & Peters)

2) 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. 3) 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 ($\text{CH}_4$) molecules?" (Spain & Peters). 4) When discussing the mole concept, the tutorial connected atomic and macroscopic levels by the mole concept as was done in the text. And, 5) there were no depictions of matter used in the tutorials.

**Student Interviews**

Six student volunteers were interviewed for this study. The students were asked to volunteer during a class meeting with additional students recruited during class recitations. Each student interview took place during the final week of the course or during Finals Week. The first three interviews (Anna, Beth, and Cara) were interviewed during the last week of classes and the final three (Deb, Ed, and Frank) were interviewed during Finals Week. The students completed the tasks outlined in Chapter 3. An account
of the results from each student was written and a profile of each student was developed. The students' card sort structures are included in Appendix F. 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.

Anna's Interview

Anna is a 25-year-old female majoring in Exercise and Sports Science. She had not previously taken any chemistry courses but had taken high school and college courses in biology and college courses in physiology. Her mathematics background included courses in algebra, precalculus, geometry, and statistics.

Anna approached the card sort task as if preparing a notecard for an exam. She asked many questions of the interviewer to ensure that she completed the task correctly. She noted that the topic was presented differently in the card sort than in the course and that there were no pictorial representations of matter presented in the class.

Anna's structure (see Appendix F) was constructed by grouping similar representation types, such as definitions. The first group consisted of definitions and examples of simple calculations. The second group also consisted of definitions, but only definitions she felt she already knew. The third group consisted of graphical representations of balanced equations. The remainder of the cards were placed in groups of one to three cards where there was a common feature connecting them, such as the $\Delta H$ notation of enthalpy. She connected the three cards with the $\Delta H$ notation (Cards #12, and 27-28), but did not connect these to the other enthalpy-related cards (Cards #29-32). No explicit connections between groups that contained similar concepts were made unless they were represented in the same way. When discussing her structure, Anna repeated her use of a notecard framework as the overall structure.
Anna: This stuff here [First group] is the most important stuff to me right now out of all this. I know all of these, but sometimes it's better just to write it down. So I don't have to commit them to memory, you know – 12 grams is how much carbon. That's stuff I would want. This stuff [Second group] is stuff I would just know, that I wouldn't even bother writing down. I don't really know. None of this stuff [remainder of cards] really makes sense to me at this point. If that's how you had taught the class I might know it.

It was possible that her use of the notecard framework affected how her structure was put together. It was significant that she mentioned several times that she did not understand the concepts on many of the cards.

When asked to balance the equations in the Balancing Task, Anna easily balanced the equations correctly, but she often asked the interviewer if her answers were correct. When asked how she knew if the equations were balanced, she referred only to the first symbols in the equations (N and K) saying that there were the same number of each on both sides of the equations. The Drawing task proved stressful for Anna, as it was something that she had not been tested on previously. She discussed her habit of second-guessing her answers when asked to solve a problem that appeared easy. Anna eventually drew a correct representation but again asked if her answer were correct.

Anna had difficulty solving the problems asked of her in the Problem-Solving Task, as she was unable to correctly solve any of the problems without assistance from the interviewer. She approached all of the questions as computational, typically determining the molar masses as the first step in her attempted solutions. During the interview when Anna said that she could not go further in solving a problem, the interviewer offered assistance by offering hints, asking clarifying questions, or giving the next step in the process. The purpose of the assistance was to prompt her to continue discussing her thought processes instead of stopping the inquiry when unable to continue. The same process was followed for all interviews, and the use of assistance is noted in the descriptions of the interviews. It is assumed that this assistance did not taint the study, but
added information on thought processes was of more importance than correct or incorrect solutions.

The first question asked of Anna was Problem #1, which asked for the number of moles of chloride ions in two moles of magnesium chloride. This problem was similar to several seen in the software tutorial where she claimed to have earned all possible points. She began to solve the problem by asking for the periodic table and determining the molecular weight of magnesium chloride. She then incorrectly solved the problem by dividing the molecular mass of diatomic chlorine by the molecular mass of magnesium chloride. She made a remark that was similar to ones repeated throughout the remainder of the interview. “That's another thing, if he does a problem on the board, I'll understand where the numbers are coming from. When it comes time for me to do a problem, I can't do it unless I copy the problems and copy the steps. So I'm not really sure what I should be doing.”

The second problem was Problem #2 concerning the combustion of 1.00 gram of ethane, C₂H₆. Anna said she felt she should know how to solve this problem, but without her notecards was unable to solve it. The interviewer gave her some assistance by guiding her through the first steps and showing her Card #15 which outlined the method used by her instructor. She was then able to solve the problem but made a minor error on the final step.

On the third problem, Problem #3, she was asked to describe what information was provided by a balanced equation. Anna was only able to provide a few points concerning moles and molar mass that a balanced equation would provide.

Anna: It tells you like how much chlorine or whatever needs to react with methane.
Interviewer: What else does it tell you? What other information can you get from the balanced equation?
Anna: You can get . . . . I don't know. You see I don't usually get asked questions like this. You can figure out the molar mass and the moles and all kinds of things.
She mentioned that she did not usually get asked questions like this, implying that this accounted for her difficulty.

The final question asked of Anna was Problem #5 where she was asked to draw the products of a reaction between chlorine gas and excess aluminum. She was confused by the problem because there were six squares representing aluminum atoms but the balanced equation had a coefficient of two for aluminum. She realized that the reactant diagram was part of Card #23 from the Card Sort Task and pulled that card from her structure.

**Anna:** This doesn't make sense. I don't do well with these pictures. The same things that are in here [Card #23] are in here [Problem #5], so I want to just draw exactly what's here, but I don't know if that's right or wrong. But, I feel like it doesn't make sense to me in pictures because if aluminum are the squares, there are six squares, but there are not six aluminums. I see several.

After she realized that the diagram on the card was the correct solution, she copied two of the aluminum chloride diagrams from the card. Even after seeing the solution, Anna struggled to see the connection between the reactants diagram and the balanced equation. She did not seem to understand that the balanced equation was a representation of the ratios between products and reactants. She asked several times why if there were six aluminum atoms in the diagram the coefficient of aluminum was not six. She also failed to see that the diagram represented a limiting reactant problem with chlorine as the limiting reactant.

During the Problem-Solving Task, Anna added some information about her method of study. She described the software tutorial as very useful: “I think it helps a lot. A lot of things don't make sense to me exactly when he is doing them in class like. Doing a lot of problems over and over again helps me to catch on.” Anna also mentioned that she rarely read the textbook, instead relying on course instruction, her Teaching Assistant (TA), and the software tutorial.
Anna: You see, I don't really use the textbook much. I pretty much go by what he does on the board and what my TA does. And what goes on in the ChemSkill Builder. I have done some stuff in the book, but I find that he pretty much explains things a lot better to me. I learn them better when he works things out on the board rather than looking at the problem.

At one point in the interview she compared chemistry to her other courses.

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.

During the Perceptions Task, Anna described her method of preparing for an exam, as attending the review sessions to determine what would be on the exam.

Anna: Well, he does a review. Or he'll have objectives like he'll have 10 things that will be on the test. So we'll go over things, and he usually does a problem for each objective, so he'll do like 10 things on the board. So I'll look at what I need to know for each problem, so do I need a conversion or a certain number, so I'll write those down for each problem. If I know something really well I might not write those down. If I have a problem with something I will write as much information as I can. And if I have a real problem, I usually write out the whole problem. Like with the limiting reagent problems I have to write out the whole thing. I understand most of it, but after a few steps, I kind of get lost. So I have to write out all of the steps.

Anna went into more depth on an issue raised previously in the interview, that she was not able to determine where numbers for the problems came from.

Anna: A lot of times with numbers, I don't know where they come from. My TA finally will explain it and some of it seems really basic. Some people will plug in numbers in places and I won't know where the numbers are coming from, like the molar mass. I know the molar mass and how to
get the molar mass, but I don't always know that's where the number is coming from. Sometimes I need that spelled out for me.

She also raised an issue with sample problems in science and mathematics textbooks. "That's one thing I have problems with textbooks. I remember my math class; it just seemed to me that they were just taking numbers from someplace random. Where did they get that? Sometimes it is really easy once you get the number."

At the conclusion of the interview Anna was asked what grade she expected from the course, she replied that with a 140 score out of 165 possible on the final exam she would earn an A for the course and that she had received an A on the first exam, a B on the second, and had "dropped" the third exam on stoichiometry because she had done poorly.

Anna's Profile

Anna came to the course with the prerequisite courses but had no previous experience in the physical sciences. From the Problem-Solving Task it was obvious that Anna relied on algorithms in chemistry. She admitted that she relied on formulas and algorithms to solve problems and did not understand the concepts behind the formulas and algorithms. She showed that she was an algorithmic problem solver in chemistry with little conceptual understanding; she acknowledged this tendency in her interview but seemed to place the blame on chemistry. Her perception of chemistry was one of a computational science with the concepts either unnecessary or unimportant for success. She unfavorably compared chemistry with other courses where she felt that she understood the concepts.

Anna's lack of conceptual understanding appeared in her particulate view of matter. She said that the course did not incorporate particulate views, but as seen in the class observations, it did. Her difficulties with any microscopic representations in the Card
Sort Task or Problem-Solving Task implied that she did not make connections at that level. This difficulty was also apparent in her attempt to solve Problem #5.

Anna was an algorithmic learner, yet had little success on the computational problems given to her. Her lack of success could be tied to her lack of conceptual understanding and her reliance on cues like the notecard. She knew the general algorithmic steps required in stoichiometric calculations but because she did not understand the big picture she was not able to correctly use the algorithms. Anna mentioned in the interview that she had a grasp of some of the concepts, but agreed that she did not have a grasp of the big picture. She also admitted to a reliance on the notecards when solving problems.

From the interview it could be seen that Anna focused on the exams as the main factor determining what was important. During the Card Sort Task she stated that they did not have to answer questions like that in the class and implied that was a good reason for her inability to understand some of the representations. During the Perceptions Task and Problem-Solving Task, she mentioned the review and class lectures were crucial for determining what material was important to learn. She seemed to focus on the computational components of chemistry in her preparation for exams.

An important difficulty interfering with Anna's ability to solve chemistry problems was her lack of connections between related concepts. In the Card Sort Task she grouped the cards based on their presentation (i.e.; definition, example calculation, etc.) rather than grouping cards related by concept. In the Problem-Solving Task, she demonstrated this by her inability to solve problems, especially those different in some way than problems she had seen previously. Anna's problem solving was hindered by her lack of connections.

Based on her own projections, Anna probably received an A or B for the course, so she could be considered a successful college chemistry student. Despite her success, she showed that her knowledge of chemistry was limited.
Beth's Interview

Beth is a 21-year-old, female General Agriculture major who was also pursuing an International Degree. This course was her first chemistry course and she had not taken a physical science course previously. She had taken two years of biology in high school and one quarter in college. As part of her agricultural studies she had taken a forestry course, an animal science course focused on horses, and an introductory geosciences course. Her high school mathematics coursework included courses in pre-algebra, Algebra I and II, and geometry. In college she had taken a pre-college algebra course and a college algebra course.

Beth had little difficulty in creating her structure (see Appendix F) in the Card Sort Task, though she asked the interviewer if she was doing it correctly. She discarded six of the cards that she did not understand. These cards included five cards that represented reactions at a molecular level (Cards # 6, 13, 18, 20, and 23) and one card showing a calculation of the mass of silicon in 224 grams of silicon tetrachloride, SiCl₄ (Card #21).

In her structure, the first group of cards contained cards dealing with different representations of the mole concept, including molar mass. The second group included representations of molecular weight. The third group contained representations of reactions, stoichiometric calculations, and the definition of a limiting reactant. The fourth group contained the enthalpy concepts as well as the card containing a generic reaction with enthalpy (Card # 12). Beth reversed the definitions of endothermic and exothermic reactions, but acknowledged she was unsure if a positive enthalpy change meant exothermic or endothermic. Her description of her structure illustrated her thoughts well.

Beth: I have set them up [Fourth group] because they are all about changing enthalpy. I can't remember if a negative or positive energy is released or absorbed in a reaction. So, I have grouped them all together, they are all the same concept. The limiting reagent [Third group] those kind of all go with that I think. To do limiting reagents you have to have the equation – moles to gram and back again. I think that these are all kind of examples of limiting reactant. And then [Second group], you can find
the molecular weight of some molecule by the sum of the masses of the atoms that make up the molecule. And these [First group] figure out like the moles and how many atoms per mole and how many moles because the molar mass is how many grams per mole. That's why I grouped all these together. And these ones [discard pile], I don't really know where they go.

In the Balancing Task, Beth had no difficulties balancing the two equations. She followed steps seen taken by her instructor in class and she appeared to understand the concepts behind the balanced equations. She had difficulty when asked how many moles of hydrogen would be needed to react with one mole of nitrogen because she attempted to answer the question by converting grams to moles and did not notice that the question had been asked in terms of moles making the step unnecessary. When asked a similar question for the potassium reaction, she stated that it was too easy but that she could not explain how she was thinking about the problem. With probing questions from the interviewer, she correctly described how to do the calculation using molar ratios taken from the balanced equations.

Beth: I don't know what the equation is. If that's the equation I have set up, then I have to figure out the grams of potassium then the moles, I already have the moles. I would do a ratio of K to water, so that would be two to two, and then I would change that from moles to grams to find how much I actually needed. Or leave it in moles if you wanted moles. So times the top number, so I guess you need four moles H₂. I guess that's obvious when you see they need the same moles.

It was interesting to note that she said she did not know the equation (there is not an equation but an algorithm), but determined how to do the calculation using logic, conceptual understanding, and some computational steps.

In the Drawing Task, Beth correctly drew a molecular representation of the nitrogen/hydrogen reaction, though she made an error that she corrected herself. She drew two nitrogen atoms each bonded to three hydrogen atoms but included a line/bond
connecting the two nitrogen atoms. When describing her drawing she noticed the error and corrected it (see Figure 6).

The first problem asked of Beth was Problem #1. Beth had difficulty with this problem for the same reasons that she had problems in the Balancing Task, she immediately attempted to convert grams to moles though the question was posed in moles.

The second problem presented was Problem #5. Beth had no difficulty solving this problem and showed good understanding of the tie between macroscopic/symbolic

![Figure 6. Beth's reaction drawing](image)

(balanced equation) and microscopic/symbolic (reactant drawing) representations. Her drawing was equivalent to the answer supplied by Nurrenbern and Pickering (1987).

Problem #2, a standard computational stoichiometrical problem, was the third problem asked. Again, Beth had little difficulty solving the problem. She first set up a skeleton equation with units to allow her to place the numbers correctly and check her calculations using the factor-label method. She then calculated the answer. Her solution method was the same as her instructor's and similar to methods shown in general chemistry textbooks.

Beth was then asked Problem #3 concerning balanced equations. She answered this question correctly though not completely. “That for every CH₄ molecule you need two chlorides [sic] to produce one mole of CCl₄ and two hydrogen.” There were other
levels of relationships, such as moles, that this equation symbolized that she did not mention.

Because Beth was able to answer the problems quickly the interviewer was able to ask her more questions than other subjects. Beth was asked Problem #7, which asked the students to determine if reversing an exothermic reaction (combustion of methanol) would release or absorb heat. Beth correctly answered that the reverse reaction would be endothermic. Her logic was correct though her statement implied that she was not certain. “Because it does one thing going one way, it will do the other thing going back. That's just what I think. Is the reaction endothermic?”

Problem #6, a computational thermodynamic problem, gave Beth difficulty at first because the factor-label method did not work in setting up the problem. The enthalpy change for a reaction was given in energy units but more correctly should be represented as energy per mole. This fact confused Beth until the interviewer clarified the point. She then set up an equation correctly to compute the solution.

During the Perceptions Task, Beth outlined how she determined what was important.

Beth: I guess whatever the teacher writes on the board and says. I kind of read the chapter before we discuss it and have a basic overview of it. And listen to what they're saying and write things down. Whatever he repeats at least twice or more I know is the most important. Whatever he says will be on the exam.

During the Problem-Solving Task she gave a list of the things she used to determine what to brush up on for an exam. “From the reviews and old tests and from lab and lecture, and review sessions.”

Earlier in the interview she also explained what she wanted to gain from the course. “Well, it's required, but it's also interesting to just find out how the world works


in life. To just get a general understanding of how things work, plus I was a little afraid of chemistry.” Beth predicted that she would get an A in the course.

Beth’s Profile

Beth was able to answer most of the problems presented to her and in a testing situation with a notecard and more time could have correctly answered all problems. She showed both conceptual and computational understanding of chemistry. Beth showed ability to think about chemistry at the conceptual level rather than only at the computational level. She also drew connections between different concepts in the Card Sort Task and between symbolic, microscopic and macroscopic levels in the Card Sort Task and in solving some of the problems.

There was one issue that popped up several times in the interview. Beth seemed to assume that all problems began with amounts of chemicals in grams and attempted to determine the number of moles from the amount of the given chemical. In problems where the amounts were given in moles, she did not catch her mistake, though she caught her own mistakes on several other problems. There are two possible causes of this problem: 1) errors in problem solving strategy, and 2) reliance on algorithms. Despite her careful laying out of all problem solutions, including emphasizing the solution's units, Beth missed the units of the given quantity. This problem seemed partly due to the emphasis she placed on knowing what the questions asked for, and ending with the correct units. Another reason for this problem was her reliance on algorithms. Card #15 illustrated an algorithm for solving stoichiometric problems, and this algorithm was similar to the “Mole City” algorithm used by the instructor and the algorithm illustrated in the textbook (Hill & Petrucci, 1996). The first step in the algorithm was to convert grams of reactant A to moles of reactant A by use of the molar mass. It appeared that Beth had this step firmly entrenched in her mind and so missed the fact that it was unnecessary.
Beth's description of how she prepared for exams and how she determined what was important showed that she had good study skills and was willing to work hard to succeed. Chemical educators hope that all of their students are like her. Her curiosity about how things work would seem to add to her success in the course.

Cara's Interview

Cara is a 28-year-old Horticulture major who had previously studied to be a nurse. As part of her nursing studies she had taken an allied health chemistry course. She had also attempted this introductory chemistry course previously, but had withdrawn from the course. In high school she had taken an integrated physical science course and had taken two quarters of introductory biology and anatomy and physiology in college. Her college math background included a college algebra course and she was enrolled in the next course in that sequence. She had also completed a statistics course.

Cara seemed uncomfortable while doing the Card Sort Task. She continued to ask questions of the interviewer to clarify how to complete the task. It was obvious that she was becoming frustrated with the task and she eventually cleared the workspace of all but the enthalpy cards (see Appendix F). She put these cards into two parallel columns matching the three representation types for endothermic and exothermic reactions in the columns. She incorrectly placed the definitions of endothermic and exothermic, but otherwise tied the concepts together. From the tapes of the interview it could be seen that Cara had begun to put the mole concepts together before she got frustrated and quit the task.

Cara had difficulty with the Balancing Task and failed to correctly balance either equation. In her comments made during the interview it can be seen that she was confused.
Cara: OK, so I have two N₂, so I need two here and then two here and I have two here. Does that mean that I have two H₃'s? . . . OK, I'm just going to say the 2 applies to both of these so that makes six H's and so I need three H₂'s to make six. Is that right?

While doing the potassium reaction she also showed signs of confusion.

Cara: Just checking K here and K here. Two H's, have three over here. I think there is something that always screws me up, because the way I first learned it was the buns and wiener thing. Do you know what that is? I think it's scarred me for life. So, I have enough K's, have enough O's, have too many H. OK, so if I put three here there are six H's and there are two . . .

After she made this statement, Cara erased all of her work and started over. In both cases she did not correctly count the number of atoms in diatomic species. This discrepancy was interesting because she correctly incorporated subscripts on other chemical formulas, including hydrogen in the first equation, which she did incorrectly in the second. Her incorrectly balanced equations were:

\[ 2 \text{N}_2 + 3 \text{H}_2 \rightarrow 2 \text{NH}_3 \] \quad \text{and} \quad \[ 2 \text{K} + 2 \text{H}_2\text{O} \rightarrow 2 \text{KOH} + 2 \text{H}_2 \]

When asked what the balanced equations said about the reaction it symbolized, Cara again was confused and could not answer the question except by guessing. It was interesting to note that throughout this part of the interview, Cara always referred to the elements by their symbols and not their names, which might be indicative of her perceptions of symbols.

Cara's drawing of the ammonia reaction reflected her misunderstanding of the subscripts (see Figure 7). In the drawing she included two separate nitrogen atoms rather than diatomic molecules.
The first problem given to Cara was Problem #2, a computational stoichiometric problem. Cara was unable to begin the problem and asked the interviewer for the first step, which was to convert 1.00 gram of ethane, $\text{C}_2\text{H}_6$, to the number of moles of ethane. Given that piece of information, she was able to determine the number of moles of ethane given, but again was unable to continue without leading from the interviewer.

**Cara:** OK, I don't know what to do with it.

**Interviewer:** OK, what do you know about that system? So, we know how many moles of $\text{C}_2\text{H}_6$ are going to react, what else do you know about the system? What does the question ask you to find out?

**Cara:** How many grams of oxygen. [Long pause].

**Interviewer:** Is there a way to figure out how much oxygen you would need if you know how much $\text{C}_2\text{H}_6$ you have?

**Cara:** I don't know. I mean . . . . [Pause].

**Interviewer:** OK, you've figured out how many moles of $\text{C}_2\text{H}_6$ you have.

**Cara:** Right.

**Interviewer:** What do the 2 and the 7, what do those numbers mean in the balanced equation?

**Cara:** It means how many of each of these I have, so I have two of these, and I have seven $\text{O}_2$'s.

The interviewer eventually solved the problem as Cara watched. At the end she admitted that the method looked familiar.

The second problem was Problem #5. Cara was not able to solve the problem completely, but her partial solution and her discussion were enlightening.
Cara: So, I'm going to draw two AlCl₃'s?
Interviewer: Based on that many aluminums and chlorines, how many would you end up with?
Cara: Where do these go [excess aluminum]?
Interviewer: What happens when they have nothing to react with?
Cara: I don't know.
Interviewer: Then they become the limiting reactant.
Cara: The Cl₂?
Interviewer: You're right, the Cl₂ becomes the limiting reactant and the aluminum becomes the excess.
Cara: Then where do they go?
Interviewer: Well, if there was nothing for them to react with, what would you expect?
Cara: They would just stay there and hang out?

It was clear from the discussion that Cara was unable to connect the molecular representations with the computational way in which limiting reactant problems can be solved. In drawing only two aluminum chlorides she used the coefficient taken from the balanced equation, not from the numbers of aluminum atoms and chlorine atoms in the reactant drawing. She was quite confused when the interviewer implied that her answer was incorrect. She eventually drew a partially correct representation (see Figure 8) but with bonds between the aluminum atoms in the aluminum chloride, creating two Al₂Cl₆ molecules. After being shown the answer on Card #23 she changed one of the Al₂Cl₆ to two AlCl₃ molecules.
Due to the subject's frustration level and lack of success, she was given only the two preceding problems. Cara's response to the question of how she determined what is important showed her view of chemistry.

**Cara:** It helps if he has, you know he has objectives on the web, and past tests, because that gives you an idea, because chemistry is so . . . I can't think of a good word. It is hard to pick out what I think is important, what he thinks is important. I usually go by things that he emphasizes in class. If he says in class more than once, that's what I look for, but, usually, I go by what's posted on the web.

The interviewer also asked Cara how this course compared to her allied health chemistry course; her response dealt primarily with the greater depth of material covered in this introductory chemistry course. Cara added statements that further delineated her views of chemistry. She praised the instructor because she was able to understand the material as he presented it and because the notecards allowed her to see examples when taking the exams.

**Cara:** It's different though, because he is completely different than any chemistry professor I've had so far. It's amazing because I actually understand what he is saying. It doesn't show because I can't retain it, but I do at the time understand.

**Cara:** This is really hard because, um, I need examples. The way I can do chemistry is if I have examples. Which is why [Instructor's] class is so much easier for me because he let's us have a 3 X 5 card, so that we can remember how to do these, because there are so many. It's very hard, I don't think it's right.

Cara said that she could earn an A if she “aced” the final, but would probably earn a B for the course.

**Cara's Profile**

Though Cara claimed to have the possibility of earning an A for this course, she demonstrated little chemical knowledge in the interview. It was possible that the
unfamiliar situation of the interview setting may have caused her to perform below her ability, but even leading questions, hints, and suggestions from the interviewer did not prompt her to demonstrate knowledge. She admitted that she needed an example to follow to solve problems, but it appeared that her examples were “crutches” that she relied on rather than learning the concepts or computations. It was interesting to note that though this course was her third exposure to this material she could not perform even a simple chemical manipulation, such as balancing a chemical equation.

As Cara started the Card Sort Task she tried to impose some order on the structure but was easily frustrated by the task. She also referred to the elements by their symbols rather than by their names though the interviewer often referred to them by name. All of the names and symbols should have been familiar to her since the elements used were common elements such as oxygen and carbon.

It appeared that Cara relied on algorithms, but not memorized algorithms as many students do, she relied on worked out examples to serve as algorithms. Though notecards or formula cards are a common resource allowed by instructors (Perrin, 1997), it appeared that Cara had abused the intent of the system.

Deb's Interview

Deb is a 19-year-old female General Science major who intended to go to Veterinary School. She had taken one year of high school chemistry where she had earned C grades and she had been enrolled in chemistry for science majors during the previous quarter but had withdrawn. She viewed this course as a refresher course as it had been two years since she had taken high school chemistry. In high school she had taken physics, biology, general science, and a survey course for students interested in health occupations. Her mathematics background included high school algebra and geometry, and college algebra.
Deb had little hesitation in approaching the Card Sort Task and had little difficulty completing the task. She began her structure (see Appendix F) with the definition of a mole and linked it to the molar mass and Avogadro's Number. The second row of concepts dealt with gram-to-mole conversions, which she linked to the fact that chemicals react in mole ratios and not mass ratios. The next row contained the definition of a limiting reactant. She included one reaction card (Card # 14) that was not a limiting reactant reaction, a card showing the steps to calculate the molar mass of carbon dioxide (Card #2) and a card showing an example of how to calculate the mass of silicon in silicon tetrachloride (Card # 21). In her description she tied them together as calculations that were part of limiting reactant calculations. The fourth row were cards she linked as demonstrations of reactions. The fifth row were diagrams of how molecules mix and react. The sixth row contained the enthalpy concept cards. Deb's description went into the depth of her thinking about the structure.

Deb: I was moving across, and so here [First row], I have the definition of the mole and then kind of linked it to the molar mass. The molar mass is $6.022 \times 10^{23}$, so that's virtually the same. It's saying that one mole of sodium is going to be $6.022 \times 10^{23}$ it's all going to be the same in atoms. And this is to me just demonstrating a mole for each carbon, oxygen, carbon dioxide. Does that make sense? Should I just take these out [cards already discussed]? Then we start talking about molecular weight [Second row]. And I identified it with you can't compare two reactants, you have to put them in moles, so that you can combine them that way and then you can get different products, reactants. Then limiting reactants [Third row]. First you have to get your change [Card # 2] ... oh you're supposed to change grams to moles. Anyways, grams to moles you're starting to figure out the thing. And then you can start by balancing the equation. And that's what that is kind of doing. Once you figure out like, say this is chemical A and then chemical B and which is excess and then when its producing chemical C then you have to change it back to grams to see how much is produced. And this was another part that I thought played into limiting reactant. Basically figuring out the different mole and gram ratios. And to me these [Fourth row] were just demonstrations of reactants and products and how they move and how they are like dynamic ... and stuff. And this stuff [Fifth row] I have to think about [Cards # 23 & #18], I think these things demonstrated how they move and how they form. OK, going from
reactants to products [Sixth row], I think, I don't know. I might have thought that heat released is going to be energy released during reaction and with different equations it could be energy absorbing. Do you understand? I'm not very familiar with this [enthalpy]. We didn't go over this a lot or I wasn't there. And then this [Cards # 31 & #32] is just demonstrating what it looks like.

Some of the terms used and the links were different than how an expert might describe them but she showed that she was tying the concepts together and tied the entire structure together. Deb used the limiting reactant calculations as an overall structure to her card sort.

In the Balancing Task, Deb had few difficulties with balancing the equations. It took her an extra step to balance the potassium equation because the preliminary coefficient that she chose for potassium led to a fractional coefficient for hydrogen. This difficulty was a common occurrence and she solved the problem as she was instructed to do by her instructor. Deb also had no difficulty determining the number of moles of ammonia that would be produced from a given amount of reactants. Deb's drawing for the Drawing Task correctly reflected the rearrangement of bonds and atoms in the ammonia, though she expressed some doubts while attempting the task.

The first problem given in the Problem-Solving Task was Problem #2, a computational problem. Deb had no difficulty solving the problem except for a minor mistake that she caught while explaining her answer. Her method of solution followed the method done in class.

**Interviewer:** OK, could you explain how you went about solving the problem?
**Deb:** Well, I knew that I needed to, . . . back to when I was doing my cards, I knew that you could only compare when you got moles. So I converted C₂H₆ to its moles, and then I did the mole ratio, . . . shoot I wrote that down wrong [Noticed error and changed ratio from 7/1 to 7/2]. I took it from the balanced equation [recalculated answer]. OK, that's right?
**Interviewer:** I think that's right.
**Deb:** Back to what I was saying, I converted C₂H₆ to moles and then I took the mole ratio that was from the equation and then I needed to
convert my oxygen into grams. I could have done it each step, but I just ran it all together.

Deb was given Problem #5 next, and she at first was confused because there were six aluminum atoms and six chlorine molecules symbolized in the reactant drawing but the coefficients in the balanced equation were 2 and 3. She felt that there was more of each element than needed. She then drew the reactants and products in her own representation (see Figure 9).

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 Cl3. 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.

She was still confused about the connection between the balanced equation and the reactant and product mixtures. "Yeah. And that [Cl2] goes with that [Al] and the other half [Cl] goes there [another Al]. And that [Cl] goes with that [Al]. But see, I'm thinking . . . that there's not enough. We've got two extra aluminums." After the interviewer
suggested that it would be a limiting reactant problem, Deb drew a product picture (see Figure 10) but was still confused. "The chlorine would be the limiting reagent. But from what . . . I don't know. For some reason for me this doesn't match from the reactant to the product. It doesn't seem, shouldn't you have plus Al2 or something?" Her drawing was nearly correct but she drew two of the chlorine atoms bonded to each other and that grouping bonded to the aluminum rather than all three chlorine atoms being bonded to the aluminum individually.

![Figure 10. Deb's answer to Problem #5](image)

The next problem given was Problem #1 and Deb answered it almost immediately though she initially had some difficulty explaining her answer.

**Deb:** It's going to be two moles. This is all they're asking about, right? Is this equation? It's going to be two moles because . . . [noticed error] no, it's going to be four.

**Interviewer:** Why will it be four and not two?

**Deb:** I was thinking if I were to . . . Let's say I was going to balance it with Cl, in order for me to balance it with chloride ions, it would have to be four. I don't know.

Because Deb answered the problems quickly she was able to do more problems than other students were. The fourth problem was Problem #3, where she was asked to explain what could be learned from a balanced equation, in this case for the reaction between methane, CH₄, and chlorine.
Deb: We know that one mole of CH\textsubscript{4} plus two moles of Cl\textsubscript{2} is going to produce CCl\textsubscript{4} and two H\textsubscript{2}'s. That's because you only have one carbon to split up and the H\textsubscript{4}, it actually once it's split from the carbon, it becomes its own molecule so we need it H\textsubscript{2} to balance it with two. And chlorine reacts with carbon. Carbon needs to have four bonding, so that's why when it's with hydrogen it has four and when it is with chlorine it has four. And so vice versa you need to balance it back.

The interviewer asked Deb a question that dealt with gas volumes and went beyond what she had studied. This question was asked to view her thought processes and to determine if she recognized the limits of a balanced equation.

**Interviewer:** Say if we had these at a temperature where all four of these were gases. If I gave you one liter of methane, which is CH\textsubscript{4}, and two liters of chlorine gas and did the reaction, how many liters of those two product gases would you expect to get out?

**Deb:** So, one liter and two liters?

**Interviewer:** Yes.

**Deb:** You would get one liter and two liters.

**Interviewer:** How would you know that?

**Deb:** Basically, all you're doing is switching your units. It can be one unit two units; it can be one orange two oranges. It's the same thing it's just units.

**Interviewer:** What if I gave you one gram methane and two grams chlorine, what would you expect then?

**Deb:** My system didn't work then.

**Interviewer:** Why didn't your system work then?

**Deb:** [Started to work out problem.]

**Interviewer:** You don't have to work it out, just tell me what you would do. Why wouldn't your system work?

**Deb:** [Continued to work on problem.] Well, because if you were to do it in grams, you're going to carbon. Well, shoot, it should. This is one of those things where I second guess myself.

The final problem asked of Deb was Problem #7, a conceptual enthalpy question. She answered the question correctly, but showed some signs of doubt.
Deb: It's going to take in heat.

Interviewer: Why would it do that, why would you think it would take in heat?

Deb: So, like if we were to have CO₂ on the product side?

Interviewer: The reactant side.

Deb: Or the reactant side. Because . . . [wrote equations from problem.]

Deb: This, both CO₂ and H₂O have an excess amount of heat. You know, I think it needs to be . . . Well, methanol in the original equation, it's going to give off heat, it's got too much it's excess. So you would think that the CO₂ and H₂O don't have enough, but if you reverse the equation . . . yeah it would be exo because they don't have enough. Heat enters that and heat exits that. [Reversed notes on paper and showed reaction as endothermic.] Like that?

She answered the problem correctly though she at times switched terminology. She answered logically but did not base her solution on any physical principal.

When Deb was asked about what she focused on in preparing for an exam she answered that she primarily focused on equations.

Deb: Usually, I take things like the equations, things that are more complicated, that kind of require a lot more math type stuff. But what I've found is I tend to forget the simple things, too. I don't get those on the notecard, and I'll sit in the room [gestured]. You know I'll get the hard ones down, but the easy ones I skipped over because they're so easy, so I kind of sit there and think how I saw it in the book or in my notes or what exactly I read.

This statement matched with an earlier comment where Deb described her tendency to "second guess" herself and her need for example problems.

Deb: You start to second guess yourself. That's the hard part. For me to really learn something I have to have sample problems and follow the sample problems to exact. Once I figure it out once or twice doing that, following the sample problems, then I'll do it on my own and I can do it. That's why I don't test very well either, because I don't have those sample problems to guide me through and I depend on those a lot.

Interviewer: Do you put those on your notecard?

Deb: I do a little bit, but you can only do so many. I've been doing very well in [this course], which shocked me. But, I've been trying to do just equations now, and get myself to look and actually look at the equation
rather than where you put the numbers. And that's been working pretty good.

When asked what grade she expected to receive, she predicted that she would earn a B, but she could receive an A. She went further to describe her experiences in chemistry.

**Deb:** Depending on the final, I have a high B and depending on the final I could get an A, but I should stay in the B. I hope I did well on the final, it would be awesome. When I took chemistry in high school I maintained a C all year long and that was all. It's not an easy subject. **Interviewer:** What makes it hard for you?

**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. **Interviewer:** That's frustrating for instructors. You put together a lab that nicely illustrates what you are learning in the class and no one catches on.

**Deb:** But you don't really put the two together, it's separate. When I had lab in [chemistry for science majors], last term it was, it was separate. I think that was a hard thing that I wasn't putting them together. I could easily perform the labs, that's easy, if you do everything right it just does it. But when you do it on paper, you have to know what is happening in every single thing, and I didn't know that. You didn't see that, you just picked up table salt and put it in or whatever. I tend to take things apart and try to understand it that way and do what I did on the paper. I second guess myself. I do that on the tests, then I think too hard, I go in and study and study and study and then I panic and it's gone from there. I don't usually do too well on tests, but this term I've done excellent, which is shocking. Even to do things that are second nature to me, I don't do well on tests.

**Deb's Profile**

Deb demonstrated both computational and conceptual understanding of chemistry, but lacked confidence in her understanding. She had struggled in her previous studies of chemistry and so her lack of confidence was understandable.
In the Card Sort Task, Deb created a structure that had an overall organization and links between concepts, though she admitted to a limited understanding of enthalpy. Some of the connections were different from that of her instructor, but her description justified the connections in her own thinking. Both the card sort and Problem #5 showed that Deb had created links between the symbolic, microscopic, and macroscopic levels though she demonstrated some confusion concerning limiting reactant reactions.

Her description of difficulties with chemistry paralleled the descriptions of difficulties for many chemistry students. One area in which Deb seemed to have potential difficulties was in her focus on the equations and calculations of chemistry. Her experiences may have conditioned her for that focus, but she demonstrated an adequate conceptual understanding.

In the interview it became clear that Deb's greatest obstacle was her lack of confidence. Her first response in the interview was "I don't know what problem solving strategies I have, I just do it." Her lack of confidence surfaced as "second guessing." While solving several problems her first response was correct, but because she could not justify it in her mind she attempted to change her answer. She was aware of this problem and discussed it with the interviewer.

Essentially, Deb had the potential to be a strong chemistry student – demonstrating both conceptual and computational understanding. She also showed an eagerness to learn as she discussed her solution and the correct solution to Problem #5 with the interviewer.

**Ed's Interview**

Ed is a 19-year-old male Pre-Vet major with a minor in chemistry. He had taken chemistry and physics in high school, but this course was his first exposure to college chemistry. His high school math included only algebra, and he had taken pre-algebra, and two terms of college algebra in college.
Ed completed the Card Sort Task easily. He described his structure (see Appendix F) in a circular manner starting with the upper right-hand group and working his way around in a clockwise fashion. The first group of cards was related by the concept of the mole. The second group was made up of three subsets, in the first was the definition of a limiting reactant which served as the connecting concept. In the same subset were the algorithm for stoichiometric calculations (Card # 15) and an example equation that listed the ratios of reactants and products (Card #14). The second subset was connected to the first by an arrow labeled "examples of limiting reactants." This subset contained one generic problem (Card # 22) and two pictorial representations of limiting reactant reactions (Cards # 18 and 23). The third subset was a card that pictured a balanced equation (Card # 25) and was connected to the other subsets with an arrow labeled "not an example of a limited reactant." The third group was centered on the concept of molecular weight, with definitions and examples. The fourth group was a microscopic (Card #6) and macroscopic (Card #7) representation of the reaction between carbon and oxygen to form carbon dioxide. The fifth and final group was the enthalpy concept cards split into two columns, one exothermic and one endothermic, with similar concept representations across the columns. Overarching the columns was the generic reaction with enthalpy (Card #12). Ed's description outlined his thinking.

**Ed:** Here's [First group] a definition of a mole, and that's the number of atoms in a mole, that's what a mole would be. This one [Second group] is a limiting reaction definition, and then that's how you figure out what the limiting reactant is. And I put this one here because it is kind of the type of problem you could have. And then I went ahead and put a little arrow over here, it says "X grams of chemical A reacts with an excess of chemical B. How many grams of chemical C is produced?" And those are examples of what that would look like. And I put that this was not an example because all of it's used up in the reaction. And then this molecular weight one [Third group], molar mass, ... you use the molecular weight to figure out the molar mass. So there are the steps here. This one [Fourth group] is describing what the reaction is. This little thing here is how you describe the reaction, I guess, you have carbon and oxygen and CO₂ and shows a picture of what it is. This [Fifth group] I'm confused. I guess I need to
look at 'em again. These aren't the same, but they're kind of alike. If you added an O₂, it would be the same.

Ed's structure was well developed with connections within each group, but the connections between groups were not explicitly drawn or stated.

In the Balancing Task Ed had no difficulty balancing the two equations. His method was similar to that of his instructor and that seen by Yarroch (1985). When asked how many moles would be formed from a given amount of nitrogen and hydrogen he answered easily. Ed was asked about a reaction with specific volumes of the reactants, he answered that the volume of the products would be additive, one liter of nitrogen plus three liters of hydrogen would produce four liters of ammonia gas. When asked a probing question he responded, "You're saying one and three, which I think is a trick, because you have one and three. You could lose two liters, which I don't know about, you would if it was two, and I don't understand about losing, and maybe three, and maybe four." His initial answer was incorrect but was understandable since he had not studied Avogadro's Law of Combining Volumes. Ed understood that it could be two from the balanced equation, but could not find a way to justify that answer.

Ed was first asked to solve Problem #2 in the Problem-Solving Task. Ed was confused by this straightforward computational problem. "I'm confused with this one. This is one of those mole problems." With some leading from the interviewer he began to calculate the molecular weight of ethane but did it incorrectly, incorporating the coefficient into the calculation. At that point, Ed claimed to be at a dead end and the interviewer moved on.

The second problem was Problem #5. Ed began with a correct interpretation of the problem.

Ed: So, for every two Al's, you get six chlorines, you have an excess of the aluminum to start with, so there'll be some left. And, then, this other stuff I'm not quite sure what the relationship is, exactly the placement of the chlorine.
He then drew his solution but drew a bond/line connecting the excess aluminum atoms and on the first drawing did not break the bond between the chlorine molecules, even leaving one forming a bridge between the two aluminum atoms (see Figure 11). When asked a probing question, he admitted his confusion.

**Interviewer:** Now the equation says two AlCl3's and I noticed that you have two AlCl3's connected. Why wouldn't that be Al2Cl6?

**Ed:** [Pause.] It's all messed up.

**Interviewer:** Why's it all messed up?

**Ed:** Let's say you had two AlCl3. [Pause]. I guess this is saying if you had two Al's and three of the Cl2's and then it goes to see, two Al's, two Cl3's. [Redraws reactants with stoichiometric ratios.]

**Interviewer:** What's confusing you?

**Ed:** This [subscript.]

**Interviewer:** What does that subscript mean in the molecular formula?

**Ed:** Well, Cl₂ is two Cl's, and Cl₃ would be three, so AlCl₃ that would be Al and 3 Cl's but that two?

![Figure 11. Ed's answer to Problem #5](image)

It was clear from his drawing and the discussion with the interviewer that he was having difficulty understanding how the atoms would rearrange. This difficulty was surprising since he had no difficulty drawing the products for the ammonia reaction that dealt with similar rearrangements.
Problem #1 was the final problem asked of Ed and he had no difficulty answering correctly and giving a valid reason for his solution. He stated that there would be four chloride ions and supported his answer with the molecular formula.

When Ed was asked how he prepared for an exam, he was honest about not reading the textbook and went on to explain how he determined what was important.

Ed: I haven't read the textbook at all. So, I take in class, gosh, let me think. Like for the stuff you covered here, he explains directly what he wants on his test. For another teacher, I would have to study differently, of course. But he flat out tells us; you'll have a molarity problem and this, and this. So, I'll study those and probably a few other things that he might put on it that seemed to me he paid more attention to. The fact we have a notecard for the test helps, I see if I can get every possible little detail I can get on there from my notes. Let's see, I think if you had a different teacher though, it would be a lot harder, because he's a good teacher. He'll tell you what he wants exactly, so you study that. Instead of guessing what will be on there, we know what will be there for sure rather than there might be one of these and you might put it off or something.

He admitted that he felt the textbook did not help his understanding.

Ed believed that he had been earning an A for the course prior to the final, but felt that he may have done poorly on the final exam and expected to get a B for the course.

Ed's Profile

Based on his card sort structure, it could be assumed that Ed has a strong mental construct of stoichiometry, with different types of connections between the concepts. According to research studies (Bodner & Domin, 1996) those students who were able to draw more links between concepts were better problem solvers in chemistry. Yet, Ed was unable to solve simple computational problems. It was possible that Ed drew a "mental blank" and since he had just completed his final exams this reason was possible.

Ed showed that he did not have a clear understanding of how atoms and molecules rearrange in a chemical reaction. He easily drew a representation of the reaction between
nitrogen and hydrogen to form ammonia in the Drawing Task, but had a difficult time in Problem #5. Problem #5 required more thought since it was a more complicated situation, but Ed did not make the mistake of confusing the coefficients and subscripts in the Drawing Task as he did in Problem #5. His representation also showed that he was reluctant to break bonds in the chlorine to form the aluminum chloride. This result was similar to results found by Yarroch (1985) and Lythcott (1990) with high school students. Considering that Ed had previously taken high school chemistry, it could be assumed that he would have a better understanding of bonding.

Ed's card sort structure showed strong connections within the groups, including listing examples and non-examples, yet he did not explicitly discuss any overall structure. It was possible that the overall structure was there though not explicitly discussed.

Frank's Interview

Frank is a 21-year-old male mechanical engineering major. He had not taken a chemistry course before and was advised to enroll in this course rather than enrolling in chemistry for engineering majors. His previous science courses included biology, environmental science, calculus-based physics, a computational physics course, and an introductory astrophysics course. His math background included geometry, Algebra I and II, and trigonometry as well as one quarter of calculus.

Frank's structure for the Card Sort Task (see Appendix F) was made up of four groups of concepts. The first group was the enthalpy concept cards split into columns, one exothermic and one endothermic, with similar representations matched across the columns. The overarching concept was the generic reaction card with enthalpy (Card #12). The second group were definitions and numbers, such as Avogadro's Number, that he felt were important. These concepts were all related to the mole concept. The third group were cards dealing with stoichiometric calculations and the definition of a limiting
reactant. The fourth group were tied to the third group because they were all examples and representations of limiting reactant reactions in Frank's understanding.

**Frank:** This [First group] is called thermo and enthalpy from exothermic and endothermic reactions, is what that is. This [Second group] is all definitions of things, things that you need to know – terms and certain prerequisite numbers you'd need to know to move onto limiting reactions. [Third group] Limiting reaction, this is a picture, like a tangible diagram and this is a theoretical diagram. This is in words what it's saying and this is in numbers what it's saying. And this [Fourth group] is a general theorem of how it works. And this is a descriptive of a specific instance and then this would be an example of a specific instance. And if this is what this is, this would also be an example of a specific instance. This, I don't see a silicon anywhere, so I'm not able to pick up where this fits in. Whereas this has chlorines and this has fluorine, I don't see any silicon that I recognize. So, this one's kind of . . . .

It was interesting to see that Frank put representations of balanced equations with the limiting reactant representations. He also placed the card showing calculation of the mass of silicon in 224 grams of silicon tetrachloride (Card #21) with the limiting reactants. His remarks showed that he was looking for superficial connections between cards, such as the presence of the same elements.

Frank used a different method from the others to balance the equations. He first drew a representation of the reactants and products (see Figure 12) in the reaction. He then used this picture to help him determine the coefficients. He correctly described the

![Figure 12. Frank's balancing technique](image-url)
process as analogous to finding the least common denominator. Frank balanced the ammonia equation, but made a minor error by leaving the equation as $2 \text{N}_2 + 6 \text{H}_2 \rightarrow 4 \text{NH}_3$ which was not in the lowest terms.

Frank ran into a problem with the potassium equation due to a copying error. When rewriting the unbalanced equation he mistakenly added an oxygen atom to the hydrogen molecule, thus changing $\text{H}_2$ to $\text{H}_2\text{O}$. This made the equation impossible to balance. The interviewer pointed out the error and the equation was then correctly balanced.

**Frank:** The first thing that I'm going to try and figure out is how many atoms there are in the entire thing, so I know what kind of numbers I'm working with. [Pause.] I guess at this point since I can't remember an exact formula for doing it, I just go through and pick random numbers and see if they work for me. [Pause.] I remember there is something to do with fractions that you take fractions to it. So, now I am trying to remember how to do that. [Pause]. So, what I know already is that, because there is only one oxygen on both sides and only one K on both sides and I have multiple hydrogens. I have to make, I've got to increase the numbers so if I do increase the numbers I'm going to have multiple outputs and I have to balance that. [Long pause. Student is adding more and more potassium atoms and water molecules.] I know it has to do with fractions, and I've tried several experiments, plugging numbers in, but I haven't been able to get it yet.

**Interviewer:** Actually, I wasn't sure if I should stop you then or not. You did balance it correctly, but for some reason you put an O here [on the $\text{H}_2$].

**Frank:** Oh yeah, I was looking at that earlier.

**Interviewer:** Because it was balanced.

**Frank:** When I threw that O in the back, I started over again. So, I did it the first try, the first time out of the chutes.

Frank's comment on not remembering an exact formula was interesting since there was no exact formula for him to remember, but an algorithm seen in class. Since Frank had drawn representations of the equations in balancing them, he was not asked to do the Drawing Task.
Frank was asked to determine how many moles of ammonia would be produced when two moles of nitrogen and six moles of hydrogen reacted. His initial answer was to add the number of moles.

**Frank:** Eight, . . . it wouldn't be eight, I'd need to convert to grams per mole.

**Interviewer:** Why would you need to convert it to grams per mole?

**Frank:** Oh, . . . I'm thinking of a limiting reaction, I think. Four.

**Interviewer:** Why is it four?

**Frank:** Because that's the coefficient of um . . . since I had forgotten exactly what these were, immediately I saw that they were both exactly that. And the coefficient of this is four, so if this were in fact moles then that would be the answer.

He resorted to the gram-to-mole conversion, but after a leading question, changed to the correct answer. It appeared from the conversation that he was using logic and not chemistry to arrive at the correct answer. He used logic and some chemical knowledge to answer a question involving volumes in liters.

**Interviewer:** What if I gave you two liters of nitrogen and six liters of hydrogen, how many liters of ammonia do you think would be made?

**Frank:** Four.

**Interviewer:** Why do you think four?

**Frank:** [Pause.] Four doesn't have anything to do with their weight, it doesn't have anything to do with what they look like, but it does have to do with, it is correlated with the amount and so it basically says there are four of this whole product floating around in different places.

When asked the same question involving grams, he correctly stated that he would need to convert grams to moles, but relied on logic to predict an incorrect answer.

**Frank:** What I would have done was converted the grams to moles for both nitrogen and hydrogen and then done the same for ammonia and . . . it kind of left out these coefficient numbers, but I have a feeling the answer is probably four.

The first problem in the Problem-Solving Task was Problem #2. Frank began the problem correctly by determining the number of moles of ethane, but he inexplicably
multiplied the molecular weight of diatomic oxygen by the number of moles of ethane, assuming this gave him the number of moles of oxygen.

The second problem was Problem #5. Frank began by drawing a representation of the products based on the balanced equation. After he was asked to explain his answer he drew a correct representation of the product mixture (see Figure 13).

Frank: Well, when I look at this, the picture itself, I don't... see in the picture there's six blocks, but in the equation for the reaction, there's two. So, this is based on my picture for the equation, but if I were to take it off here [problem diagram]. [Drew second picture.] So, if I used that picture this is what I get. And if I use this equation right here I get this thing. Does that make sense?

Figure 13. Frank's answer to Problem #5

The next problem was Problem #1, a conceptual problem. Frank's answer of two may have come from confusing two chloride ions with one chlorine molecule. When the interviewer asked him to explain his response, Frank sought a computational solution.

Frank: Two.
Interviewer: What makes you say two?
Frank: Well, I see where it's wrong. [Grabs a calculator.] Well, the way I see starting out is there is two moles of this entire compound. And I see two pieces. I get one magnesium and two chlorines. And so it's two-thirds chlorine. And if I did so then the chlorine would equal 1.3 moles. Because it isn't giving me any grams ratios. However, I guess a more accurate way is to say I had two moles was to convert this compound into grams, and
that would be [calculated]. [Pause]. And then I'll divide out, so and then I know the grams per mole for the chlorine will be 70.9. And so that compound times two, 141.8 and then [Pause]. OK, I get about the same answer, I get 1.342. So, I guess that's the way I check my answer. I submit that's right.

The method used by Frank showed similarities to the algorithm for determining mass percents of a chemical formula and he used the coincidental similarity between the two answers to justify his methods.

The final problem was Problem #3. Frank was able to answer this question in more depth than the other students were.

**Frank:** Well, we know what the molar ratio is because the one's that don't have anything we can assume to be one. So we know what the molar ratio is. We know what to expect out of the reaction, how much carbon chlorinate, carbon tetrachlorinate.

**Interviewer:** It's carbon tetrachloride.

**Frank:** H₂ and the molar ratios. We'd know if you wanted to make so much of each product how much to put in. Micro basis, for macro we'd have big amounts, but we'd have the ratios so it wouldn't be that critical. We could also find out what the limiting reactant would, which runs out first. Which in this case I think it's, since it's balanced, it's gonna be the second one.

Frank was confused about what a balanced equation would tell him about the limiting reactant since a balanced equation does not contain that information, but otherwise showed a good understanding.

When asked about how he determined what was important, Frank mentioned his use of the software tutorial.

**Frank:** In general, I follow ChemSkill Builder, because this is the first time I've ever used the disks for any kind of class before, so it's kind of a new deal, but for me it was a lot easier. In some ways it was easy because it was interactive and it told me right away whether I was right or I was wrong. Whereas problems in the book, sometimes, if it's an even problem, you won't find out unless you have the solution manual, which I actually do. Whereas if I hadn't had ChemSkill Builder, I would have read the book more often. As a result, I didn't read the book very much; I did the ChemSkill Builder quite a bit. And then of course the exams I just studied practice exams to get what I expected to be on the exam.
Frank also compared his instructor to other instructors.

**Frank:** For some of my other professor's it's not so easy. For some of my professors it's been more difficult to figure out what they really want, because they throw out a lot of information and they don't accentuate very much of it. While it seems with [Instructor] it seemed that when someone asked a question that was far ahead of the class, he didn't go that far. He would keep it, "Remember this, remember this." Accentuated to the point that he would write it across the board in huge letters. He made it really simple to know what to use and what not to use. But, I think it was a lot easier having the practice exams, because I got the practice exam a few weeks before the final and so I know that's the stuff to learn and you know there's other stuff. But it seemed like he didn't teach us stuff that wasn't going to be on the exam. It wasn't like this course we worked a lot of extra material. I didn't always take notes, but there were times when I took lots of notes and that was when we had things like quantum numbers. Where it seemed . . . he said, "You better take notes because it's going to be more complicated."

Frank believed that he would earn a B in this course, though he had an opportunity for an A; his final grade depended on his performance on the final.

**Frank's Profile**

With his background in engineering and his math background it could be expected that Frank would have a strong computational understanding, but he did not demonstrate it. He was unable to solve the computational problem, Problem #2, that he was given. It was interesting that Frank attempted to solve the conceptual problem, Problem #1, by computations. He attempted to convert grams to moles though the problem was given in moles. Frank also seemed unaware that his method was not based on a chemical principle. This was surprising given his responses on other problems and in the Balancing Task.

When balancing the first equation, Frank drew a pictorial representation of the equation and used that to assist him in balancing the equation. Frank had no problems with Problem #5 where he was asked to draw a picture of the product mixture. His solution method included an extra drawing used to make sense of the balanced equation.
He also mentioned in the interview that he used pictures to assist him with many problems. It appeared from the preceding tasks and from his card sort structure, that Frank found other means of representing the problem, essentially creating another view. Though he was a mechanical engineering major, he might be classified as Tobias' (1990) "second-tier student."

In his description of how he determined what to study, he emphasized his use of the software tutorial and class lectures for learning the concepts. He especially emphasized the immediate feedback from the tutorial when compared with textbook problems. He admitted to rarely utilizing the textbook. He also relied on the sample exams that were available on the course web site, often getting them several weeks in advance so he could use the tests as an outline of what was important in class lectures.

Comparison of Students

In the following section, all six students are compared to highlight similarities and differences.

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, with Cara taking a general physical science course, and Deb, Ed, and Frank taking physics. Only Frank had taken math courses beyond college algebra. Since each student had a unique background prior to enrolling in this course, no patterns appeared significant.
Card Sort

The card sort structures constructed by the students showed some interesting similarities and differences. 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, with four of the six making a grouping similar to Figure 14. 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 structure (see Figure 4). 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

![Figure 14. Students' enthalpy card structure](image-url)
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 $\Delta H$ symbol. Anna's structure
demonstrated this trend differently than the others as the three cards with prominent $\Delta H$
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 was structured 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. 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 the 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

Yarroch (1985) and Lythcott (1990) used the task of balancing simple chemical equations with high school students and all of their subjects were able to balance the chemical equations correctly. 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, H₂, and nitrogen, N₂. 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.

**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 (see Figure 11). 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 6). Cara's drawing (see Figure 7) further showed her
misunderstanding of the 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; 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, MgCl₂, 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. Cara was not asked Problem #3 because she was confused and grew frustrated by the questions asked earlier. Her earlier responses were coded along with the other students' solutions. 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 her failure to answer the question.

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 (see Figure 8). 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. Their drawings were incorrect because the chlorine-chlorine bonds were not replaced with aluminum-chloride bonds (see Figures 10 and 11). Their solutions were coded as Mixed, Confused for mixed 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 results from the interviews are highlighted in Table 2.
Table 2: Interview Results

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

@ Initial attempt partially correct
*Problem was not asked, earlier answers were coded
#Minor labeled answers include partially correct answers with minor errors.
%M 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.

The resources available for the course were the textbook (Hill & Petrucci, 1996) and the software tutorial (Spain & Peters, 1997). 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. Both Frank and Beth mentioned being unable to remember the equation for balancing chemical equations, though it was assumed that they were referring to an algorithm. Both students appeared to follow an algorithm similar to that seen by Yarroch (1985) (see Figure 3) and taught by their instructor. Both 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. Cara said that Dr. Dalton was different than any other instructor and that she was able to understand what he did though she had a hard time retaining the information. 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. Frank mentioned that the instructor would explicitly tell students what to include in their notes. Beth discussed the technique of keying on what the instructor mentioned several times as a means of picking up the important points. Ed pointed out that they were told what would be on the exams, so expectations were clear. Several of the students brought up the practice exams that were provided on the course web page as beneficial exam preparation tools.

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.

Nakhleh's Scheme

Nakhleh (1993) devised a scheme (see Figure 2, page 19) for categorizing chemistry students based on their ability to solve conceptual and algorithmic/computational problems. The dichotomous division of Nakhleh's scheme placed students into one of four categories – High Algorithmic/High Conceptual (A1C1), High Algorithmic/Low Conceptual (A1C0), Low Algorithmic/High Conceptual (A0C1), and Low Algorithmic/Low Conceptual (A0C0).
The students from this study were classified using this scheme (see Figure 15). Beth and Deb were classified as A1C1, Frank as A0C1, and Anna, Cara, and Ed were classified as A0C0. Placing students based on this high/low scheme was difficult because it was apparent from watching the students solve problems that there was no clear delineation between high and low ability, but rather a continuum. For example, Frank's clear card sort structure showed conceptual understanding despite his difficulties in solving Problem #1 and misunderstanding seen in Problem #3. It was also clear that Ed's conceptual understanding was better than that of Anna or Cara, though he was classified in the same group.

<table>
<thead>
<tr>
<th>Conceptual Thinking</th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithmic Problem</td>
<td>High</td>
<td>(A1C1)</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>(A0C1)</td>
</tr>
<tr>
<td>Solving</td>
<td></td>
<td>Frank</td>
</tr>
</tbody>
</table>

Figure 15. Possible categorization of students in study.

The intent of Nakhleh's (1993) scheme was to help identify students, especially "second-tier" students (Tobias, 1990), so that instruction could be adapted to assist them. This study showed that individual students learn differently and even students who perform similarly, such as Beth and Deb or Anna and Cara, are different in many significant ways. It was interesting to note that in this study no students fit into the A1C0 category where the majority of students in other studies (Lin et al., 1996; Mason et al., 1997; Nakhleh, 1993; Nakhleh & Mitchell, 1993) were found.
Discussion

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.

The results from Problem #5 showed a limitation of the students' understandings. Beth was the only student who was able to answer the question without difficulty, while Frank correctly solved the problem after devising a new representation. The other four students were confused by the problem and had difficulty answering the problem. The difficulties took two forms: 1) inability to reconcile the stoichiometric coefficients from the balanced equation with the representation of the reactant mixture; and 2) uncertainty concerning how three diatomic chlorine molecules could "split" to react with two aluminum atoms and form two aluminum chloride, AlCl₃, molecules. The reasons for the first difficulty could be due to several conditions, the most likely of which was a superficial understanding of the significance and meaning of a balanced equation. Several of the students questioned the interviewer about the coefficients and subscripts, implying that the
coefficients should match the numbers of chlorine molecules and aluminum atoms represented. Deb suggested that the excess aluminum atoms should be represented in the equations as Al₂. They appeared to not understand that the balanced equation represented the ratios among atoms and molecules that reacted. Ed and Cara also demonstrated incorrect conceptions of the subscripts in chemical formulas, several times seeming to ignore the subscripts in diatomic molecules. 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. Other possible reasons for the students' difficulties included a continuous view of the nature of matter, and difficulty understanding the problem. Novick and Nussbaum (1981) and Nakhleh and Samarapungavan (1999) found that some of the students, even college students in the earlier study, held a continuous view of matter rather than the scientifically accepted particulate view. 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. Niaz (1989) and Niaz and Robinson (1992b) have examined the number of factors, or M-demand, that must be accounted for in the solving of chemical problems and their effects on students success. Based upon discussions during the interviews, the previous two explanations were supported, and the latter two were not. 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. These results were similar to those of Carter (1987; cited in Bodner, 1991; Herron, 1990, 1996) where the views of the nature of chemistry of the subjects were indicators of their problem-solving success.

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 et al., 1987; Gabel et al., 1984; Lin, 1998; Lythcott, 1990; Mason, 1995; Mason et al., 1997; Nakhleh et al., 1996; Niaz, 1995c, 1998a; Phelps, 1996) including the statistical significance found by Niaz (1995c).

An intriguing result from the Card Sort Task was the overall organization seen in four of the six structures. Those structures used the solving of limiting reactant problems as an organizing principle, with the structure viewed as analogous to an algorithm for solving a computational limiting reactant problem. The students organized each similar group of concepts into an overall structure that outlined the steps necessary to solve a limiting reactant problem. Two possible reasons for this trend were: 1) solving limiting reactant problems required the application of most of the stoichiometry concepts; and 2) Dr. Dalton referred to limiting reactant problems as the most difficult that they would see in the course. To correctly solve a computational limiting reactant problem would require a balanced equation, the calculation of the number of moles of all reactants present, and calculation of the amounts of each reactant needed to react completely with the other reactants. The final step would be to identify the limiting reactant and calculate the amount of product that could be formed. These steps would thus require most of the
algorithms and concepts learned previously. The other reason was similar to the first, as Dr. Dalton often referred to limiting reactant problems as the most difficult problem seen in the course, probably for reasons discussed. Being that solving a limiting reactant problem would require an organized algorithm or conceptual approach both factors could lead to limiting reactants as an organizing principle. Beth's description of her structure illustrated this trend.

**Beth:** The limiting reagent [Third group] those kind of all go with that I think. To do limiting reagents you have to have the equation – moles to gram and back again. I think that these are all kind of examples of limiting reactant. And then [Second group], you can find the molecular weight of some molecule by the sum of the masses of the atoms that make up the molecule. And these [First group] figure out like the moles and how many atoms per mole and how many moles because the molar mass is how many grams per mole. That's why I grouped all these together.

As mentioned previously, few of the students made connections between the microscopic, macroscopic, and symbolic levels of chemistry. This lack of connections was evident in most of the card sort structures, as the students did not articulate ties that incorporated these levels. Frank was the only student who explicitly mentioned connections between the levels, though the cards contained representations from all three levels.

**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 the students' 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. Cara and Deb showed a lack of confidence in their chemistry ability and had taken chemistry previously. They had performed poorly in their prior courses, thus creating a feeling of inadequacy. 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. This lack of confidence was also seen as the students asked the interviewer for feedback on their processes and solutions. Cara's frustration with the card sort may also have been due to lack of confidence. 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. "I may not have shown it here, but I expect to get an A." A lack of confidence was also seen when students correctly solved a problem and made a comment similar to, "That was too easy." The comments seemed to imply that if they answered that easily then they must have made a mistake. 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. It was possible that there was a greater effect, but that could not be discerned in this study. 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. Frank mentioned that he would have used the textbook more with another instructor, implying that he had used the textbook somewhat. 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. Several students said that Dr. Dalton's lectures gave them enough knowledge to succeed on the exams, so they did not need to read the text, but those who had read it had a deeper conceptual knowledge and more success in the interview. This trend might also tie to Dr. Dalton's comments about students spending the proper amount of time making sense of the concepts.

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. Beth and Deb mentioned relying on the notecards, but only as an aid to memory. By overreliance on the notecards, some of the students subverted the purpose of the notecards. Notecards and "crib sheets" have many positive features and benefits (Perrin, 1997) but in this study it was seen that
like most learning aids, they could be misused. It was possible that the reliance on and misuse of the notecards could be tied to the confidence factor discussed previously.

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.

The organizational principle for most of the students' card sort structures was analogous to an algorithm for solving limiting reactant problems. This organizational principle reflected the course instruction on stoichiometry. 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. The focus in the tutorial and on the exams has already been discussed, but these added to the computational focus. 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.
CHAPTER 5: DISCUSSION AND CONCLUSIONS

Introduction

This study examined possible factors influencing general chemistry students' understanding of chemistry as seen in their views of the nature of matter and their abilities to solve stoichiometry problems. The factors examined included the instructor, course instruction, resources used by the students, and the students' backgrounds. Another area of investigation was the effect the students' conceptual knowledge had on their computational problem-solving abilities.

The research questions for this study 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?

The students' understandings of the nature of matter were generally acceptable, as all showed some level of understanding of the accepted particulate view of matter. There were three responses to the molecular-level limiting reactant problem (Problem #5) that could indicate a continuous view of the nature of matter, but the same students showed a particulate view in the Drawing Task. The results showed that many of the students had a superficial understanding of balanced equations and the meanings those equations hold for chemists and other scientists. Most of the students showed confusion concerning the difference in meaning between the coefficients and subscripts in balanced equations and chemical formulas similar to the results found in other research (BouJaoude & Bakarat, 1999; Lythcott, 1991; Smith & Metz, 1996; Yarroch, 1985). Some of the students also demonstrated a shallow understanding of the broader meaning of a balanced equation as a symbolic representation of the rearrangement of atoms in a chemical reaction. The
students showed weak understanding of ties between microscopic, macroscopic, and symbolic levels of chemistry, and the ways that the three levels can be used to explain, predict, or communicate chemical behaviors at other levels. Ben-Zvi et al. (1986) and Boo (1998) also saw difficulties in students' ability to make connections between macroscopic and microscopic levels.

The students' perceptions of chemical reactions varied with their conceptual understanding. The students were able to draw representations of simple reactions used in the Balancing Task, and all but one of the drawings were correct or had a minor error. The drawings reflected a particulate view of matter with separate molecules. Based solely on the Balancing Task the students appeared to have understandings of the nature of matter that matched with current scientific understandings, namely that matter is made up of particles called atoms that can combine to form larger particles called molecules. Other studies (Ahtee & Varjola, 1998; Boo, 1998; Lythcott, 1991; Nakhleh, 1993; Novick & Nussbaum, 1981; Nurrenbern & Pickering, 1987; Sawrey, 1990; Yarroch, 1985) have found that students could give a balanced equation or solve stoichiometric problems but showed a lack of understanding of interactions at the molecular level.

The students' solutions to Problem #5, a conceptual problem asking for a drawn solution (see Appendix D), showed that though the students understood the particulate nature of matter, they still remained unsure of the rearrangement of atoms in chemical reactions and of the connections between symbolic representations and the representations of atoms and molecules in an equation. The students became confused and concerned because the numbers of reactants in the reactant drawing did not match with the stoichiometric coefficients in the balanced equation. Several students also had difficulty because they were uncertain how chlorine molecules, Cl₂, could react with aluminum atoms to form AlCl₃. The students seemed unwilling to break chlorine-chlorine bonds to form chlorine-aluminum bonds, though they did not show similar unwillingness in the
Drawing Task. Yarroch (1985) and Lythcott (1990) saw similar misunderstandings in their subjects as were seen in Problem #5.

The students' abilities to solve conceptual and computational stoichiometry problems and their conceptual structure of stoichiometry were found to be related in several ways. The card sort structures created by the students were good indicators of both their problem-solving abilities and their conceptual understandings. The students' conceptual understandings were a good indicator of their ability to solve computational problems in stoichiometry. Niaz (1995a) saw similar connections between conceptual and computational success, as those with stronger conceptual understanding did better on computational problems. Four of the students showed the same organizing principle in creating their card sort structures by using an algorithm for solving a computational limiting reactant problem as the organizing principle. The card sort structures also showed that five of the students did not make strong connections between microscopic, macroscopic, and symbolic levels of chemistry.

Many factors were examined for possible effects on students' conceptual understandings. Previous science and math backgrounds of the students were examined and found to have no discernible correlation with the students' problem solving. Lack of confidence in chemistry ability and perception of the difficulty of chemistry appeared to be factors in the conceptual structures of all of the students. The software tutorial, ChemSkill Builder (Spain & Peters, 1997), appeared to have a positive effect as a means for encouraging problem-solving practice, but the tutorial may have encouraged a computational focus in stoichiometry because there were few, if any, conceptual problems to solve. The textbook, General Chemistry (Hill & Petrucci, 1996), also may have encouraged a computational focus because of the lack of conceptual problems beyond the comprehension level. The textbook also used few illustrations of particulate matter when discussing stoichiometry. This finding is similar to that of DeBerg (1989) who examined the discussion of gas laws in textbooks. Though chemistry concepts were introduced and
discussed, instruction in the course focused on the computational aspect of stoichiometry by emphasizing the calculations necessary to solve computational problems. The instructor's stress on computational limiting reagent problems as the most difficult problems encountered in the course may have encouraged the students' focus on computations. The computational emphasis of the course exams appeared to play a major part in the students' computational focus as was also seen by BouJaoude and Bakarat (1999).

Interpretation and Discussion

The six volunteer students interviewed for this study provided a variety of views and data concerning general chemistry and their understanding of stoichiometry. The ties between their conceptual, computational, and symbolic understandings of chemistry were enlightening and provided clues to their perceptions of chemistry and the factors that affected their learning.

Previous research (Ben-Zvi et al., 1986; Novick & Nussbaum, 1981; see Nakhleh, 1992) found that some college and high school chemistry students held a continuous view of matter, but none of the subjects of this study demonstrated a continuous view in the Drawing Task. Though some of the misunderstandings shown in the solutions of Problem #5 may have suggested a continuous view of matter, the discussion throughout the interviews negated this possible interpretation. The results in this study may have differed because the topics covered in the previous studies were the microscopic behavior of gases (Novick & Nussbaum, 1981) and the macroscopic properties of copper (Ben-Zvi et al., 1986), thus examining students' understandings from a different point of view. In this study, the focus on stoichiometry may have prompted the students to answer in a particulate manner. All students, except Beth, struggled with Problem #5 and only Beth and Frank had correct solutions to the problem. The major issue appeared to be that the students had difficulty thinking of a limiting reactant problem in molecular terms. Other
causes of difficulties were: 1) superficial understanding of the meaning of balanced
equations; 2) vague understanding of limiting reactant situations; 3) inefficient ability to tie
macroscopic, microscopic, and symbolic levels together; and 4) weak understanding of
atomic rearrangement in reactions. Weak understandings of atomic rearrangement in
reactions were also found in previous research both in general reactions (Lythcott, 1991;
Yarroch, 1985) and in solution (Smith & Metz, 1996). Since few limiting reactant
problems in the text and no problems in the tutorial or exams were posed at the molecular
level it was not surprising to see their difficulties. Dr. Dalton did discuss limiting reactants
at the molecular level in the course lectures, for example during his demonstration of the
acetylene cannon, but he did not hold the students accountable for understanding at that
level.

The Card Sort Task was devised to gather information on the students' personal
constructions of stoichiometry, and the task worked well for this purpose. The card sort
structures offered insight into how the students viewed stoichiometry and chemistry.
Several trends were seen in the data: 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 stoichiometry
problems; and, 4) few of the students showed strong connections between microscopic,
macroscopic, and symbolic levels in chemistry. The two successful students in the
Problem-Solving Task, Beth and Deb, had structures with explicit structures, while the
structures built by Ed and Frank had an overall structure, but they were not explicit in
describing the structures. Ed and Frank were also less successful in solving problems.
Anna and Cara, whose structures lacked coherence, had little success solving problems. It
appeared the greater the conceptual knowledge of the student the better the performance
on computational problems. Prior research on problem solving in chemistry (Anamuah-
Mensah, 1986; Anamuah-Mensah et al., 1987; Gabel et al., 1984; Lin, 1998; Lythcott, 1990; Mason, 1995; Mason et al., 1997; Nakhleh et al., 1996; Niaz, 1995c, 1998a; Phelps, 1996) supports this finding though most examined how conceptual knowledge was applied.

Four of the students' Card Sort structures had similar overall structures; they each used the solution of a computational limiting reagent problem as an organizing structure. Each of the students grouped cards representing the individual steps together and had an overall structure following the algorithm for solving a limiting reagent problem. Two possible reasons for this trend were: 1) solving limiting reactant problems requires application of most of the stoichiometry concepts; and 2) Dr. Dalton emphasized that limiting reactant problems were the most difficult problems that would be seen in the course, so students had developed a general limiting reactant algorithm that was used to organize the concepts on the cards.

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. In many ways, this assumption was correct, since 80% of their course grade was determined by their performances on the exams, and many students view the final grade as a measure of their success. 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, 1998a). 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. He succeeded
in many ways as all of the students expected to receive a grade of B or better for the
course. 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. Beth and Deb demonstrated
more engagement because they read the text and studied more closely those concepts of
which they were unsure. They demonstrated active participation that went beyond
learning what would be on the exam. The other students did not utilize the course
textbook and showed a lack of depth in their chemistry understanding. It is unclear from
the results of this study if the lack of textbook use was a cause of lack of depth of
understanding or a symptom of lack of commitment on part of the students. Though all of
the students showed belief that they were meeting the objectives of the course, Dr.
Dalton's interview showed higher expectations than most of the students met and those
expectations may not have been expressed to the students. 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 reasons why the 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). The use of algorithms is essentially an empty framework. Friedel et al. (1990) found that the framework given to students to aid in problem solving, in this case the Factor-Label Method, became algorithms applied without understanding. 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).

Herron (1996) adapted the work of Zipf (1949) to propose a principle he called the Principle of Least Cognitive Effort. This principle suggests that when students face a cognitive decision, the choice is made that requires the least cognitive effort over a lifetime. Many of the limited conceptual frameworks seen in the subjects of this study could be useful in the lifetime of the student because the subjects may never encounter a situation where a more scientific concept would be needed. Chemical educators need to 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, 1995b, 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.
The students felt that from the clear expectations 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. The students' perceptions of course expectations were made clear in the interviews; Deb talked of focusing on equations and worked out problems while Ed and others spoke of filling their notecards with as many equations and worked out problems as would fit. 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. Educators should expect students to feel they can determine what is necessary to succeed and what is not based on their 12 or more years of education.

Nakhleh et al. (1996) and Phelps (1996) found resistance to implemented innovations that included conceptual questions and discussions in lectures as well as conceptual questions on exams, but students adjusted, in part because of the extrinsic motivation of grades. 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.

All of the students in this study showed reliance on algorithms to solve problems, both conceptual and computational. Algorithms are intended to be used in solving
computational problems, essentially to provide a step-by-step method for determining a solution. Some chemical educators (Kean & Middlecamp, 1994; Kean et al., 1988; Middlecamp & Kean, 1987; Schrader, 1987; see Lagowski, 1987) have advocated the use of algorithms to reduce the algebraic difficulties experienced in computational problem solving. What was seen in this study and in Nakhleh and Mitchell (1993) was an attempt by all students to use an algorithm to solve a conceptual problem where it was not appropriate. In many of the conceptual problems the students began their solution by determining the molecular weight of the compounds involved and then attempting a gram-to-mole conversion. They did not examine the problem to check if the step was appropriate or useful. Even Beth, who was meticulous in setting up calculations prior to attempting a solution, performed the unnecessary calculations. These unnecessary and often misleading steps seemed to indicate an algorithmic dependence in the students and a perception that all stoichiometry problems could be solved through the application of the "Mole City" algorithm taught by Dr. Dalton and discussed in the textbook (Hill & Petrucci, 1996). Nakhleh and Mitchell attributed this phenomenon to the students' lack of trust in their conceptual understandings.

Application of algorithms in computational problems is expected and sometimes encouraged (Kean & Middlecamp, 1994), but it is also expected that algorithms be applied with conceptual understanding. Researchers have devised several labels for students that apply algorithms without applying conceptual understanding. The students that display this behavior have been labeled as rule learners (Herron & Greenbowe, 1986), or algorithmic learners (Nakhleh, 1993; Nakhleh & Mitchell, 1993), and the problem-solving methods as
algorithms without understanding (Gabel et al., 1984), the Rolodex Method (Bunce et al., 1991), or the Formula Approach (Anamuah-Mensah, 1986).

Limitations of the Study

Several limitations were present that affected the findings of the study. The limitations included analysis of the data, the subjects of the study, and the methods utilized in gathering of the data.

The primary limitation of the study was the researcher. The researcher conducted all data collection and analysis, and so the background and experience of the researcher may have led to unintentional bias in the collection and analysis of data.

Precautions were taken to minimize any introduced bias. The instructor interview took place following instruction on stoichiometry to avoid the problem of looking for evidence of the instructor's teaching philosophy in his instruction while missing other important data, or the opposite bias of finding evidence supporting his philosophy that may not have been evident prior to discussion of philosophy. Three chemical educators and two science educators validated all problems and cards used in the interviews prior to the interview. All materials required at least 80% agreement of the committee before they could be incorporated into the study. Problems and cards were examined for clarity, importance of the subject, and intellectual level of the problems. Analysis of the student interviews did not take place until after all interviews were completed to prevent introduction of bias in the subsequent interviews.

A further limitation was the number of subjects interviewed for the study. The sample size was acceptable for the research method and design of individual case studies,
but the six volunteer students can not be assumed to be a representative sample of the 196 students enrolled in the course studied. The subjects were not representative because no purposive sampling was employed to gather the sample and it is possible that the volunteers were different in some way than the remainder of the students. Extrapolation to all introductory chemistry students is not justified. The students utilized in this study were a diverse group having different majors, backgrounds, and interests. Others can base their judgement on the usefulness of the findings by comparing these students to a population of interest.

A related limitation was the focus on one course and one instructor. Focusing on one course allowed the researcher to gather a broader set of data then could have been gathered from a less focused study, but generalizability to other courses is limited. The choice of using an off-sequence, or trailer section of the course may have also affected the data. The trailer course contained students, like Cara and Deb, who had previously enrolled in a chemistry course but had not successfully completed those courses in the preceding quarter. Determining the number of students who fell into this category was not a factor in the results, as each student was studied as an individual.

Relying on the instruction and instructional philosophy of one instructor for data was a further limitation in this study, though studies focusing on one instructor are common and have added much to the field of education (Borg & Gall, 1989; LeCompte & Preissle, 1993). Dr. Dalton was selected for several reasons; the most important of which was his experience teaching general chemistry courses. His interest in education and teaching also made him an excellent subject. His M.S. in Science Education spoke for his
interest and commitment to instruction. The findings from a course taught by someone who had little interest in education would be less applicable to other chemical educators.

The think-aloud protocol asks subjects to inform the interviewer of their thoughts as a means of investigating their problem-solving methods. As could be anticipated, there were varying levels of verbal sharing among the students while problem solving. Despite prompting, some of the subjects shared little information while solving problems, but were willing to discuss their methods after completing a problem. This slight deviation raises the question of the accuracy of their discussion of thought processes. The interviewer asked more probing questions of these students and used written solutions to stimulate recall with some subjects. The think-aloud protocol had been used successfully in several other studies of chemical problem-solving (Anamuah-Mensah, 1986; Bunce et al., 1991; Gabel et al., 1984; Herron & Greenbowe, 1986; Lin, 1998; Lythcott, 1990; Mason, 1995; Mason et al., 1997; Nakhleh & Mitchell, 1993; Yarroch, 1985), and with the added modifications worked well in this study.

The Card Sort Task was also a possible limitation because presumably most of the subjects had not displayed their understanding in that way before. Based on the transcriptions of the interviews, Cara was the only student to have major difficulties with the task. Anna expressed some confusion with microscopic concepts, but she completed a structure that she was able to discuss. The rest of the subjects expressed no concerns with the task and completed enlightening structures.

The study took place during a limited time to focus on factors that could affect students' understanding of stoichiometry. This limiting of focus was done to limit the effect of outside factors and to examine a fundamental aspect of chemistry. The limited
focus was also a limitation as the students did not have the opportunity to apply their stoichiometry understandings to other concepts in the course and so did not have the opportunity to test the usefulness of their conceptual framework. Examining the students' understandings after a complete sequence of chemistry courses may have led to a different understanding of their learning and the factors affecting learning.

By focusing on stoichiometry the study was able to examine a narrow but vital part of chemistry (Bunce & Gabel, 1994). This tight focus limited the topics examined and the findings might have been quite different for another chemistry topic, but research by others (Anamuah-Mensah, 1986; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990) suggests that a different result for another topic would not be the case. Given the fundamental character of the understanding of the nature of matter and stoichiometry, it could be argued that the findings would be more pronounced with an aspect of chemistry, such as kinetics or equilibrium that build on stoichiometry.

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. For example, Shusterman and Shusterman (1997) outline several applications of computer-generated electron density models for helping students understand bonding, atomic size, and physical properties. Noh and Scharmann (1997) emphasized microscopic representations of matter in instruction to strengthen conceptual understanding. Chemical educators should emphasize the use of models of matter with ties to the behaviors that they explain, while addressing their limitations.

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 ties between concepts and levels help students
solve problems that go beyond what they have experienced previously and so build reflective judgement (King & Kitchener, 1994). 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. The ties should be part of classroom instruction and resources such as textbooks and tutorials. Emphasis on the uses and meanings of balanced equations could strengthen the limited understanding seen in the majority of the students in this study. Methods suggested by Nakhleh et al. (1996) and Towns and Grant (1997) show promise by allowing guided discussion among students of the important concepts of chemistry.

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.

Students' understandings of the nature of matter often are not consistent with a chemical view of matter (Ben-Zvi et al., 1986; Gabel, 1993; Gabel et al., 1987; Lee, 1999; Novick & Nussbaum, 1981) and those misunderstandings interfere with their ability to understand chemical reactions (Ahtee & Varijola, 1998; Andersson, 1986; Boo, 1998; Gabel, 1993; Lee, 1999). Chemical educators must tie the perceptions of chemical
reactions and an understanding of the particulate nature of matter. The students in this study had an understanding that matter is made up of particles but had difficulty applying that understanding to molecular problems like Problem #5. Curriculum and instruction should emphasize the scientific understanding of matter and how particles interact during reactions and not rely solely on the computational aspects of stoichiometry.

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 is taught in most general chemistry courses (see Taft, 1997), but the balancing of chemical equations can easily be an algorithmic exercise to students (Niaz & Lawson, 1985; Moore, 1997a; Yarroch). Without curriculum and instruction emphasizing why balanced equations are necessary and useful students will learn the algorithms and demonstrate reasoning like that seen by Yarroch where students followed certain rules because that was what their instructors expected of them. 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.

There appeared to be a correlation between the students' conceptual structures and their problem-solving ability. The findings were consistent with Phelps' (1996) assertion that conceptual aspects need to be emphasized and that this emphasis could lead to better
ability in solving computational problems. Many researchers (Anamuah-Mensah, 1986; Bunce et al., 1991; Gabel et al., 1984; Herron & Greenbowe, 1986; Nakhleh & Mitchell, 1993) have seen students attempt to solve problems without application of conceptual knowledge. This algorithmic approach works for chemical exercises but does not work for problems and real-world applications. Chemical educators should emphasize the application of concepts and their importance; this emphasis could take the form of the curriculum changes suggested by others (Nakhleh et al., 1996; Phelps, 1996; Towns & Grant, 1997), but the most important factor must always include encouraging students to apply conceptual knowledge. The cycle must include instruction on the concepts and requiring students to apply conceptual understanding on homework problems, tutorials, class examples, and exams.

Many factors affecting the students' conceptual structure of chemistry were examined, and several trends were seen. The textbook, instruction, tutorial, and exams all showed some possible correlation with conceptual structures, but most appeared to work against developing conceptual understanding. Students were rarely, if ever, asked to demonstrate conceptual understanding during the course and did not develop an acceptable level of conceptual understanding. As Yarroch (1985) stated, "Unfortunately, the mechanical manipulation of symbols is enough to satisfactorily pass the evaluation instruments prepared by most teachers" (p. 458). Chemical educators should require that students practice applying concepts while solving problems of all types so that it becomes a common practice. Expecting students to have conceptual understanding without practicing application of that knowledge is poor pedagogical practice. Chemical educators
must ensure that instruction is complete if introductory chemistry students are expected to learn the concepts of chemistry that are deemed important.

Implications for Future Research

The findings of this study suggest several areas for further research. The areas include alterations of the current study, comparisons between different groups, and examination of students' perceptions of chemistry. The results of this study have indicated further directions for research specifically into students' understanding of chemistry and their application of concepts in problem solving.

One of the findings of this study was that the computational focus of the exams influenced the computational focus of the students. It could prove useful to test this finding by changing only course exams. Two parallel courses would keep all aspects of instruction the same, but exams for one course would be devised to have balance between conceptual and computational questions. The students' conceptual and computational understandings would then be examined in the same manner as this study. A difference in the findings between courses could indicate the level of influence of assessment.

Students were allowed to use notecards on exams for this course, but were not encouraged to use them in the interview. It could prove informative to allow students to use notecards or some equivalent in the problem-solving portion of the interview. The interview problem solving would then be consistent with exams. By allowing the use of notecards or providing a standard equation sheet, the use of notecards by students could be examined, and a comparison of solutions with and without the notecards could also
show how the students use the notecards. The use of the notecards might appear to be the physical equivalent of the mental Rolodex method (Bunce et al., 1991).

The research design utilized in this study could be repeated with another fundamental topic of chemistry. Equilibrium has been studied previously (Camancho & Good, 1989; Gussarsky & Gorodetsky, 1990; Niaz, 1995c, 1998a) and it has been shown to be an important topic where students have conceptual difficulties (Niaz, 1995c, 1998a). Conducting a study utilizing the same design with equilibrium as the content could examine whether the findings of this study are limited to stoichiometry or are present in other content areas of chemistry.

The small sample used in this study was appropriate, but the findings from a larger group of students could show trends that were not evident with this group and give an idea of how prevalent the trends are in a larger group. Replicating this study with a larger group of students would require several interviewers to ensure that interviews all took place within a short period of time.

It may prove enlightening to interview subjects of this study after completion of the chemistry sequence to see if trends continue. It would also be informative to interview them after they have taken more science or science-related courses. A longitudinal study, like that done by Pickering (1990), could show how the students' reliance on algorithms and focus on exams might change over time as was suggested by Pushkin (1998). The students could also be interviewed after they have completed their degrees and while employed in a science-related field. This type of longitudinal study could demonstrate how their intellectual development progresses, whether similar to the scheme proposed by
Perry (1970/1999) or other proposed schemes (Belenky, Clinchy, Goldberger, Tarule, 1986; King & Kitchener, 1993).

Nakhleh (1993) and Mason et al. (1997) compared groups of students based on their majors and found some differences in their conceptual understanding. It might be informative to examine students in the three levels of introductory/general chemistry courses offered, for non-science majors, engineering majors, and science majors. Their problem solving and conceptual structures could be examined for similarities and differences that could be due to instruction, or educational focus. The students in this study were enrolled in a variety of majors, but were enrolled in the same course. A similar study could be conducted on each of these courses and the results compared. A study of this type would introduce more variables, but might prove enlightening concerning students' problem solving.

The course studied is also offered during fall quarter where two sections are offered, each taught by a different instructor. The influence of the instructor could be more closely examined by comparing students from the two sections. The effect could be more evident if the sections used the same exams. It is already the practice to utilize the same textbook and software tutorial for both sections, so extraneous factors from different resources could be negated. The study would be similar to that of Lin et al. (1996), but course instruction would be observed to verify instructional patterns.

Two areas for further study concerning students' perceptions of chemistry were raised from this study. Both areas fit under the general topic of the nature of science (see McComas, Clough, & Almazroa, 1998). The first area is the students' understandings
concerning the use of models of atoms and molecules and the second is the students' general understandings of the nature of chemistry.

The differing results on the Drawing Task and Problem #5 showed the students' difficulties in connecting microscopic, symbolic, and macroscopic levels. A possible cause of this difficulty may be misunderstandings of the use of models in chemistry. One of the myths about the nature of science that was listed by McComas (1998b) was the belief that models used by scientists represent reality rather than reflect a theoretical construct of how nature works. Several studies (Goedhart & van Duin, 1999; Grosslight, Unger, & Jay, 1991; Harrison & Treagust, 1996, 1998) have been done concerning students' understanding of the uses and limitations of models used in chemistry, but the studies examined pre-college students. Because several of the students had difficulty with some of the representations it could prove useful to examine their understanding of molecular models as inferences more closely.

Some of the students in this study implied that chemistry was a formula-dependent science, and this misperception of the nature of chemistry may have played a role in the students' dependence on algorithms. Since the science reform documents (AAAS, 1990, 1993; NRC, 1996) have included the understanding of the nature of science as important goals for science students (see McComas, 1998a; Orna, 1997), it might prove beneficial to study introductory students' understanding of the nature of science in concert with studying their conceptual and computational understandings and problem-solving strategies.
REFERENCES


Herron, J. D., & Greenbowe, T. J. (1986). What can we do about Sue: A case study of competence. *Journal of Chemical Education, 63*, 528-531.


Laing, M. (1996). Bring back equivalent weight -- If you want the kids to "think"! *Journal of Chemical Education, 73,* 1007-1012.


Meeting of the National Association for Research in Science Teaching, Oak Brook, IL. (ERIC Document Reproduction Service No. ED 405 211).


APPENDICES
APPENDIX A: INSTRUCTOR INTERVIEW INFORMED CONSENT

Instructor Informed Consent

By signing this form below, I attest to the following:

1. I understand that I am participating in a research study. The purpose of the research is to examine college students' chemistry knowledge and factors that affect that knowledge. My participation will consist of taking part in an interview and allowing the researcher to observe instruction in my course.

2. I understand that my participation in this study is voluntary and that I may withdraw my participation at any time with no penalty.

3. The researcher has explained the purpose and procedures of this research study and I have been given an opportunity to receive answers to my questions.

4. I understand that the researcher will keep my responses confidential and will destroy all records at the completion of the research.

5. I understand that I will not receive any compensation for my participation in this study.

In understanding of the above, I agree to participate in this study, and understand all expectations of me.

Name (printed) ___________________________ date ____________

Signature _______________________________

Questions concerning this research, my rights, or any research related injuries should be directed to Adam Wolfer at (541) 737-1824 or wolfera@ucs.orst.edu.
Research Consent Form [Schedule Consent]

By signing this form below, I attest to the following:

1. I understand that I am participating in a research study. The purpose of the research is to examine college students' chemistry knowledge. My participation will consist of participating in a one-hour, videotaped interview. I will also provide contact information to the researcher for scheduling an interview.

2. I understand that my participation in this study is voluntary and that I may withdraw my participation at any time with no penalty.

3. The researcher has explained the purpose and procedures of this research study and I have been given an opportunity to receive answers to my questions.

4. I understand that the researcher will keep my responses confidential and will destroy all records at the completion of the research. The course instructor will not have access to student responses to protect participants' confidentiality.

5. I understand that I will not receive any compensation for my participation in this study.

In understanding of the above, I agree to participate in this study, and understand all expectations of me.

__________________________  ________________________
Name (printed)               date

__________________________
Signature

Questions concerning this research, my rights, or any research related injuries should be directed to Adam Wolfer at (541) 737-1824 or wolfera@ucs.orst.edu.
Contact Information

Name ____________________________________________

Telephone Number ____________________________________________

E-Mail Address ____________________________________________

The best way to contact me is by: ____________________________

The best times to contact me are: ____________________________
Research Consent Form [At time of interview]

By signing this form below, I attest to the following:

1. I understand that I am participating in a research study. The purpose of the research is to examine college students' chemistry knowledge. My participation will consist of taking part in this interview, where I will be asked to solve several chemistry problems, and will be asked about my chemistry problem-solving strategies. This interview will be videotaped.

2. I understand that my participation in this study is voluntary and that I may withdraw my participation at any time with no penalty.

3. The researcher has explained the purpose and procedures of this research study and I have been given an opportunity to receive answers to my questions.

4. I understand that the researcher will keep my responses confidential and will destroy all records at the completion of the research. The course instructor will not have access to student responses to protect participants' confidentiality.

5. I understand that I will not receive any compensation for my participation in this study.

In understanding of the above, I agree to participate in this study, and understand all expectations of me.

Name (printed) ___________________________ date ________________

Signature ________________________________

Questions concerning this research, my rights, or any research related injuries should be directed to Adam Wolfer at (541) 737-1824 or wolfera@ucs.orst.edu.
Background Information

Age __________

Gender ________

Major(s) ______________

Please list all previous and current chemistry courses that you have taken (include high school and other college courses):


Please list all previous and current science courses (other than chemistry courses) that you have taken (include high school and other college courses):


Please list all previous and current mathematics courses that you have taken (include high school and other college courses):


APPENDIX C: 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.

<table>
<thead>
<tr>
<th>Card #1</th>
<th>Card #2</th>
</tr>
</thead>
</table>
| **Molecular weight** is the average mass of a molecule of a substance based on a mass of 12 amu for carbon-12. | C: \(1 \times 12.011 \text{ g/mol} = 12.011 \text{ g/mol}\)  
O: \(2 \times 15.9994 \text{ g/mol} = 31.9988 \text{ g/mol}\)  
\(\text{CO}_2 = 44.010 \text{ g/mol}\) |

<table>
<thead>
<tr>
<th>Card #3</th>
<th>Card #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of the masses of the atoms represented in a molecular formula.</td>
<td>(6.022 \times 10^{23} \text{ atoms/mol})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #5</th>
<th>Card #6</th>
</tr>
</thead>
</table>
| **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. | (Hill & Petrucci, 1996)  
One C atom  
\((12.0 \text{ u})\)  
One \(\text{O}_2\) molecule  
\((32.0 \text{ u})\)  
One \(\text{CO}_2\) molecule  
\((44.0 \text{ u})\) |

<table>
<thead>
<tr>
<th>Card #7</th>
<th>Card #8</th>
</tr>
</thead>
</table>
| (Hill & Petrucci, 1996)  
[Diagram of atoms and molecules] | **Molar mass** – mass of 1 mole of a substance |

<table>
<thead>
<tr>
<th>Card #9</th>
<th>Card #12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mol Na = 22.99 g Na = (6.022 \times 10^{23}) Na atoms</td>
<td>Reactants (\rightarrow) Products (\Delta H)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #13</th>
<th>Card #14</th>
</tr>
</thead>
</table>
| (Hill & Petrucci, 1996)  
[Diagram of molecules] | \(\text{C}_3\text{H}_8 (\text{g}) + 5 \text{O}_2 (\text{g}) \rightarrow 3 \text{CO}_2 (\text{g}) + 4 \text{H}_2\text{O} (\text{g})\)  
- 1 mol \(\text{C}_3\text{H}_8\) reacts with 5 mol \(\text{O}_2\)  
- 3 mol \(\text{CO}_2\) is produced for every 1 mol \(\text{C}_3\text{H}_8\) reacted  
- 4 mol \(\text{H}_2\text{O}\) is produced for every 3 mol \(\text{CO}_2\) produced | (Hill & Petrucci, 1996) |
<table>
<thead>
<tr>
<th>Card #15</th>
<th>Card #16</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Diagram of reaction]</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction</td>
</tr>
<tr>
<td>(Kotz &amp; Treichel, 1999)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #18</th>
<th>Card #16</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Diagram of reaction]</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction</td>
</tr>
<tr>
<td>(Nurrenbern &amp; Pickering, 1987)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #21</th>
<th>Card #20</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mol SiCl₄ * 224 g SiCl₄ = 1.32 mol SiCl₄</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction</td>
</tr>
<tr>
<td>169.9 g 1 mol Si</td>
<td></td>
</tr>
<tr>
<td>1.32 mol SiCl₄ * 1 mol SiCl₄ = 1.32 mol Si</td>
<td></td>
</tr>
<tr>
<td>1 mol SiCl₄ 28.09 g Si</td>
<td></td>
</tr>
<tr>
<td>1.32 mol Si * 1 mol Si = 37.1 g Si</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #22</th>
<th>Card #25</th>
</tr>
</thead>
<tbody>
<tr>
<td>X grams of chemical A reacts with an excess of chemical B, and forms chemical C. How many grams of chemical C is produced?</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction</td>
</tr>
<tr>
<td>(Nurrenbern &amp; Pickering, 1987)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #23</th>
<th>Card #25</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Diagram of reaction]</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction</td>
</tr>
<tr>
<td>(Nurrenbern &amp; Pickering, 1987)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Card #27</th>
<th>Card #25</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Diagram of reaction]</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction</td>
</tr>
<tr>
<td>(Kotz &amp; Treichel, 1999)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #28</th>
<th>Card #25</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Diagram of reaction]</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction</td>
</tr>
<tr>
<td>(Kotz &amp; Treichel, 1999)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #29</th>
<th>Card #30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy is released during a reaction</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #30</th>
<th>Card #30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy is absorbed during a reaction</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Card #31

Reactants

\[ \Delta H > 0 \text{ (Positive)} \]

Products

Extent of reaction

Card #32

Reactants

\[ \Delta H < 0 \text{ (negative)} \]

Products

Extent of reaction

(Hill & Petrucci, 1996)

(Hill & Petrucci, 1996)
APPENDIX D: EQUATIONS AND PROBLEMS FOR INTERVIEW

Equations for Balancing Task

\[ \text{N}_2(\text{g}) + \text{H}_2(\text{g}) \rightarrow \text{NH}_3(\text{g}) \]

\[ \text{K(s)} + \text{H}_2\text{O(l)} \rightarrow \text{KOH (aq)} + \text{H}_2(\text{g}) \]

\[ \text{CH}_4(\text{g}) + \text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) + \text{H}_2\text{O(g)} \]

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 (MgCl₂)?

**Problem #2 (Computational)**
How many grams of oxygen would be needed to react completely with 1.00 g of C₂H₆?

\[ 2 \text{C}_2\text{H}_6 \, + \, 7 \text{O}_2 \rightarrow 4 \text{CO}_2 \, + \, 6 \text{H}_2\text{O} \]

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

\[ \text{CH}_4 + 2 \text{Cl}_2 \rightarrow \text{CCl}_4 + 2 \text{H}_2 \] (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 $2\text{Al} + 3\text{Cl}_2 \rightarrow 2 \text{AlCl}_3$. Consider the mixture of Al (squares) and Cl$_2$ (00) in a closed container as illustrated below:

![Starting Material](image)

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)?

$$\text{H}_2(\text{g}) + \text{Cl}_2(\text{g}) \rightarrow 2 \text{HCl}(\text{g}) \quad \Delta H = -184.6 \text{ kJ}$$
(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$_2$H$_2$) 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.

$$\text{CaC}_2(\text{s}) + \text{H}_2\text{O}(\text{l}) \rightarrow \text{CaO} (\text{s}) + \text{C}_2\text{H}_2(\text{g})$$
APPENDIX E: RESEARCHER'S CARD SORT TASK STRUCTURE
APPENDIX F: STUDENT CARD SORT TASK STRUCTURES

Anna's Card Sort Task Structure
Note: Cards # 13, 18, and 23 were left out of structure. Numbers and references were not included on cards given to students. Cards are edited and lines between groups have been added for clarity.

Card #9
1 mol Na = 22.99 g Na = 6.022 x 10^{23} Na atoms

Card #8
Molar mass - mass of 1 mole of a substance

Card #21
1 mol SiCl_4
224 g SiCl_4 \times \frac{1.32 \text{ mol}}{169.9 \text{ g}} = 1.32 \text{ mol SiCl}_4

Card #4
6.022 \times 10^{23} \text{ atoms/mol}

Card #2
C: 1 \times 12.011 \text{ g/mol} = 12.011 \text{ g/mol}
O: 2 \times 15.9994 \text{ g/mol} = 31.9988 \text{ g/mol}
CO_2 = 44.010 \text{ g/mol}

Card #7
12 \text{ g C} + 32 \text{ g O}_2 \rightarrow 44 \text{ g CO}_2

Card #6
One C atom + One O_2 molecule → One CO_2 molecule

Card #14
C_3H_8 (g) + 5 O_2 (g) → 3 CO_2 (g) + 4 H_2O
*1 mol C_3H_8 reacts with 5 mol O_2

Card #15

Card #16
Limiting reactant is the reactant that is completely consumed in a reaction

Card #30
Energy is absorbed during a reaction

Card #29
Energy is released during a reaction

Card #20
CH_4 + 2O_2 → CO_2 + 2H_2O

Card #12
Reactants → Products ΔH

Card #27
ΔH > 0

Card #28
ΔH < 0
### Beth's Card Sort Task Structure

Note: Cards #6, 13, 18, 20, 21, and 23 were left out of the structure. Numbers and references were not included on cards given to students. Cards are edited and lines between groups have been added for clarity.

<table>
<thead>
<tr>
<th>Card #5</th>
<th>Card #1</th>
<th>Card #16</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mole</strong> is the amount of a substance that contains as many elementary units as there are atoms in exactly one mole.</td>
<td><strong>Molecular weight</strong> is the average mass of a molecule of a substance based on a mass of 12 amu for</td>
<td><strong>Limiting reactant</strong> is the reactant that is completely consumed in a reaction.</td>
</tr>
<tr>
<td>Card #9</td>
<td>Card #3</td>
<td>Card #22</td>
</tr>
<tr>
<td><strong>1 mol Na = 22.99 g Na = 6.022 \times 10^{23} Na atoms</strong></td>
<td><strong>Sum of the masses of the atoms represented in a molecular formula</strong></td>
<td>X grams of chemical A reacts with an excess of chemical B, and forms chemical C. How many grams of chemical C is produced?</td>
</tr>
<tr>
<td>Card #4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>6.022 \times 10^{23} atoms/mol</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #8</th>
<th>Card #2</th>
<th>Card #15</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Molar mass</strong> - mass of 1 mole of a substance</td>
<td><strong>C: 1 \times 12.011 g/mol = 12.011 g/mol</strong></td>
<td><strong>Energy is absorbed during a reaction</strong></td>
</tr>
<tr>
<td><strong>O: 2 \times 15.9994 g/mol = 31.9988 g/mol</strong></td>
<td><strong>CO_2 = 44.010 g/mol</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Card #14</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>C_3H_8 (g) + 5 O_2 (g) \rightarrow 3 CO_2 (g) + 4 H_2O</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>1 mol C_3H_8 reacts with 5 mol O_2</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Card #17</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>12 g C + 32 g O_2 \rightarrow 44 g CO_2</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #12</th>
<th>Card #28</th>
<th>Card #27</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactants \rightarrow Products \Delta H</strong></td>
<td><strong>\Delta H &lt; 0</strong></td>
<td><strong>\Delta H &gt; 0</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card #30</th>
<th>Card #29</th>
<th>Card #32</th>
<th>Card #31</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy is absorbed during a reaction</strong></td>
<td><strong>Energy is released during a reaction</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cara's Card Sort Task Structure
Note: Cards # 1-9, 13-16, 18, 20-23, and 25 were left out of the structure. Numbers and references were not included on cards given to students. Cards are edited and lines between groups have been added for clarity.

Card #12
Reactants → Products ΔH

Card #27
ΔH > 0

Card #28
ΔH < 0

Card #31
Energy is absorbed during a reaction

Card #32
Energy is released during a reaction

Card #30
Energy is absorbed during a reaction
Deb's Card Sort Task Structure
Note: All cards were used. Numbers and references were not included on cards given to students. Cards are edited and lines between groups have been added for clarity.

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 #8
Molar mass – mass of 1 mole of a substance

Card #4
6.022 x 10^23 atoms/mol

Card #9
1 mol Na = 22.99 g Na = 6.022 x 10^23 Na atoms

Card #7
12 g C + 32 g O₂ → 44 g CO₂

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 #15

Card #3
Sum of the masses of the atoms represented in a molecular formula

Card #16
Limiting reactant is the reactant that is completely consumed in a reaction

Card #2
C: 1 x 12.011 g/mol = 12.011 g/mol O: 2 x 15.9994 g/mol = 31.9988 g/mol

Card #14
C₃H₈(g) + 5 O₂(g) → 3 CO₂(g) + 4 H₂O
• 1 mol C₃H₈ reacts with 5 mol O₂

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 #21
1 mol SiCl₄
224 g SiCl₄ * = 1.32 mol SiCl₄
169.9 g

Card #6
One C atom + One O₂ molecule → One CO₂ molecule

Card #20
CH₄ + 2O₂ → CO₂ + 2H₂O

Card #25
P₂ + 6Cl₂ → 4PCl₃

Card #13
2H₂ + O₂ → 2H₂O

Card #31

Card #32
Reactants → Products ΔH

Card #12
ΔH > 0

Card #28
ΔH < 0

Card #30
Energy is absorbed during a reaction

Card #29
Energy is released during a reaction
Ed's Card Sort Task Structure

Note: Cards # 13, and 21 were not used in the structure. Numbers and references were not included on cards given to students. Cards are edited and lines between groups have been added for clarity.

**Card #6**
One C atom + One O₂ molecule → One CO₂ molecule

**Card #20**
CH₄ + 2O₂ → CO₂ + 2H₂O

**Card #7**
12 g C + 32 g O₂ → 44 g CO₂

**Card #12**
Reactants → Products ΔH

**Card #10**
Energy is absorbed during a reaction

**Card #29**
Energy is released during a reaction

**Card #28**
ΔH < 0

**Card #28**
ΔH < 0

**Card #30**
Mole is the amount of a substance that contains as many elementary units as there are atoms in exactly 12 g of the

**Card #4**
6.022 x 10²³ atoms/mol

**Card #9**
1 mol Na = 22.99 g Na
= 6.022 x 10²³ Na atoms

**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

**Card #3**
Sum of the masses of the atoms represented in a molecular formula

**Card #8**
Molar mass = mass of 1 mole of a substance

**Card #16**
Limiting reactant is the reactant that is completely consumed in a reaction

**Card #15**
Example of limiting reactant

**Card #14**
C₃H₈ (g) + 5 O₂ (g) → 3 CO₂ (g) + 4 H₂O
1 mol C₃H₈ reacts with 5

**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

**Card #23**
Not example of limiting reactant

**Card #25**
P₄ + 6Cl₂ → 4PCl₃
Frank's Card Sort Task Structure
Note: All cards were used in the structure. Numbers and references were not included on cards given to students. Cards are edited and lines between groups have been added for clarity.

Card #12
Reactants \( \rightarrow \) Products \( \Delta H \)

Card #27
\( \Delta H > 0 \)
Card #28
\( \Delta H < 0 \)

Card #30
Energy is absorbed during a reaction
Card #29
Energy is released during a reaction

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

Card #1
Molecular weight is the average mass of a molecule of a substance based on a mass of 12 amu for

Card #8
Molar mass – mass of 1 mole of a substance

Card #3
Sum of the masses of the atoms represented in a molecular formula

Card #4
6.022 x 10^{23}

Card #27
\( \Delta H > 0 \)

Card #28
\( \Delta H < 0 \)

Card #30
Energy is absorbed during a reaction
Card #29
Energy is released during a reaction

Card #16
Limiting reactant is the reactant that is completely consumed in a reaction

Card #17
12 g C + 32 g O\(_2\) \( \rightarrow \) 44 g CO\(_2\)

Card #6
One C atom + One O\(_2\) molecule \( \rightarrow \) One CO\(_2\) molecule

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 #2
C: \( 1 \times 12.011 \text{ g/mol} = 12.011 \text{ g/mol} \)
O: \( 2 \times 15.9994 \text{ g/mol} = 31.9988 \text{ g/mol} \)

Card #15

Card #14
C\(_3\)H\(_8\) (g) + 5 O\(_2\) (g) \( \rightarrow \) 3 CO\(_2\) (g) + 4 H\(_2\)O

Card #20
CH\(_4\) + 2O\(_2\) \( \rightarrow \) CO\(_2\) + 2H\(_2\)O

Card #13
2H\(_2\) + O\(_2\) \( \rightarrow \) 2H\(_2\)O

Card #25
P\(_4\) + 6Cl\(_2\) \( \rightarrow \) 4PCl\(_3\)

Card #21
1 mol SiCl\(_4\)
224 g SiCl\(_4\) * \( \frac{1}{160.0} \) = 1.32 mol SiCl\(_4\)