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STUDENT CONCEPTIONS OF CHEMICAL CHANGE

By

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ABSTRACT

STUDENT CONCEPTIONS OF CHEMICAL CHANGE

By

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Shortly after completing an instructional unit on chemical change, about 100 first year high school chemistry students were to write explanations for the rusting of an iron nail, the heating of copper in air and the burning of a wood splint. From the larger population, 11 students were selected for clinical interviews. An in-depth analysis of three students formed the major portion of this study.

Analysis focused upon three interrelated aspects of chemical understanding: (a) chemical knowledge which includes facts and theories; (b) conservation reasoning which is related to the students' ability to conserve mass and substance; and (c) explanatory ideals, or the standards by which the acceptability of scientific explanations is judged. Modern notions of chemical change, for example, assume that chemical changes can and should be explained in terms of atomic-molecular theory.

Only one of the 11 students stood as possessing the chemist's understanding in all three areas. This goal-conception student consistently indicated a preference for the atomic-molecular theory to explain the changes before him and could quickly detect and correct minor errors in his conservation reasoning.

The remaining 10 students were classified as transitional or naive -- with four of the ten clearly holding naive conceptions across all three areas. The naive students possessed little chemical knowledge, very seldom conserved mass or substance, and seemed oblivious to the notion that atoms/molecules and their interactions formed the basis of an acceptable explanation of chemical change. These students preferred homespun analogies (e.g., describing rusting as "like" mold growing on bread) as their only form of chemical explanation. In addition, these students believed that the difference between their explanations and those of the chemist lie in the chemist's scientific vocabulary.

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CHAPTER 1

THE PROBLEM

Introduction: Change in the Physical World

The question of change within the physical world is one that is dealt with by the professional scientist and the average person alike.

The wearing of a tire, the rusting of a nail, the melting of ice, and the burning of wood are common examples of change within the everyday experience of many persons. For the most part just about everyone has an explanation as to how these and other everyday changes take place.

In the realm of science, chemistry is among the disciplines that share an interest in change. There are, however, types of change that are of greater interest to the chemist than others. These are termed 'chemical changes' and form a major focus of the chemist's work. Other kinds of change, termed 'physical and nuclear' while part of the chemist's realm are normally not the focus of interest. For a chemist, the classification of changes within the physical world becomes a rather routine matter of isolating those concerned with chemistry from those which do not and proceeding from there.

Chemistry as a school subject is often initiated at the secondary level. One of the topics discussed is that of change. Most text books allocate a number of sections to the development of this topic. A typical goal statement reads, "Students will gain an understanding of the ways in which matter is classified and of the changes undergone by matter." This statement is followed by other goals pertaining to the identification of and discrimination between physical and chemical changes.

As the above indicates, an understanding of changes within the physical world represents an important topic within the discipline and as such becomes an integeral part of any first year chemistry course.

The Theoretical Assumptions of this Study

This is a study of student understandings of chemical change. It is based upon a number of assumptions about the learning process and what it means to say that someone 'understands' chemical change. This study assumes that much of learning in the sciences is a process of conceptual change. New understandings are not acquired directly from experience, but through an interaction of present experience with existing understandings. Students bring to the chemistry classroom a set of naive theories or alternative conceptions on the nature of change in the physical world that are acquired prior to formal instruction. These conceptions predispose the students to think in certain ways when faced with new situations that are decidedly within the domain of chemistry. Naive conceptions almost always contain elements that would be considered unacceptable by the chemist. These naive or alternative conceptions often outlive the instruction that was meant to supplant them.

This conceptual change perspective of learning can be found in the writings of Toulmin (1972), Posner, Strike, Hewson and Gertzog (1982), Smith (1975), and Strike (1983). Research on student understandings of various science concepts has been carried out using a conceptual change viewpoint; Smith & Lott (1983) on photosynthesis, Clement (1982) on force and motion, Roth, Smith & Anderson (1983) on photosynthesis and food for plants, Anderson & Smith (1983) on light and color, Minstrell (1985) on Newtonian Laws of Motion and Yarroch (1985) on equation balancing in chemistry.

It seems clear that an understanding of students' alternative conceptions is instructionally useful. Some researchers have demonstrated that this is so by designing instruction to specifically help the student change or modify the pre-existing conception. Recently, Anderson and

Smith (in press) have completed a chapter for "The Educator's Handbook: A Research Perspective" in which they suggest strategies for teaching for conceptual change based upon a synthesis of empirical studies and upon the Posner et.al. (1982) model for conceptual change. Some research on teaching for conceptual change has been conducted in the area of photosynthesis, Roth (in press), in the area of mechanics, Minstrell (1985) and on the particulate nature of gases, Nussbaum & Novick (1986).

While this line of research promises fresh insights into the problems associated with the teaching and learning of science, more must be learned about the understandings of students in specific content areas. My study is being presented with this goal in mind. The primary goal of this study is to present a more detailed understanding of students' conceptions of chemical change.

In addition to a general conceptual change perspective, this study is based on a three-part model of learning chemistry which may be useful in understanding the explanations given by students of typical chemical changes. This model of learning states that students must acquire three different types of understandings in order to produce an explanation that would be acceptable to a trained chemist: (a) a certain amount of chemical knowledge including specific facts and theories associated with the change being described, (b) an understanding of how conservation reasoning applies to chemical changes and (c) an understanding of the chemist's explanatory ideal for chemical change. Each of these three areas will be briefly introduced.

Chemical Knowledge

To explain chemical changes like rusting or burning, students must acquire a vast amount of chemical knowledge in the form of facts and theories. Students must understand how the chemist represents atoms and molecules alone and in groups, the different roles of material substances and energy, the notions of reactants and products, and the rules for equations writing to mention just a few aspects of the atomic molecular theory that are part of the chemist's mental domain. The chemical knowledge of interest in my study focuses upon student understandings of reactants and products. Only material substances, elements and compounds, are considered to be legitimate reactants and products to the chemist. It seems evident that for the beginning chemistry student, the facts are numerous and the theories are complex. For students to acquire enough chemical knowledge to explain a chemical change like rusting is a challenging task. There is a growing body of research that has explored the problems of students acquiring this chemical knowledge. A portion of this will be reviewed in the next chapter.

Conservation Reasoning

The second part of my model deals with conservation reasoning. The work of Piaget/Inhelder suggests that the ability to conserve mass in physical transformations is an insight that is independent of the specific materials being transformed. Whether or not this is true for chemical transformations is not known. A mature chemist could probably arrive at mass conservation as a corollary of the atomic molecular theory. Yet, for the beginning student, it is assumed in my study that mass conservation does not explicitly depend upon chemical knowledge of the atomic molecular theory and will be treated as a separate area of understanding.

Regardless of how students come of conserve mass, mass conservation in chemical transformations represents an important aspect of understanding chemical changes. Chemists would look for mass conservation in an explanations of chemical changes. Mass conservation is one difference between chemical changes and nuclear changes. Lacking an understanding of the chemist's version of the Law of Conservation of Mass it becomes all to easy to dismiss mass changes as subtle forms of matter-energy interconversion which is the norm in nuclear transformations but which violates all the rules for accounting for mass changes in chemical transformations. Conservation reasoning as applied to chemical transformations deals with the conservation of elements and mass as compounds are being created and broken down.

Explanatory Ideals

A Personal Experience that Highlights My Interest in Explanatory Ideals

A few years ago, I had a chemistry student who has since gone on to become an electrical engineer. His work was well above average in chemistry. One day he brought up an old exam that he had recently completed and asked me to explain some questions about chemical changes. I was surprised in that he wanted me to explain the questions that he had gotten correct on the exam. I asked him what was troubling him and he confided that his answers didn't make sense to him even though he knew they were scientifically correct. He then proceeded to ask me a series questions about the exam. All of his questions aimed at making sense of the exam were of the simile/metaphor/analogy type. "Is it like this....?", he would ask. He would then proceed to relate the test item to something from his everyday life. That experience was quite a revelation to me. This student showed me that there was more to learning chemistry than right answers. There seemed to be another area of understanding that ran parallel to chemical knowledge. This other area dealt with his perceptions of what constituted acceptable explanations in chemistry. From that point on I began to take a different look at the relationship between my science teaching and my students' understandings of science.

An Overview of Explanatory Ideals

The third area of understanding required by students involves gaining an understanding of the chemist's explanatory ideals for chemical change. By explanatory ideals I mean the theories that form the basis of an acceptable explanation in chemistry. Explanatory ideals are statements about the real world that a person considers to be self-explanatory. The atomic molecular theory is the chemist's explanatory ideal for chemical change. Chemists accept and expect that explanations of chemical transformations will draw upon this theory. A chemist would not be satisfied with an explanation that did not use the atomic molecular theory as its basis. More will be said about these three areas of knowledge in Chapter 2.

Research Questions

The above statements suggest a complexity to teaching and learning about chemical change. It is the nature of this complexity that is unraveled in this study. Interesting possibilities emerge when attempts are made to answer the question, "What understandings must students possess in order to produce an explanation of chemical change that is satisfactory to the chemist?" The following questions give the focus of this study:

1. What chemical knowledge is used by high school students when they describe chemical change?
2. What role does conservation reasoning play in the responses given by students explaining a chemical change?
3. What is the nature of the explanatory ideals used by these students?

Overview of this Study

The heart of this study is an in-depth examination of how three students explained typical chemical changes. These three students were representative of students who were receiving above average, average and below average grades in a first year chemistry course. In all, eleven students were clinically interviewed out of 100 who were tested with a written instrument. There will be some comparisons drawn between the three students who formed the basis of my study and the remaining eight who were also clinically interviewed. All the students in this study had studied chemistry for about three months.

This is a study of cognition or understanding. No attempts are made to trace learning as it changes during instruction. A particularly rich set of data was amassed after instruction and it is from this data that my study is derived.

Summary Chapter 1

To properly explain phenomena involving chemical changes like rusting and burning, a knowledge of chemistry is useful. The study of chemical change is an important topic covered in all first year chemistry courses. Unfortunately, research has shown that even after instruction, students in many areas of science, including chemistry, have problems explaining scientific phenomena in a manner that would be acceptable to a scientifically trained adult.

This study examines how students explain three common chemical transformations. This study proposes a three-part model for understanding their explanations. This model postulates that when students learn chemistry they are really gaining knowledge in three areas: chemical knowledge, conservation reasoning and explanatory ideals.

In all, about 100 students were given a written instrument designed to uncover their chemical knowledge of reactants and products, their conservation reasoning used to account for mass changes and their explanatory ideals. Eleven were selected for clinical interviews. This study focuses upon the chemical explanations of three representative students who fall into the loosely defined categories of above average, average and below average chemistry students. Comparisons are made with the remaining eight students who were interviewed in this study.

CHAPTER 2

LITERATURE REVIEW

Introduction

The purpose of this chapter is to review a body of research that forms the theoretical underpinnings of this investigation. This chapter will show how this study both draws from and goes beyond previous attempts to explain student difficulties in chemistry.

Part I of this chapter begins by examining the problems students have in learning chemistry and science in general. This section draws from an existing body of research which focuses upon the role of student misconceptions as a barrier to the acquisition of the desired scientific conception. Form this larger body of research, I will examine in detail two recent studies, Ben Zvi, Eylon & Silberstein (1982) and Yarroch (1985). These studies discuss problems associated with the acquisition of explicitly chemical knowledge and present interesting perspectives from which to understand the source of the student difficulties.

Part II will examine the role that conservation reasoning plays in the production of an adequate explanation in chemistry. The focus will be Piaget's work on conservation reasoning. Piaget studied how young children explained physical changes. Piaget's findings will be used as a basis for understanding the problems of adolescents acquiring chemical conservation skills. In addition to Piaget, the work of Rosland Driver (1986) will be reviewed. Driver examines a number of studies, together with her own work, that assess the conservation reasoning patterns used by students as they explain various chemical and physical transformations.

Finally, Part III will review the writings of Stephen Toulmin. His notions of an adequate explanation in science will be explored. The concept and function of explanatory ideals will be introduced. Explanatory ideals will be presented as statements about the physical work that a person accepts as true. Explanatory ideals provide the context within which explanations are constructed. An historical example focusing upon Aristotle's conceptions of matter-theory will be reviewed. This historical example is used by Toulmin in his argument for the existence and function of explanatory ideals. Toulmin argues that by understanding the explanatory ideals of a given age, a certain rationality appears in the "unexpected" explanations proffered by respected scientists throughout history. The analysis of Toulmin is concluded by arguing that different explanations of the same phenomena can be equally scientific though containing different content.

In addition to Toulmin, the work of Solomon (1983) will also be reviewed. Solomon's paper on the kinds of scientific explanations given by children only a few years younger than those in my study gives additional insights into the kinds given by students in my study.

The objective of this chapter is to draw support for my premise that when students learn about chemical change they are really acquiring understanding in three different areas: chemical knowledge, conservation reasoning and explanatory ideals. Misunderstandings in one or all of these areas make it difficult for the student to explain chemical change in a manner that would be acceptable to the chemist.

Part I

Introduction

A growing body of research indicates that there are often discrepancies between performance on academic tasks and student understanding of the scientific concepts which form the underpinnings of the task. A recent study by Yarroch (1985) was conducted on the understanding of equation balancing by high school students. While all of the students could balance the equations presented, less than half could adequately represent in diagrams what they had balanced and possessed little understanding of the role of subscripts in equation balancing.

Unfortunately, researchers who are interested in student understanding of science are finding situations similar to that uncovered by Yarroch in many areas of science. Above average grades and correct answers do not always equate with understanding. Recent studies by Anderson and Smith (1983), Smith and Lott (1983), Nussbaum and Novick (1981), and Solomon (1983) illustrate the problems science students have in mastering both the specific knowledge and theories presented in typical general science and chemistry courses.

This research builds an argument that much of learning in science involves a process of conceptual change rather than the simple acquisition of facts. Even after well planned lessons by experienced teachers many of the students were shown to have difficulty understanding the "simplest" concepts. These researchers have shown that students think about science in ways that make sense to them. These personal understanding are naive ways of thinking based upon unscientific concepts. Since traditional approaches to the teaching of science have proved unsatisfactory in helping the students learn the scientific conception, modern research has begun to focus upon students' current conceptions of the physical world.

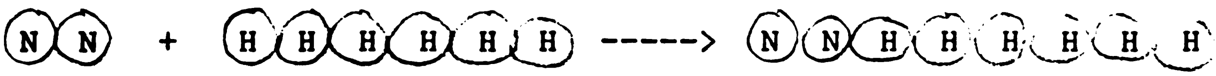
The uncovering of current naive conceptions is the first step in understanding how teachers can help their students abandon their naive conceptions and to eventually adopt the scientific conception. To illustrate the new focus in educational research, I will review two recent studies taken from the field of chemistry that have been conducted within the spirit of the conceptual change viewpoint.

The Yarroch Study: Student Understanding of Equation Balancing

Yarroch (1985) analyzes student difficulties in representing chemical change in his study of equation balancing. This study addressed student understanding of the specific knowledge and theories associated with balancing equations. Students were asked to balance and diagram four equations during a half-hour clinical interview. Yarroch found that while all the students could correctly balance the equations, there were noticeable differences in their personal understanding of the specific knowledge associated with balancing equations. Students had not learned the scientific conceptions supporting the rules for equation balancing. Rather, many students adopted a loosely connected algebraic approach to balancing which freed them from learning the scientific concepts that would lead to understanding. Even though many of the students in his study could correctly use coefficients and subscripts, their understanding of these concepts consisted of manipulating numbers to get the symbols to add up on both sides of the equation. Although these students appeared to understand the Law of Conservation, it consisted more of a conservation of symbols than of "mass or elementary Particles" (p. 456).

Another aspect of the Yarroch study is its focus on student understanding of chemical change at the atomic-molecular level of chemistry. As part of the study, students were also asked to diagram their notions of the equations they had just balanced. It is here that students demonstrated that, "...although they could balance simple chemical equations to achieve a correct result, they had little understanding of the chemical implications of the equation" (p. 458).

What follows is an example of a student's representation of the chemical equation $N_2 + 3H_2 \text{----->} 2NH_3$ taken from the Yarroch study.



Yarroch concludes that this diagram suggests an understanding of chemical conservation as there are equal numbers of nitrogen and hydrogen atoms on both sides of the equation. This diagram clearly demonstrates that this student does not hold a working knowledge of the Law of Definite Proportions, diatomic gases and typical bonding characteristics of covalent molecules. This student ignores many of the properties of individual atoms and molecules. There is a definite inconsistency between the subscripts and coefficients used in the correctly balanced chemical equation and this student's diagrammed representation of that equation.

In an interview with another student who has also correctly balanced all the equations, Yarroch shows there is little understanding of the concepts of subscripts and coefficients.

INT : ....this little two here and this little four there. Is there a name for those things?

SUB : Subscripts?

INT : Subscripts, that's a good name. What do they do? What use do they have?

SUB : They tell...(let me think now)...they refer to the number of electrons in the outer shell....(I'm not sure of that)....I just know their function, not what they are....

Later in the interview-

INT : What about this big number here? This two....does that have a name?

SUB : ....I know there's a name, but I can't think of it right now.

INT : How about coefficients? What does that do?

SUB : It helps balance the equation, by.....having this number here and multiplying it by the subscript...or vice versa...you can get an equal number of the element on both sides.

Similar difficulties in acquiring the chemical knowledge associated with the atomic-molecular theory are found in other students as well. Yarroch states that over half of the students by the end of the clinical interview, "...were reluctant to use terms like atom and molecule even if the interviewer introduced the terms..." (p. 457). It must be emphasized that all the students in the Yarroch study were classified as above average chemistry students by their teacher. If these responses typify the A & B students, one wonders what the C & D students' understand of chemical change and equation balancing.

<u>The Source of Student Problems</u>

Yarroch suggests that the source of the problem is that even something as fundamental as equation balancing requires students to operate at two levels: a higher level that focuses upon the scientific concepts (laws and theories) and a second level that directs the proper application of a set of mathematical rules for the actual balancing of the equation. The students in Yarroch's study were unable to move efficiently between the two levels and focused their attention upon the rules for balancing rather than upon the scientific concepts. Lacking the ability to make this transition between levels, Yarroch suggests that many of these students conceptualized equation balancing as a mathematical game of getting the atomic symbols to add up across an imaginary equals sign.

Yarroch concludes his study with a suggestion that chemistry teachers emphasize not only the specific knowledge associated with balancing equations but with the theories that give structure and meaning to this knowledge as well.

The Ben-Zvi, Eylon and Silberstein Study: Chemistry as a Multileveled Discipline

Another recent case study of student understanding of chemistry by Ben-Zvi, Eylon and Silberstein (1982) presents several important findings. Ben-Zvi et.al. examine student conceptions of structure and process in chemistry. One part of this study points out the difficulties encountered when high school chemistry students were asked to sketch their conceptions of individual molecules in various states. In another part, students were asked to diagram and explain their understanding of a synthesis and dissociation reaction involving diatomic molecules. Results show that students have very different ideas of structure and process than the chemist.

The Sources of Student Problems

Ben-Zvi et. al. suggest that the source of naive conceptions lie in: (a) the abstract nature of the concepts being taught, (b) the need for students to shift between the three different levels of the discipline and (c) the specialized language of chemistry. While all three sources of difficulty are insightful, the most interesting analysis from the perspective of this dissertation is their analysis of the three levels of chemistry. This topic is discussed below.

One of the difficulties in learning chemistry lies in the very way in which chemistry as a discipline is organized. Ben-Zvi et. al. argue that chemistry demands an understanding at three distinct levels: (a) the individual atomic molecular level, (b) the multi-atomic or mole sized level and (c) the level of phenomenology. Ben-Zvi et. al. cite the following example.

> To describe correctly the structure of a given gas or solid, it is necessary to know both the structure of each molecule (atomic-molecular level), and also know how these molecules are related to each other (multi-atomic level of description). Another important task is to relate the properties of a given gas or solid (phenomenology) to their structure (other two levels). If the student is unaware of the existence of these levels right from the beginning and cannot coordinate them, he or she will not be able to use the atomic model correctly. (p. 2-3)

Verbal descriptions of solids, liquids and gases including color, quantity of material, odor, properties like malleability and statements about reactivity (the iron nail was covered with corrosion) all belong to the level of phenomenology. The multi-atomic level is the level at which many of these properties come into existence such as the state of the material, the color and the structure.

The multi-atomic and the phenomenological levels are closely related. For example, I see the differences lying in the context of the discussion. I would interpret the statement, "copper metal when heated in the presence of oxygen will oxidize to cupric oxide," to be a description at the multi-atomic level. While the statement, "the copper skillet turned black with oxidation," to as a description at the phenomenological level of chemistry.

The lowest level of description is that of the individual atoms and molecules. There are a whole host of properties that are important descriptors at this level: atomic mass, electron configurations, the size of individual atoms and molecules, the kinds of bonding between atoms in a molecule and the structures of individual molecules are but a few. Ben-Zvi et. al. feel that many of the problems of students can be explained by their inability to associate respective properties to the level at which they exist. For example, it would make no sense to the chemist to talk about the color or the state of an individual atom or molecule. To talk about a liquid water molecules suggests a continuous model for matter theory rather than an atomic-molecular theory (p. 63).

Ben-Zvi et. al. feel that much of chemistry instruction at the introductory level focuses upon the concrete and pictorial representation of individual atoms and molecules. Little emphasis is placed upon the multi-atomic level in these presentations (p. 65). Even when discussing the kinetic theory of gases, little is said about the numbers of particles involved. Also, the kinetic theory by its very nature overlooks many of the properties like bonding and other interactions. The multi-atomic level is often generic in that all atoms and molecules are often represented as a collection of little spheres and not as many units all with an internal structure (p. 65). Students are directed to think almost exclusively about atoms and molecules at the lowest, atomic-molecular level.

Yet, students are regularly asked by textbook authors and teachers to conceptualize atoms, molecules and their interactions at one or all of these levels almost simultaneously. A factor inhibiting the smooth transition between levels is that, "some symbols and notations in chemistry have different interpretations depending on the context" (p. 66). For example, the symbol Cu is used to represent a single copper atom while Cu (s) represents mole sized amounts of copper atoms.

A more detailed examination of their study will is given below.

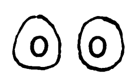
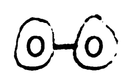
A Cross-Section of Results

Students were asked to respond to a written questionnaire which addressed student conceptions of the structure of individual molecules and of the process of chemical change. Out of 337 who responded to the written exercises, 8 were chosen to be clinically interviewed. Selection for the clinical interview was based upon the responses to the written exercise.

As the scope of this study was broad, only those results that are most pertinent for this study will be reviewed at this time.

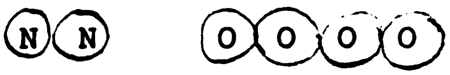
Properties of Elements and Compounds: Difficulties in Shifting Between the Atomic and Multi-atomic Level

Students were asked to represent by a diagram the structure of O_2 (g), 2O and O_2. Only 10 percent of the 293 students responded correctly. Examples of typical drawings are given below:

(a) O_2 (g)  (b) 2O  (c) O_2 

The expectation for (a) was that students would represent many molecules. Most students only represented a single molecule. In (b), the students equated two oxygen atoms with one diatomic oxygen molecule. In (c), students incorrectly represented a single diatomic oxygen molecule as two distinct atoms bonded together at a great distance.

Students also hold naive conceptions of the structure of individual molecules. When asked for diagrams of individual molecules of N_2O_4 inconsistencies in understanding were apparent. On individual questions, 64 percent correctly represented a molecule of N_2O_4 with about 16 percent representing the molecule as fragments of 2N's and 4O's apparently glued together. Examples are cited below.



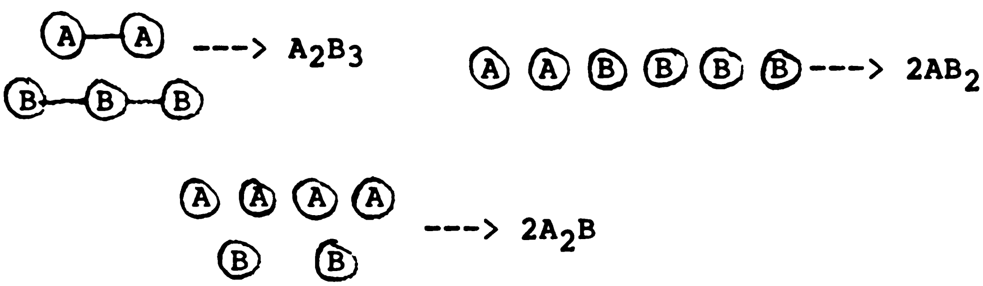
and

Another question asked of students is to diagram the structure of the Cl_2O (g). In this instance, only 43 percent of the students correctly represented the structure of an individual molecule. Again, some students represented the molecules as fragments glued together (p. 24). Additionally, 27 percent of the students represented Cl_2O in the gaseous state as only one molecule (p. 24) with a total of 66 percent incorrectly representing gaseous Cl_2O in some way (p. 34).

A cross-tabulation on the kinds of representations given by students for both N_2O_4 and Cl_2O was performed. Results indicate that 50 percent of the students drew the same type of structure for each molecule (correct or incorrect) for the two questions (p. 22). While this percentage does not appear to be unusually high, Ben-Zvi et. al. feel that it does suggest a consistency and state, "the drawings may very well represent a well rooted view of molecular structure (correct or incorrect) by these students" (p. 23).

Other crosstabulations show consistencies of 90 percent between student representations of O_3 (g) and Cl_2O (g). In this instance the students only drew one molecule whereas the chemist recognizes elements and compounds in the gaseous state as being composed of trillions of particles.

Ben-Zvi et. al. relate these errors to difficulties in shifting from a monoatomic to a multiatomic state. During the clinical interviews that followed the written exercise students were asked to diagram the structure of another set of generic molecules A_2B_3 , 2 AB_2 and 2 A_2B. Students were questioned on their representations. The diagrams of Student 4 are shown below.



During the interview, Student 4 comments upon the diagrams (p. 30).

E: What do the lines between the atoms mean?

St 4: Bonding

E: You have lines here (between the A's) and lines here (between the B's), but not here (between the groups of A's and B's).

St 4: Because these are two atoms of A and they belong to this part, and these three atoms of B and they belong to that part (points with finger to the two parts).

This sequence is illustrative of other students who thought that individual molecules were composed of fragments that in this case are not even bonded together. More importantly, these kinds of results demonstrate that these students lacked an understanding of the properties of individual atoms and molecules. One question, (Question 5), used during the clinical interview addressed the problem of properties directly. Students were asked to identify which of a given set of properties of a fictitious element in the solid state would belong to an individual atom of the solid and which properties would belong to an isolated atom of the same element in the vapor state. A majority of the students (70 percent) made errors in relating the properties of a substance to the properties of its atoms. For example, students thought, "...that an atom of a gas has all or part of the macro properties of the gas and an atom of a solid has all or part of the macro properties of the solid" (p. 63). In general, students did not recognize the relationship between structure and properties.

Student Understanding of Chemical Change: More Difficulties at the Lower Two Levels

The misconceptions over the structure of individual molecules and molecules in the multiatomic state are carried over into student understanding of simple synthesis and decomposition reactions. Results show that a sizable portion of the students in this study could not represent the two chemical changes in a manner acceptable to a chemist. For example, students were asked to describe, by drawing, the dissociation of Cl_2O (g) into elemental chlorine and oxygen. Students were reminded in the question that both chlorine and oxygen are diatomic gases. In spite of this information, many students wrote an equation consisting of Cl_2 and O, as if a single molecule had just become unglued. This is not too surprising given the difficulties these same students had in representing individual molecules. Ben-Zvi et. al. state that if the students, "do not see a substance as a collection of many molecules, then it can be inferred that the only possible decomposition product of one molecule of Cl_2O would be Cl_2 and O" (p. 44). Examples of student responses are given below.

Cl_2O ---> Cl_2 + O

In the synthesis reaction of $N_2 + O_2$ ----> N_2O_5, many of the students suggested that the product N_2O_5 was not possible because O_5 was not among the reactants. One student responded, "No, the given elements were N_2 and O_5. Therefore, how is it possible that the product will have three additional oxygen atoms?" (p. 41). Ben-Zvi et. al. suggest two reasons for these naive conceptions of chemical changes:

> One is that students do not consider the fact that many molecules take part in the reaction and concentrate on the single entities specified....and the second...seems to be a wrong idea the students have as to what happens in a chemical reaction. Instead of conceptualizing the reaction as a process of bond breaking and bond formation, these students think that in a synthesis reaction the reactants become glued together. (p. 39-41)

> In both of these reactions the students appear to hold, an additive rather than interactive view of structure and process; a compound is viewed as made up of fragments rather than as a new entity. Similarly, the chemical process viewed as a process of mixing and gluing reactants or as a split of a compound into fragments rather than as a process of bond breaking and bond formation. (p. 50)

This approach was confirmed in the clinical interviews when two students reformulated the task of drawing the synthesis of $A_2 + B_2$ -----> A_2 B, by representing B_2 only as B in their drawings in order to more easily produce the product of A_2B. While other students represented the products as A_2B , "although they drew two atoms for both elements, the compound contained only one B. It seems that ideas of conservation did not bother them" (p. 50).

Summary of Part I

The Yarroch and the Ben-Zvi et. al. studies pinpoint various difficulties that students have in acquiring the most basic chemical facts and theories. The students in both studies had problems with the atomic-molecular theory. Students misrepresented the structure of individual molecules like $N H_3$, O_2 and N_2O_4. Both studies indicate that even students skilled at symbol manipulation have many misunderstandings about properties of atoms and molecules. For example, these misunderstandings influenced students to attribute such properties as color and state to individual atoms and molecules, to draw impossible structures for molecules and to make gross errors in the size of individual molecules and in the numbers of molecules involved in laboratory reactions. Thus, these students cannot take full advantage of the explanatory power in these symbols.

Student diagrams from both studies suggest that chemical change is treated as the gluing and ungluing of particles rather than the interaction of substances where existing substances loose their identity on their way to producing new substances. While Yarroch's students were able to conserve mass it often appeared that his students were, "...more prone to conserve symbols rather than mass or elementary particles" (p. 456). In the Ben-Zvi et. al. study, conservation of mass was often overlooked when NO_2 was produced from the reaction of N_2 and O_2. Individual atoms of nitrogen and oxygen were ignored.

Both studies suggest that adequate explanations in chemistry demand students to make mental transitions between various levels in the discipline. Both studies have shown that first year chemistry students lack this ability. Expectations are that students will have problems in adequately explaining chemical phenomena if they are required to make transitions between levels.

Finally, both studies intimated that "good teaching" took place and that the students in these studies did not learn in spite of this teaching. It is evident that even the best students have problems giving explanations that would be acceptable to the chemist. My study suggests that in explaining the problems of students learning chemistry, the problems in acquiring even the most basic chemical knowledge must be considered. Yet, I believe that one needs to look beyond chemical knowledge to other factors such as those described in the following sections of this chapter.

Part II: Conservation Reasoning

The Interrelationship Between Chemical Knowledge and Conservation Reasoning

From a chemist's standpoint, the Law of Conservation of Matter is one of the key organizing structures for the specific knowledge surrounding chemical change. Conservation reasoning is important not only for explaining mass changes, but it is also used in writing and understanding the meaning of the balanced chemical equation.

For the chemist who has acquired vast quantities of chemical knowledge, mass conservation is almost a corollary of the atomic-molecular theory. The chemist, upon observing a chemical transformation such as the burning of a wood splint, would be able to correctly account for the mass that is lost by the splint during the transformation. The chemist is aware of the invisible reactants like oxygen gas and of the invisible products like carbon dioxide gas and water vapor. The chemist is also aware that these reactants and products, even though invisible, are substantive. The chemist's superior chemical knowledge makes mass conservation an anticipated outcome.

It can also be argued that conservation reasoning about mass could play a key role in the acceptance of the atomic-molecular theory in the mind of the beginning chemistry student. If a student in a naive state observes the same burning splint as the chemist, it is conceivable that with an insight for mass conservation, the student may wonder, "Where did the mass go?" Such thinking could conceivably make the student more receptive to the existence and substantive nature of invisible reactants and products and in general open all the possibilities of the atomic-molecular theory.

In addition to phenomenological considerations, such as the burning splint weighs less, there is another area where chemical knowledge and conservation reasoning overlaps. The Law of Conservation of Matter as it applies to chemistry at the atomic-molecular level draws from the following specific knowledge of chemistry.

1. Conservation of atoms during chemical transformations.
2. Compounds may be created and destroyed during chemical transformations.
3. Only material substances are considered as legitimate reactants and products. While energy may be included in some forms of equation writing, the chemist knows that this energy cannot be used to account for mass changes during that transformation.

These are areas where chemical knowledge is integrally intertwined with conservation reasoning. This brings up an interesting approach to thinking about mass conservation and chemical changes.

Conservation Reasoning Associated with Physical, Chemical and Nuclear Changes

There are distinct differences between chemical, physical and nuclear changes. One interesting analysis answers the question, "What is conserved in each of these changes?" In everyday language, the question boils down to what is left unchanged after each of these changes occurs. This approach to conservation reasoning represents a different way of thinking about the law of conservation in that emphasis is directed away from the more global definitions found in a traditional chemistry text that focus upon the conservation of the total amount of matter and energy in the universe.

In a physical change, mass is conserved. Molecules are conserved and atoms are conserved. There is no matter-energy interconversion. Compounds are not destroyed and no new elements are produced. Changes of state are good examples of physical change that prove troublesome for some students as the products of such changes may have a different appearance than the starting materials and may even be invisible.

In a chemical change, mass is conserved. Elements are conserved but compounds are not conserved. Chemists know that energy changes accompany every chemical change. In the case of an exothermic reaction, chemists would argue that such changes only 'release' the potential energy that was stored within the bonds of the compound. In everyday chemical reactions, matter-energy interconversion does not enter into mass calculations. Chemists also recognize that the essence of a chemical change is the decomposition of old compounds with the production of new ones. In chemical changes, elements cannot be created or destroyed but only rearranged.

Nuclear changes follow the Law of Conservation of Matter and Energy which states that the total amount of matter-energy in the universe remains constant. In nuclear changes, unlike physical and chemical changes, mass is not conserved. In fact, in nuclear changes, nothing in the ordinary world need be conserved. In a nuclear change it is reasonable to explain changes in mass by stating that matter has been converted into energy. In nuclear changes, elements may undergo transmutation. Elements can lose their identity and form new elements. In nuclear changes, both elements and compounds which are composed of elements lose their identity.

This analysis of the Law of Conservation is a useful one. From this analysis I would like to restate the Law of Conservation from a chemist's perspective: In ordinary chemical changes, matter cannot be created or destroyed but only rearranged.

It is interesting that both the Yarroch and the Ben-Zvi et. al.'s studies reviewed earlier comment upon the abilities of students to conserve mass during chemical transformations. Yarroch indicates that while the students did symbolically conserve mass and elements during their attempts to balance equations, there remains some question as to their understanding of the relationship of coefficients to conservation of mass. Students in the Yarroch study seemed to blindly follow a set of algorithms rather than recognizing their physical significance. The students in the Ben-Zvi et. al. study appeared to treat conservation of mass as insignificant. Students overlooked the use of coefficients in writing the equations for simple synthesis and decomposition reactions. In fact, both of these studies seem to suggest that conservation of matter during chemical transformations is more problematical than commonly assumed.

Other research by Piaget/Inhelder and Driver directed at the topic of conservation reasoning shows that students not too much younger than those taking part in the Yarroch and Ben-Zvi et. al. studies have difficulties conserving during physical transformations like deformations and dissolving. Unfortunately, chemical transformations are considerably more complex than any of these physical transformations. Conservation reasoning is a topic that goes beyond chemistry. It seems to be one of those intellectual hurdles that all students negotiate on the way to mature thinking.

Piaget's Work on Conservation Reasoning Used in Physical Transformations

Piaget's work gives some indication as to the difficulties posed by conservation. Piaget investigated the ages at which students made the transition from non-conservers to conservers. This section will review some of the findings of Piaget/Inhelder (1941) on the ability of children to conserve quantities. Following this discussion, arguments will be made indicating where this study on chemical change departs from the work of Piaget/Inhelder on conservation reasoning in physical changes.

Conservation of Matter, Weight and Volume Using a Clay Ball

Some of the specific conservation tasks that Piaget and Inhelder investigated include conservation of number, weight and volume using balls of clay and liquids in containers. They found that by age nine or ten, most students could regularly conserve substance and weight for matter that had been deformed. Demonstrations involved the deformation of a single clay ball into a coil and the division of a larger clay ball into smaller balls. Typical responses for the deformation of a single large ball are given by Ber, No and Rug, three of Piaget/Inhelder's subjects.

Ber (age 9) There is still the same clay. It's still the same as the ball. You have just changed its shape.

No (age 9) It's the same thing as before. When it's drawn out (into a coil) or when it (it's shape) is changed, it's the same (quantity of matter). -WHY?- It's longer, but it's thinner: it's still the same.

Rug (age 10) They are both the same, because it's the same amount even though one is longer now. -WHY IS IT THE SAME AMOUNT? (He looks attentively at the coil that is still being rolled our.) -I'm looking to see if it is the same when it is all rolled out. Yes, it is. I guessed right, because you can turn it back into the same ball.

Next, the clay ball is divided into smaller balls. Here are two more examples of student responses demonstrating students abilities to conserve substance.

Va (age 8) It's the same amount but less big. -WHY?- Because if they were stuck together again, they'd get flattened out and smaller, but it's the same amount.

Gol (age 10) It's the same and it's got the same number on either side.-THE SAME NUMBER OF WHAT?- Of bits, one could make a single ball out of them by pressing them hard together: that would make the same thing. -HOW CAN YOU TELL?- Because it's the same clay.

An interesting trend emerges when examining the conservation reasoning of children across tasks of varying subtlety. While students of nine or ten could easily conserve substance and in many cases weight, many of these students could not consistently conserve volumes in which the objects submersed in water were clay balls of equal densities but differing shapes. Here is another example of one of Piaget/Inhelder's subjects.

Got (age 11) FIRST BALL-The water will rise because that will take up room. WHY? It's big, it'll make the water bigger and make the water rise. -AND THIS OTHER BALL-It's as big as the first.-AND IF I CHANGE IT INTO A COIL?-It won't be as big, it'll be thinner and take up less room.

Piaget/Inhelder conclude after reviewing the problems with conservation of volumes by saying, "...the child can only grasp the conservation of volume if he assumes that matter has an atomic or granular structure whose density is unaffected by changes in shape or by division."

Piaget/Inhelder also state,

> Now, while egocentrism and phenomenalism will persist, all changes in shape or position and all division seem to go hand in hand with changes in concentration; only an implicit or explicit atomic approach can therefore lead to the idea of conservation of physical volume. (p. 52-53)

This example together with Piaget/Inhelder's own conclusions seem to suggest that the age at which children can fully conserve increases with the complexity of the conservation task.

Conservation of Matter and Weight Using A Sugar Cube in A Cylinder of Water

In addition to the studies involving clay balls, Piaget/Inhelder also investigated more complex conservations associated with physical changes and density. I will review parts of his work on physical changes to emphasize the difficulties children have in learning to conserve matter. This will serve as a springboard into a discussion of chemical conservation which appears to provide even more difficulties for students than do the conservations of matter associated with the changes of state.

Piaget/Inhelder studied children's conservation reasoning when asked to explain the dissolution of sugar. They interviewed 400 children ages four to 12. Each child was shown,

> two glass vessels filled to the three-quarter mark with water. The vessels are placed on a balance to demonstrate that they are of identical weight, and the child is asked what will happen if a lump of sugar is dropped into the first glass..... Next, he is asked to predict the level of the water once the sugar has dissolved. He is also asked to weigh the glass before the sugar has dissolved and to predict its weight after dissolution. (p. 68)

This passage is representative of the tasks and predictions asked of the students during clinical interview situations.

Piaget/Inhelder also found that the youngest children were unable to conserve weight or volume and thought that the sugar "just vanished." Typical responses come from Fer and Man.

Fer (age 6) WHAT TASTE WILL THE WATER HAVE? -It'll be sugary...it's like steam, in a few days it will be gone...WILL THE WATER STAY UP (After the sugar dissolves?)- No it's going to drop for sure, because there won't be any taste left.

Man (age 6) The sugar will melt...you can't see anything, there's nothing left...it would taste like sugar....it's (taste) like smell, you can smell it but you can't see it.

Conservation reasoning requisite for adequate explanation of the sugar task was not fully developed even in children of twelve and thirteen. Piaget/Inhelder found that students of this age who had difficulty explaining the lack of conservation of volume in the sugar task as the volume of the sugar-water did not increase by the volume of the sugar cube. Here is response of one such student.

Jae (age 13) ...the sugar weighs as much in the water as when it's dry. AFTER DISSOLUTION, -It'll (the volume of the water in the vessel) drop back a bit. WHY? -First the sugar is dry then the water gets into it and the sugar dissolves, so the water takes the place of the sugar....but I'm not sure, we'll have to see...

Reversibility: A Key to Conservation Reasoning

There are two aspects of the student responses cited above that are worth noting: first, in Piaget/Inhelher's own words, "We see how clear all these reactions are: the conservation of matter is affirmed by all subjects as if it were inconceivable that it should be otherwise" (p. 13). Second, conservation of substance seems to be keyed by the ability to comprehend the reversibility of the processes; that recombining the small clay balls can reconstitute the original large clay ball.

At the onset of their discussion on conservation reasoning associated with dissolution, Piaget/Inhelder state that,

> ...while the clay ball merely changed its shape, dissolution constitutes a change in the state of matter and hence a much more profound transformation. Moreover, when sugar dissolves it seems to do a sort of vanishing act, and when we ask a child whether it is nevertheless conserved we are demanding a much greater mental effort from him and, in any case, an entirely different intellectual construction. (p. 67)

Conservation of substance, weight and volume are much more closely interrelated in the dissolution of sugar than in the deformation of the clay ball and also requires the child to conquer, "the problem of atomism" (p. 67). By atomism, Piaget/Inhelder mean that the sugar dissolves into particles of atomic/molecular size, invisible to the child yet existent.

One important empirical observation that can direct a child toward conservation of substance and atomism is the fact that the water after the dissolution tastes sugary. Piaget/Inhelder state that,

> The fundamental discovery that some of the substance persists even after the dissolution of the sugar must, of course, be attributed first of all to experience itself: the persistence of the taste...we must not underestimate the role that experience plays in the genesis of what is, in fact, the dawn of conservation. (p. 85)

Piaget appears to be suggesting that mass conservation in complex physical transformations may actually precede the conception of atomism and be triggered by the insight that the sugar-water still contains the sugar. This provides an interesting sequence of thought that explains how atomism is finally realized by the student. If the student thinks, "I have tasted the water and it tastes sugary...therefore, the sugar did not cease to exist, but why can't I see it?" The answer may lead to a rudimentary conception of atomism. If this sequence is accepted as plausible for the development of atomism in younger students, then it would appear that for high school aged students, acceptance of atomism can be broached both through school learning and direct experience.

Conservation Reasoning During Chemical Changes

My main objective for reviewing Piaget/Inhelder's work is to show that conservation reasoning represents an important and difficult cognitive step in the explanation of changes much simpler than those of associated with chemistry. While I believe this point is well-documented, there are other aspects of conservation reasoning, perhaps not as well-documented, that seem relevant to my study.

First, Piaget/Inhelder discovered that students, only a bit younger than those participating in my study, still struggle with mass conservation in complex physical transformations. The problems surrounding conservation in the chemistry classroom are much different than conserving volumes as liquids are poured from short-fat containers into tall-thin containers. These are physical transformations. In chemistry, students are asked to practice conservation on changes in which chemical compounds are actually being destroyed and created before their very eyes. It is not unreasonable to think that students of high school age may have problems conserving the first time they are faced with tasks much more complicated than the conservation of volumes. One might also think that students might carry over into chemical conservations the recently acquired understanding of physical conservations. Such a tact would prove disastrous and probably preclude the student from adequately explaining

Second, I have tried to present Piaget/Inhelder's argument that experience itself is an important vehicle for overcoming the barriers of naive phenomenalism in explaining the dissolution of sugar. Until the child comprehends the significance that sugar-water must contain the sugar even though it is not visible, conservation of substance is a remote possibility. These findings provide some interesting insights as I begin my argument for the importance of conservation reasoning in chemical changes.

Many chemical changes involve transformations that elude everyday sense perceptions. Piaget/Inhelder had their subjects taste the sugar-water to confirm the presence of sugar and to overcome the visual observation that the sugar had vanished. In chemistry, many of the changes require a trained eye or instrumentation or some sort of indicator to detect that a change has indeed taken place. I am thinking here of using a thermometer, pH paper, a pH meter or an organic indicator to monitor the neutralization of hydrochloric acid by sodium hydroxide. For example, few instructors would have their students drink the resulting salt solution as the confirmatory test for a chemical change. The point is that confirmatory tests in chemistry are considerably more subtle than those associated with physical transformations and the significance of such tests would be difficult for first year students to comprehend.

Third, the conservation reasoning associated with the deformation of clay balls and liquids and the dissolution of sugar required the student to eventually recognize that these transformation were ultimately reversible; the small clay balls could be mushed together to reconstitute the original large clay ball. In the sugar task, the "dawn of conservation" hinged upon the significance that the sugar-water tasted sugary, suggesting that the sugar was retrievable. Unfortunately, in chemical changes, most of the observable reactions are not reversible. One of the key premises of chemical change is that compounds can be destroyed and reconstituted to form new compounds. Piaget/Inhelder's work suggests that the harder it is for the students to reverse the transformation, the greater difficulty the students will have in conserving the quantity under consideration. The dissolution of sugar posed additional problems for the students not encountered with the deformation of the clay balls and chemical changes should pose still further problems.

Fourth, it is interesting that as the conservations became more difficult for the students, they began to use simile/analogy to explain the transformation. Fer and Man use steam and smell to explain why the sugar has or will vanish. This is a trend worth noting in my students' explanations of chemical change. One also wonders if students' newly acquired notions of atomism as it is derived from dissolution, a physical change, will be applied to more complex chemical changes? When the sugar dissolved it became invisible yet the sugar was still present. Does burning a wood splint form invisible wood particles? An interesting question to be explored is whether chemical changes are explained as elaborate versions of physical changes?

The Rosalind Driver Study ff Conservation Reasoning During Physical and Chemical Transformations

A recent study of conservation reasoning during physical and chemical transformations by Rosalind Driver (1986) is pertinent to my study of chemical change. Driver appears to take up where Piaget left off. That is, her main focus of attention is upon the kinds of conservation reasoning used by secondary students as they explain physical and chemical transformations. She starts with the physical transformations changes of state and dissolving. She then extends into the chemical transformations of burning and rusting.

Driver reviews a number of studies carried out in New Zealand, Great Britain and the continent of secondary school students' conceptions of melting, dissolving, burning and rusting. In all, she reviews some eleven studies on these topics covering both physical and chemical transformations. Most of the students in the studies reviewed by Driver are in the 11-16 year old age bracket. Driver uses these studies to further her argument that students have difficulty conserving mass during chemical changes because they apply prototypic views of the world to these changes. By prototypic Driver means that students focus upon the phenomenological aspects of the changes. Using the example of burning, Driver states, "some referred to the flame 'eating' the wood, others to it 'dissolving' or 'melting' the wood" (p. 156).

Driver calls these kinds of responses, "a prototypic view of burning: a view which is based upon children's observations of fires, matches, splints etc., burning."

Some of the characteristics of the prototypic view are that burning makes things lighter, part of the burnt material leaves as smoke and that oxygen is needed for burning (p. 158).

<u>How Students Conserve Mass in Physical and Chemical Transformations</u>

Three studies dealt with melting and student representations of the three states of matter; Cosgrove & Osborn (1981) in New Zealand, Dow, Judd & Wilson (1978) in Scotland and Brook, Briggs & Driver (1984) in Great Britain. Typical results indicate a tendency of students as old as 15 to attribute properties like states of matter that exist only at the multi-atomic level to individual molecules. For example, in the Brook et. al. study two-thirds of the students suggested that individual molecules could melt. Results like these are interesting because they are similar to those of Ben-Zvi, Eylon and Silberstein cited earlier. A typical response of a student attributing properties to the wrong level was,

> At the temperature of -10 C the particles are at their largest because at low temperatures ice expands. But when the temperature rises to -1 C it is on the way to becoming melted if the temperature rises any more and each little particle begins to get smaller in size so the overall size of the block of ice will have been slightly altered. (p. 152)

Driver next reviews a cross-section of responses given by students to the physical transformation of dissolving. The students were asked to predict the mass of a solution made by dissolving 200 grams of sugar in 1000 grams of water. Results from a study by Anderson (1984) indicated that over one-half of the students predicted that the solution would have less mass than the original sugar and water. Typical responses were, "because the sugar does not do anything to water...it just dissolves into nothing at all." "When the sugar dissolves in to the water the sugar has no mass so it is just like the 1000 grams of water."

A clinical interview of an 11-year-old girl follows. The girl appears to be in a transition state from a non-conserver to a conserver.

P: I think it might be lighter.

I: ....Why do you think it might be lighter?

P: Because its (the sugar) all dissolved away.

Later in the interview.

I: ...Do you think there is any sugar in there?

P: Yeah, but its dissolved.

I: But you think the weight is now gone?

P: No, I think its there.

Still later, she adds

P: It'll still be there because its just dissolved into the water, but it'll still be there.

I: Um....

P: 'Cos if you evap...um...put that on a Bunsen burner on the wire through to evaporate and you get the sugar, cos we did that before.....

There are two points to be made from these responses. First, like the students in Piaget/Inhelder's study, many students still are unsure about mass conservation in complex physical changes like dissolving.

Second, apparently a previous experience of seeing sugar being reconstituted upon evaporation of water served to focus the young girl's attention back to the fact that the sugar had not ceased to exist upon dissolving. The fact that this student waffles between her belief that the mass of the solution has decreased because the sugar has disappeared and that the solution weighs the same after mixing as before, indicates to me that she is at a transition point in acquiring the ability to conserve mass in one of the more difficult physical transformations.

This example is similar to that cited by Piaget where the 'dawn of conservation' was linked to the experience of tasting the sugar-water to confirm the presence of sugar. In the present example, it is unfortunate that more information is not available on the girl's understanding of the term 'dissolving'. If, as the interview suggests, dissolving means to vanish, then the girl is not using notions of atomicity to derive mass conservation. If the girl is basing her mass conservation upon the recognition that evaporation will reconstitute the sugar, then Piaget's argument for experience is all the more convincing. That is, if the girl thinks upon recalling the process of evaporation, "the 200 grams of sugar were still present in the solution, but only invisible. Why couldn't I see the sugar?" Given that sequence, then I believe that there is a case to be made for independence of conservation reasoning from content of atomicity even in a physical transformation like dissolving.

Conservation Reasoning Used in Chemical Changes

Mass conservation during chemical changes posed a critical problem for the students in the studies reviewed by Driver. Driver sought the students' intuitive ideas before instruction. One question asked students to compare the weight of a wood splint before and after burning.

Typical responses were of two types, something in the wood disappears and the ash appears to be lighter than solid wood. A sample of the later type of response is: "The ash weighs less...Because when you burn it into ash, some of it will disappear and that is why I thought it lighter."

Some of the general features of students' intuitive ideas of burning identified by Driver are summarized as follows:

1. Oxygen (or air) is needed (its function may not be clear, it may even be seen as being 'burnt away' in the process.

2. Things get lighter when they are burnt.

3. Burning drives off the smoke or parts of the material are driven off as smoke.

In another study (Driver, Child, Gott, Head, Johnson, Worsley and Wylie, 1984) two groups of English students (some after completion of a chemistry course and some before a chemistry course) were asked about the weight changes associated with burning of steel wool. Surprisingly, both the chemistry and the non-chemistry students gave strikingly similar responses. Forty-one percent of the chemistry students predicted the steel wool would weigh less after heating and 56 percent of the non-chemistry students made the same prediction. In each instance student explanations ignored the basic tenet of chemical conservation: the total mass of the reactants must equal the total mass of the products. A sample of student responses follows.

The steel wool weighs more because of a physical change to the steel wool. "When the iron wool was first put on the scales there was air going through it but now it is a powder and it is in small parts it is heavier (12-year-old)" (p. 159).

The steel wool weighs the same. Here the underlying theory is that heating is only a physical change. "It would stay the same because the powder is the wool but heated up so there is really no difference" (15-year-old) (p. 160).

The steel wool weighs less after heating because something would be burnt away. "Pan P will move up because it isn't as heavy as it was before, because some things will have been burnt out" (15-year-old) (p. 160).

Mass Conservation: Development Over Time

A point that has been made several times throughout this discussion of conservation reasoning is that as the mass conservations have become more subtle, the age of the students who can successfully conserve mass has increased. Particular difficulties arise when students are asked to conserve mass under conditions where some of the elements avoid sense perception. Here, I am thinking of the steel wool demonstration where the sparks, smoke and general compacting of the steel wool while heating suggests, from all outward appearances, that the wool should weigh less after heating. In order to show this developmental relationship between the task and the approximate ages at which mass conservation becomes an obvious feature of the task, I have prepared a chart (Table 2.1) drawing from the responses of the children in the Piaget/Inhelder and Driver studies.

Table 2.1: Conservation Reasoning Mapped Against Age for Various Conservation Tasks.

TASK	AGE OF STUDENT		
	6-10	11-13	14-17
CLAY BALL	it's the same amount only less big....if they were stuck together again ...it's the same amount. (age 8) Piaget		
DISSOLVING SUGAR CUBE IN WATER.	the sugar will melt...you can't see anything, there is nothing left.... (age 6) Piaget		
		the sugar weighs as much in the water as when it's dry...(the volume will) It'll drop back a bit ...the water gets into it (sugar)...I'm not sure... (age 13) Piaget.	

TABLE 2.1 CONT'D.

DISSOLVING 200g SUGAR INTO 1000g WATER:	when the sugar dissolves into the water the sugar has no mass, so it is just like the 1000g of water. (age 15) Driver-50% of sample gave these responses
BURNING SPLINT: THE SPLINT WILL BE LIGHTER AFTER BURNING.	when you burn it into ash, some of it will disappear... (age 11-12) Driver.
BURNING STEEL WOOL: THE WOOL IS HEAVIER.	....now it is a powder, it is in small parts it is heavier. (age 12) Driver.
THE WOOL IS THE SAME.	...the powder is in the wool but heated up so there is no difference. (age 12)
THE WOOL IS LIGHTER.	...powder is lighter than the iron wool. (age 15) Driver.
RUSTING: THE NAIL WEIGHS THE SAME.	...rust is iron that has been transformed. (age 15) Driver. The iron only reacted with the oxygen of the air which does not weigh anything.

Mass Conservation within the Perceived System

It is interesting that near the end of her discussion, Driver states that her study can't decisively state that secondary students cannot chemically conserve. Rather, the issue appear to be what aspect of the problem students are focusing on in considering their answer (p. 166).

Driver concedes that many of the students in these studies are aware of much of the chemical knowledge associated with the changes they are explaining. Students know, for example, that air is composed of gases like oxygen which are substantive. Yet, they look past these facts. Instruction in general is overlooked as students engage their prototypic views as a basis of explanation. Driver notes that chemical transformations require imagination to move away from the perceptively obvious.

I believe that students who employ prototypic views either lack the chemical knowledge or overlook their existing chemical knowledge because of the complexity of the system. That does not mean, however, that students are not attempting to conserve mass. It may very well be that the conservation reasoning is inappropriate for the kind of transformation being explained. That is, given the perceived system, the students may actually be applying correct forms of mass conservation. Reviewing the response of the student cited above who stated that the steel wool after heating would weigh the same as before, shows that if this student were treating this change as similar in form to evaporation, it makes sense that the weight would remain the same.

Driver's analysis provides fresh insights but no easy explanations as to why students have such difficulty conserving mass during chemical changes. Driver falls back on Piaget's idea that conservation of matter depends upon the child's acceptance of the particulate nature of matter: atomicity and indestructibility. This is a topic that remains open for discussion. Mass conservation in complex transformations as found in chemistry brings into question the relationship between chemical knowledge and conservation reasoning patterns. Piaget's work suggests that children develop a general schema for mass conservation that is not context specific. Yet, Piaget's work stopped short of chemical transformations. From Driver's study, it appears that the more complex the transformation, the more the students will need a theory to help them apply this generalized schema for mass conservation. For example, in burning, without some chemical knowledge of reactants and products it seems improbable that students would ever be able to conserve mass. It is hard to conceive of a real life experience that could lead students beyond the observed products of combustion, namely the ashes. It is conceivable that if students treated burning as a physical transformation like evaporation with the wood evaporating into smoke, that correct conservation reasoning would be applied, albeit the wrong system.

Summary of Part II

There are several points of interest to my study that can be derived from the work of Piaget/Inhelder and Driver.

First, conservation of mass in chemical transformations is not often acquired solely through instruction on chemical knowledge. This was seen in the similar responses of the chemistry and non-chemistry students. This suggests that mass conservation reasoning in chemical transformations is a result of experience and insight into the critical aspects of conservation such as atomicity and reversibility.

Second, the ages at which students can conserve mass seems to increase with the complexity of the transformation. Beginning with Piaget's work with young children conserving substance as a piece of clay is subdivided into smaller pieces and going through Driver's review of how high school chemistry students conserve mass when steel wool is heated; it becomes apparent the as the mass conservations become more subtle, the ages at which the students can successfully make these conservations increases. A chart was prepared mapping the task against the age at which students begin to successfully conserve mass.

Third, there are aspects of conservation reasoning in chemical transformations that require a vast amount of specific chemical knowledge. With chemical changes, the differences in mass before and after the transformation are often masked by the physical nature of the products. In many instances invisible reactants and products are masked by the evolution or absorption of energy. Here the subtlety of the conservation often evades sense perception as in the burning of the wood splint or the burning of the steel wool. In both instances the physical appearance of the products promotes what Driver calls a prototypic view in the students, making mass conservation all the more problematic. Chemical changes pose the added problem to the experience of reversibility. Reversibility in chemical changes like burning is difficult conceptually to imagine and impossible to physically reconstruct. As I have stated, the experience of reversibility plays an important role in the development of mass conservation in complex physical changes like dissolving. It is easy to see why mass conservation in chemical systems is all the more problematical for high school aged students.

Fourth, judgments on the conservation reasoning patterns used by high school chemistry students must be withheld pending an analysis of the system the students are perceiving. Students who explain chemical changes using prototypic views may well be practicing correct conservation reasoning but on the wrong system.

From the discussions above, it seems evident that a complete understanding of the development of mass conservation in chemical transformations is not yet available. More importantly, it seems probable that mass conservation reasoning in chemical transformations is an understanding that while related to chemical knowledge is not necessarily a corollary of that knowledge.

Part III: Explanatory Ideals

The Basis of My Three-Part Model

Parts I and II of this chapter indicated that the problems students have in adequately explaining chemical changes can be attributed to the problems they have in acquiring chemical knowledge and mass conservation reasoning. I believe, however, that chemical knowledge and conservation reasoning are not enough to adequately explain chemical transformations in a manner that would be totally satisfactory to the chemist. An element of an acceptable explanation is knowing why that explanation is acceptable. As a teacher, I want my students to give scientifically correct explanations, and, I also want them to understand why their explanations are correct. This other area of knowledge is related to the students' acceptance of the chemist's explanatory ideals which will be discussed in this section. But first, I will review the anecdote I first cited in Chapter 1. I cannot overstate the effect that this brief student-teacher interaction had upon my perceptions of what students must know in order to produce an acceptable scientific explanation.,

A few years ago, I had a chemistry student who has since gone on to become an electrical engineer. His work was well above average in chemistry. One day he brought up an old exam that he had recently completed and asked me to explain some questions about chemical changes. I was surprised in that he wanted me to explain the questions that he had gotten correct on the exam. I asked him what was troubling him and he confided that his answers didn't make sense to him even though he knew they were correct. In our discussion it became evident that he had a thorough grasp of the content. It was not just that he had memorized all the right words. he responded to my questions in a ways that would make a teacher feel that they had done a good job teaching. It was interesting that all of his questions were of the simile/metaphor/analogy type. "Is it like this....?" he would ask. He would then proceed to relate the test item to something from his everyday life. That experience was quite a revelation to me. Further investigations found that other A-students held similar uncertainties. From that point on I began to take a different look at the relationship between my science teaching and my students' understanding of science. I realized that learning chemistry involved much more than learning the accepted facts and theories. Thus, this study also focuses upon ideas about the nature of explanations. Unlike chemical knowledge and conservation reasoning, there are few empirical studies in this area. As a result, I will look at studies drawn from the history and philosophy of science.

The Notion of an Adequate Explanation

The notion of what counts as an adequate explanation in science is a complex one. Even within the present scientific community there remains some difference of opinion as to its nature. While some of these differences may hold more of an interest to the philosopher of science than to the reader of this dissertation, it is worth while to review how notions of an adequate explanation have changed over the course of history.

A common trait emerges when the kinds of responses that have served as adequate explanations in chemistry throughout history are examined: the puzzling events are explained through reference to something considered to be more simple or self-explanatory at that time in history. Explanation through reference to things more simple gives a certain form or structure to acceptable explanations in chemistry. Stephen Toulmin makes an argument for this in his book, Foresight and Understanding. In this study, explanations of good form or structure will have the aforementioned characteristics.

In his book, Toulmin discusses how matter-theory has changed over the course of history. Toulmin contends that from Aristotle to Dalton, there has been a changing notion of what would constitute an acceptable explanation of chemical change. Toulmin seems to suggest that acceptable explanations have retained the same form or structure over the centuries. Only the content of acceptable explanations has changed. The differences in explanation have been due to changes in acceptable content rather than changes in form. In this study, explanations of good form relate the phenomenon to be explained to some other phenomenon considered to be more simple or self-explanatory.

An article by Solomon (1983) on the nature of scientific explanations given by school children makes similar points as Toulmin on the form and content of acceptable scientific explanations. Solomon states that children often draw from two distinct domains of knowledge when asked for a scientific explanation, "Life-world Knowledge" and "Scientific Knowledge." Students refer to "Life-world Knowledge" as a basis of scientific explanations.

Solomon identifies four kinds of explanations commonly given by students. Using Toulmin's scheme of analysis, two of the four would demonstrate the acceptable form of a scientific explanation even if they failed the test for content. These four types of explanations will be briefly reviewed.

Solomon identifies the first kind of student explanation as: "Things As They Are." Here, "the children seek not so much a reason as a simple redescription which emphasizes its normality" (p. 1). In response to the question, "Why are the lights out?", a typical response of this kind might be, "Because it is night time."

The second kind of explanation Solomon calls "Explaining The Meaning." Here, one word is replaced by a simpler word of the same meaning. This approach, when applied to scientific explanations encourages semantic rather than analytic explanations (p. 2). When asked to list methods for preserving foods and explain how they work, many students stated after giving their example that preservatives work by, "Keeping them fresh" (p. 3).

The third and fourth kinds of explanations involve the use of similes, metaphors, analogies and models, and finally, theoretical explanations based upon a commonly accepted theory or law. I believe that both of these kinds of explanations would be granted good form by Toulmin because they attempt to explain the puzzling phenomenon through reference to things considered to be more simple by the student. The problem with using SAMMs (Similes, Analogies, Models and Metaphors) ultimately comes down to the question of content. Content provides the second test of an acceptable explanation and will be discussed next.

Given Toulmin's explanation, an adequate explanation in chemistry is subject to a two part test. The first deals with the form or structure of the explanation. The second part of the test focuses upon the content. If an explanation fails either part of the test, the explanation is most often found to be unacceptable.

Explanations that are merely restatements of the question or focus upon the definitions of words that make up the question lack the form of an adequate explanation and fail the first part of the test. Chemists would consider these kinds of explanations as really no explanation at all. For example, some students state that the coated copper will weigh more because it has a coating on it. This is not acceptable to the chemist because it lacks the form of scientific explanations. Unfortunately, these kinds of explanations are quite common whenever a request for an explanation is made of a group of students.

The second test of an adequate explanation focuses upon the content of the explanation. Good explanations should appeal to a commonly accepted theory or law. For example, to explain why a giraffe has such a long neck, an appeal could be made to the theory of evolution. Such an explanation would be accepted by most in the scientific community. In chemistry, if there is a singularly accepted theory; it is the atomic-molecular theory. The atomic-molecular theory is the content to which explanations of good form will appeal. An acceptable explanation of the changes surrounding the burning of a match would include some discussion of atoms and molecules as described by the atomic-molecular theory. An explanation that compared the burning match to a person growing old refers to no theory and would not meet the second part of the test for an adequate explanation.

Solomon's work is insightful as it suggests the notion of the good SAMM. Properly constructed, the SAMM can be insightful additions to scientific theory. Here, I am thinking of the usefulness of the solar-system model in guiding the early development of modern atomic theory. The problem with some kinds of SAMMs used by children is they, (a) are inconsistent and context bound, (b) are not symbolic, and (c) are well socialized or cannot be obliterated by science lessons. For Solomon, the "rich metaphorical meanings of everyday life" (p. 131) yield explanations of scientific phenomenon that would pass the test of good form for scientific explanations because everyday knowledge does represent something more simple and self-explanatory to the student but would fail the second test for content.

Reductionism: A Characteristic of a Theory with Good Form

A characteristic of the atomic-molecular theory is that it is reductionist in nature. Adequate explanations explain larger systems in terms of smaller subsystems. Reductionism requires that an explanation drop down to the next lower level to adequately explain the phenomenon. The larger, observable changes in the match as it burns to ash and smoke are best explained through reference to the particles that make-up the match and the ambient air. In fact, there is an expectation in the modern chemist that a chemical explanation of a match burning will appeal to atoms and molecules.

Additionally, Toulmin would argue that the content of adequate explanations is ever evolving. The atomic-molecular theory represents the presently accepted content for an adequate explanation. To better understand how explanations of chemical change have evolved over history, Aristotle's approach to chemical change will be reviewed.

The Aristotelian Theory of Chemical Change

Toulmin in Foresight and Understanding, describes the changing conceptions of matter-theory and dynamics among other scientific conceptions. For the purposes of my study, Toulmin's discussion of matter-theory will be reviewed.

Toulmin begins by examining the prevailing theories used by Aristotle to describe change in the physical world. Toulmin argues that the bulk of Aristotle's scientific knowledge consisted of biological/physiological processes; the life cycles of plants and animals. Aristotle was a naturalist who had very little understanding of the changes that we now recognize as chemical changes. Aristotle had very little specific knowledge of chemistry available to him at that time in history. When faced with explaining the interactions of inanimate matter, Aristotle used the processes of animate materials. The important point of this discussion is that Aristotle used the familiar to explain the unfamiliar.

The problem with Aristotle's approach, argues Toulmin, is that living materials do not change in quite the same way as do inanimate materials. For Aristotle, the world about him was dynamic. In Toulmin's words, the physical world changed through a mechanism of "organic metabolism." Organic metabolism represented an explanation of physical change in harmony with the processes of growth, change and decay as evidenced in the reoccurring life patterns of plants and animals.

Organic metabolism became the cornerstone of Aristotle's matter-theory and was accepted by the alchemists as the operating principle of change within the physical world. To understand how this could be, the Aristotelian world must be re-examined.

Alchemy operated under a number of principles that "make sense" when understood within the Aristotelian ideal of organic metabolism. When looking for the origins of Alchemy, Toulmin discusses two processes, cooking and ripening. Toulmin suggests that the idea of ripening was "the more typical and self-explanatory..." (p. 69). This familiar organic process placed the direction of matter theory as that of using the familiar physiological changes to explain the unfamiliar structural changes that would occur, for example, in cooking.

Toulmin provides an interesting analysis supporting the work of the alchemists.

> Alchemy was not just a species of black magic, camouflaged by a pretentious array of jargon. It was, rather, a premature system of chemical philosophy, founded upon a highly developed set of ideas. These ideas embodied and carried further Aristotle's developmental paradigm of material change.... (p. 89-90)

Toulmin further points out that the Alchemists were aware of the practice of seeding to improve yield. Thus, attempts to nurture the formation of gold from baser metals by seeding with small portions of gold dust represents a rational approach to the goal at hand. "The dream of producing gold in this way was never nonsensical-only vain" (p. 75).

Modern chemistry treats changes in the physical world in a much different fashion than did Aristotle. To the chemist, matter is not dynamic and changeable but is static. For the chemist, the mechanism of change is the chemical reaction, which is based upon the interaction of inanimate particles.

Atoms and molecules, the stuff of material substances, remain immutable unless reacted upon by another substance. Mercury will retain its identity, its composition and properties, unless reacted upon by another substance. This basic tenet of the Law of Conservation of Elements rejects the Alchemist's dream of converting mercury into gold. Modern chemists now believe there is no life cycle for mercury. Proper nurturing cannot ever change mercury into gold. The process of nuclear decay in which one element is really transformed into another element, is presently treated as the emission of inanimate particles according to rules governing the conservation of charge, mass and energy. Organic metabolism no longer holds any explanatory power within modern chemistry.

It is not difficult to argue that for Aristotle, the Laws of Conservation relating to elements and compounds could not apply. Conservation would be unthinkable in a world where animate and inanimate objects alike grew and changed according to inherent natural principles. Toulmin cautions, however, that much of the criticism of Aristotle's matter theory should be withheld. Pure substances form the basis of modern chemical reactions. Yet, the concept of a pure substance is relatively recent. Even today, the notion of a pure substance remains an idealized concept and a most costly reality as pure substances cost many times that of impure laboratory grade chemicals.

Toulmin's Definition of an Explanatory Ideal and the Evolving Definition of an Adequate Explanation

Toulmin uses the Aristotle anecdote as part of his argument for the existence and function of explanatory ideals. He states, "here in a man's ideas about the Natural Order, we find out what is in his eyes self-explanatory" (p. 42).

An explanatory ideal becomes a statement of the "given" in a scheme of understanding which need not be explained. An explanatory ideal outlines the theories which a person believes to be more simple or self-explanatory. An explanatory ideal defines a piece of the world as it exists for that person. For Toulmin, the content of one's explanations depends to a great extent upon, ".....our explanatory ideals..., which are,

....intellectual patterns which define the range of things we can accept (in Copernicus' phrase) as 'sufficiently absolute and pleasing to the mind'" (p. 81).

In the case of Aristotle, it was the life cycle of plants and animals that was self-explanatory. It was the life cycle that became Aristotle's explanatory ideal. For Aristotle, plants grew from seeds when properly nurtured. Physiological changes were 'self-explanatory' and were used to explain structural changes. Or, if you will, the familiar was used to explain the unfamiliar.

Toulmin contrasts the Aristotelian and modern approaches to adequate explanations of material change. Toulmin further states, "...the relation between the 'familiar' and the 'unfamiliar' may be reversed. If we were to insist on accounting for the 'unfamiliar' in terms of the 'familiar,' instead of vice-versa, we should never be able to shake ourselves loose of Aristotelian dynamics (and matter-theory)" (p. 60).

With these statements, Toulmin challenges and redefines the notions of an adequate explanation. "Our standards," states Toulmin, "must be, not what is familiar, but rather what is intelligible and reasonable in the course of nature" (p. 61).

Within a discipline like Chemistry, there will be certain theories that will dictate the standards of intelligibility. These theories, such as the atomic-molecular theory, may seem far removed from the familiar event to which they will be applied.

The Atomic-Molecular Theory: The Explanatory Ideal Associated with Modern Chemical Change

The atomic-molecular theory has been discussed from the standpoint of chemical knowledge. From this perspective the atomic-molecular theory includes the physical and chemical properties of atoms and molecules and the interactions between them to free-up elements or produce new compounds. When the atomic-molecular theory is treated as an explanatory ideal, the concepts of atoms and molecules are accepted as the legitimate explanatory format for chemical transformations. This means that the atomic-molecular theory is chosen over teleologies, word substitutions and analogies as a means of explaining rusting and burning etc.

Using the atomic-molecular theory as the explanatory ideal for chemical change means that chemical changes will be explained through reference to atoms and molecules. This, however, represents an inversion of familiar to the unfamiliar. In some respects, the familiar everyday events of students are not much different that those known to Aristotle. All students in this study have taken one year of general Biology. They are familiar with the concepts of organic growth and of seeding. Toulmin makes the claim in his discussion of matter theory that these were two processes that formed the basis of Aristotle's explanatory ideal.

The Relevance of Toulmin's Work for My Study

Toulmin provides a key to understanding the similarities and differences between Aristotle's explanations and those of the modern chemist. His description of explanatory ideals also represents a theory of explanations that can be useful in understanding the differences between the responses of first year chemistry students and those given by the chemist.

Toulmin argues that adequate explanations in science come when the familiar event is explained in terms of the unfamiliar or highly abstract law or theory. This presents a problem in that the reasons to accept the atomic-molecular theory are not obvious -- a fact alluded to by Toulmin in his discussion of matter theory. Even though most students use the terms atoms and molecules quite freely, the research cited earlier suggests that they do not really understand their meanings.

Toulmin considers Aristotle as much a scientist as the modern chemist. The differences between Aristotle and the modern chemist, are found to be more at the level of content than of structure or form. Both Aristotle's explanation and modern chemists' explanations of chemical change are equally scientific in the sense that they explain puzzling events in terms of something that they consider to be more simple or self-explanatory. The differences in their explanations is in what they consider to be more simple or self-explanatory. Both, in Solomon's (1983) analysis, would have good form. That is, Aristotle and the modern chemist have different explanatory ideals. Differing explanatory ideals have lead Aristotle and the modern chemist to contrasting explanations. An explanatory ideal becomes an important element in understanding the adequacy of a given explanation. Toulmin has shown that Aristotle's explanatory ideal for chemical change was the familiar life cycle of plants and animals, while the explanatory ideal for the chemist is now the atomic-molecular theory.

Explanatory ideals become an important aspect of this dissertation. For Toulmin, an explanatory ideal is an element of any explanation that has an acceptable form or structure. An assumption of this study is that students, like chemists, have explanatory ideals. Often, the students' explanatory ideals are different from the chemists'. Furthermore, it is assumed that these differences in explanatory ideals can be used to understand the different responses given by students and a chemist. Personal feelings of satisfaction associated with student responses are related to their explanatory ideals. In this study, an adequate explanation is seen as a specific instance that is in accord with an explanatory ideal. This study also assumes that explanatory ideals can be stable structures that are resistent to change.

Summary: Chapter 2

The purpose of Chapter 2 is to present the reader with a theoretical basis for understanding the major premises of this study. It has been documented that students have many difficulties explaining relatively common chemical changes in a way that would be acceptable to the chemist. The reasons for these difficulties are complex. The source of these difficulties are assumed to lie in student problems in acquiring three kinds of understanding: (a) chemical knowledge, (b) conservation reasoning and (c) certain explanatory ideals. Each of these three areas was discussed in chapter 2 and will be briefly reviewed at this time. Each of these areas raises issues of interest for this dissertation and for science education in general. These issues will be identified and summarized within this section.

Chemical Knowledge

Chapter 2 reviewed two studies that are taken from the same genre' of educational research. Both Ben-Zvi et. al. and Yarroch examined the difficulties of students in learning about the structure and interactions among atoms and molecules. Both used clinical interviews to uncover the chemical knowledged possessed by students in these areas.

One important finding of the Ben-Zvi et. al. study was that Israeli students attributed properties like color and state which only exist at the multi-atomic level to individual atoms and molecules. This problem is symptomatic of a larger problem; that being students' inability to make fluid transitions between the phenomenological, multi-atomic and atomic/molecular level of chemistry. This is an important theoretical framework from which to examine student problems.

The Yarroch study of equation balancing found that students often treated equation balancing as a mathematical game of getting chemical symbols to add up across reactants and products. Yarroch suggests that students must acquire understanding at two levels of equation balancing: a higher level of theory and laws and a lower level including the mechanics for the "efficient manipulation of symbols" (p. 458).

Both studies have shown the vast amount of chemical knowledge that must be acquired before a student fully grasps the significance of O_2 (g) or the role of subscripts and coefficients in chemical reactions. A great deal of specialized knowledge is required at the three levels as identified by Ben-Zvi et. al. before a student will have the knowledge to explain chemical changes. As indicated, my study will not consist solely of examining chemical knowledge. Yet, the importance of chemical knowledge in chemical conservation and in developing an explanatory preference for the atomic molecular theory cannot be overlooked. I have chosen to use the theoretical framework of Ben-Zvi as a basis for analysis of the chemical knowledge used by students as they explain everyday chemical changes.

There are three issues pertaining to students' acquisition of chemical knowledge that are raised by these studies.

ISSUE 1: Physical properties. What properties do students attribute or fail to attribute to atoms and molecules?

ISSUE 2: The nature of reactants and products in chemical changes. What kinds of things, material or non-material, do students believe can be reactants and products in chemical transformations?

ISSUE 3: The mobility of students across levels. To what extent can student make observations of chemical changes at the phenomenological level and explain these at the atomic/molecular level?

Conservation Reasoning

Ideas about mass conservation were derived from the work of Piaget/Inhelder and Driver. More specifically, those portions of Piaget/Inhelder's work that dealt with mass conservation were reviewed. Piaget/Inhelder focused their attention upon physical transformations including the deformation of clay balls and the dissolving of a sugar cube. Driver started with dissolving and went into chemical transformations like burning and rusting.

A survey of both studies shows that the age at which students can conserve mass increases with the subtlety of the task. Mass conservation during complex physical transformations like dissolving is not self-explanatory to many students near the age of 15. Mass conservation during chemical changes is difficult for most secondary school students. Students are hampered by inclinations for prototypic thinking which Driver has described as one that focuses upon the observable manifestations of the phenomenon.

Both studies seem to suggest that when the ability to conserve mass comes to a student, the conservation is obvious. Driver suggests that mass conservation during chemical transformations depends upon the student's ability to conceptualize the total system. This insight is impeded during chemical transformations by the fact that the total system is hard to visualize. In physical transformations the total system is less complex and all parts are often visibly apparent. In the Ball of Clay transformations, mass conservation was related to the insight of reversibility of the transformations. Even in the dissolving tasks, mass conservation seems linked to the insight of atomism which is aided when the students were allowed to taste the sugar water. This way the total system was within the sensory grasp of the student.

In chemical transformations the total system often involves invisible reactants and products and thus evades the sensory perceptions of the students. There is the additional problem in that the reversibility is much harder to conceptualize in chemical changes than in physical changes.

Driver suggests that some of the errors in mass conservation may be due to the students misinterpreting the size of the chemical system before them. I believe that Driver is correct on this point and wish to examine conservation reasoning by first trying to determine what system the student believes to be present, and then making a judgement upon the quality of the conservation reasoning given that system.

There is an additional stumbling block to mass conservation in chemical transformations. That is the amount of chemical knowledge required to conceptualize the total system. I believe that with chemical conservation there is an intertwining of specific chemical knowledge with conservation reasoning that was not required for mass conservation during physical transformations. The chemical knowledge that directly relates to chemical conservation deals with conservation of atoms during chemical changes and that gases are substantive.

I am suggesting three issues about conservation reasoning that are relevant to my dissertation.

ISSUE 1: Conservation of mass. To what extent and by what means do students attempt to conserve mass during chemical transformations?

ISSUE 2: The boundaries of the system. When students are asked questions directed at their ability to conserve mass during chemical changes, what are the students' perceptions of the system in which they are asked to conserve?

ISSUE 3: The nature of the change taking place. To what extent is there confusion between chemical and physical transformations?

Explanatory Ideals

Part III developed the concept and function of explanatory ideals in scientific explanations. The work of Stephen Toulmin formed the basis for this concept with some discussion of Joan Solomon's categories of children's explanations of scientific phenomena.

For Toulmin, an explanatory ideal is a state of nature that a person considers "basic" and without need of explanation. Toulmin argues that throughout history, the explanatory ideals of a given age have dictated the parameters of an adequate explanation. Using the historical development of matter-theory as an example, Toulmin demonstrates that the Aristotelian ideal for chemical change represented a rational approach to explanation. Toulmin's work suggests that the process of explanation in science is one of comparing the puzzling event to something considered more basic or fundamental. For Toulmin, such explanations have good form.

Solomon has identified four kinds of scientific explanation given by elementary school children: (a) explanations that suggest that that's the way things naturally are, (b) explanation by redefinition or word substitution, (c) explanation by simile, analogy, model and metaphor (SAMMs), and (d) explanation based upon scientific theory. The first two kinds of explanations lack the good form identified by Toulmin and would not be considered by the scientist as legitimate forms of explanation. It seems to me that explanations that are statements of the phenomenological events, such as, "the splint after burning weighs less because ash weighs less than wood," also lack good form and would fit into Solomon's first category. This explains why the prototypic explanations given by the students in Driver's study are not considered acceptable explanations of scientific phenomena.

The third and fourth kinds of explanations would be more readily acceptable to the chemist. SAMMs, however, are interesting because the form of a acceptable explanation. Solomon indicates that SAMMs can play an important role in the development of mature scientific thinking. Solomon also indicates that some SAMMs are more productive than others in this development.

This leads to two issues related to explanatory ideals that are pertinent to this study. These deal with the form and content of the explanations given by students. Toulmin suggests that explanations of good form explain the phenomenon in terms of a law or theory that appear to be more basic than the phenomenon to be explained. For Aristotle, the simpler and more self-explanatory theory was related to the familiar practices of cooking and seeding. My study is interested in the kinds of explanations that are actually preferred by students. Solomon has documented the power of analogical thinking when students are asked to explain everyday changes. Driver has shown that student explanations of everyday chemical changes often focus upon the observable features of the change. Toulmin has argued that for the modern chemist, chemical changes represent an inversion of the familiar with the unfamiliar. The atomic-molecular theory represents an inversion of the familiar with the unfamiliar for those who lack training in chemistry. And, more often than not in everyday phenomena, the familiar will be seen as simple to comprehend.

The role of explanatory ideals can be resolved by examining the form and content of student explanations.

ISSUE 1: The form of student explanations. What kinds of explanations do students prefer: analogical, prototypic, chemical or simple word substitution etc.?

ISSUE 2: The content of the explanation. What is the content of the preferred explanations given by students when asked to explain common chemical changes? What kinds of analogies etc. do students draw from when they explain chemical changes?

CHAPTER III

METHODOLOGY

Introduction

The purpose of this chapter is to review how the students were selected, the methods of data collection and analysis. In this chapter, I will show how the questions on the written questionnaire allowed me to collect information on students' chemical knowledge, conservation reasoning and explanatory preferences. I will show how the questions asked of students allowed me to gather necessary data to address the issues posed in chapter 2.

This chapter begins with an overview of the study, an explanation of the paper/pencil instrument, a review of the questions directed at each of the three areas, a summary of the clinical interview techniques and an explanation as to how the data will be analyzed.

Overview of Study

Early in the school year about 100 first year high school chemistry students were shown a series of teacher-demonstrated chemical changes. The demonstrations were presented prior to instruction on chemical change, equation writing and stoichiometry. These topics comprise chapters

3, 4 and 5 in the students' text, Chemistry: A Modern Course, (Smoot and Price, 1979). In these chapters such concepts as atoms, molecules and formula units are introduced without any attempt to discuss atomic structure or the bonding of these particles together as these topics are discussed in chapters 6-10 of the book.

The changes chosen for demonstration consisted of three redox reactions in which there was one invisible reactant or product accompanied by a measurable change in weight. The three demonstrations involved a rusty nail, the heating of copper metal in air, and the burning of a wood splint. Students were given two 46 minute class periods to respond in writing to the questions accompanying the demonstrations. The "Paper and Pencil Instrument" is described in the next section and is presented in the Appendix.

After reviewing student responses, 11 students were chosen for half-hour clinical interviews. These students were chosen on the basis of their responses and their willingness to discuss their responses with me, their instructor. The 11 students first chosen were all above-average students with extroverted personalities.

The instruction took place from the beginning of October through the middle of December. During this time, instruction focused upon Chapters 3, 4 and 5 of the text. These chapters covered the topics of chemical/physical change, the writing and balancing of equations and stoichiometry. The changes used in the demonstrations were not discussed as a separate topic but were discussed as they came up in the course of instruction. For example, students burned wood and heated copper in one of their laboratory exercises that accompanied the text. The topic of rusting was taken up during a lecture on equation writing and the types of reactions.

During instruction, particular emphasis was placed upon the Law of Conservation as it applies to chemistry. Conservation of elements and mass were treated as two corollaries to the more general law as it applies to matter and energy. The role of invisible reactants and products as a way to account for mass changes was emphasized. Students were shown through a lecture exercise that matter/energy interconversion is more an area of concern for the nuclear scientist than the chemist. Additionally, students were instructed that chemistry focuses upon changes in which existing substances rearrange to form new substances.

After instruction, lasting about ten weeks, all students were again asked to respond to the same set of demonstrations they had seen earlier. In addition to the questions pertaining to the specific changes, students were also asked to rate their level of satisfaction with their responses. Originally, this was done only with a part of the 11 students who were clinically interviewed. Depending upon their responses, students were asked to state what additions they felt should be added to their present explanations to make that explanation more acceptable to themselves and to a scientifically trained adult.

Eleven students were again chosen to be clinically interviewed. Not all of the 11 were identical with those chosen before instruction. The reasons for this were two-fold. First, I wanted information on how students across the range of achievement understood chemical change. Specific efforts were made to avoid a population of all above-average or all below-average students. Thus, students were selected from three categories, the A/B, B/C and C/D range of grading. All of the students demonstrated an ease of talking with adults and all were perceived as giving a sincere effort to learn the course material.

After the pretest it became apparent that all of the students were entering chemistry in a naive state. A majority of those interviewed were above-average students. During the process of reviewing student evaluations of their own explanations, it became evident that some of the most interesting evaluations came from students who had not participated in the first set of clinical interviews, yet were representative of the larger sample. I decided that much could be learned by interviewing these students. Given these two conditions, all students entered in a naive state and that different students were interviewed in the post-test, the analysis portion of this study will focus only upon the written post-test and post-test interviews.

Three students were selected from the 11 for in-depth analysis. Tom was an A-student in chemistry, Sue was a B/C-student and Bill was a D-student. Tom, Sue and Bill were representative of the achievement levels of the other eight students in the smaller sample. While the three case studies comprise the bulk of this study, some comparisons will also be drawn between the three and the remaining eight students.

Data Collection

The Paper/Pencil Instrument

This instrument was designed to uncover the students' understanding of three areas: (a) chemical knowledge of the changes involved, (b) the kinds of conservation reasoning used in describing chemical changes and (c) their explanatory ideals.

The instrument was based upon a series of three demonstrations. Demonstration one consisted of showing the students a clean and a rusty nail. Demonstration two consisted of showing and weighing a clean piece of copper metal, heating the copper metal with a bunsen burner until the copper was covered with a black coating, and then reweighing the coated copper. At each step, students were asked to respond in writing by making predictions of the mass changes and explaining what was happening to the copper metal. Demonstration three consisted of burning a wood splint. The splint was weighed before and after burning.

The pretest instrument did not include a section related to explanatory ideals. I felt that this topic could be better handled during the clinical interviews. After these initial interviews, however, I decided to create a set of questions pertaining to explanatory ideals that could be given to all the students as part of the post-test. This addition proved to be helpful. Student responses to this set of questions provided clues as to their explanatory ideals and more importantly provided a starting point for discussion in the clinical interviews.

The Clinical Interviews

In all, 11 students were clinically interviewed after the post-test. Most of the interviews were conducted either before school, after school, during lunch or during my preparation period. Interviews lasted between 30 and 45 minutes.

During the clinical interviews, questions were directed at clarifying the student's written responses on the paper/pencil instrument. Typical questions directed at the students were of the nature, "What were you thinking when you stated.... .?" In the early parts of the interview, students were given opportunities to respond to these very general probes. Here, further information was gained on the students' depth of specific knowledge and theories of chemistry.

In order to get a clearer understanding of the students' explanatory preferences, an additional instrument was prepared and given to the students during the clinical interviews. A full description of this instrument follows in the section on explanatory preferences.

Data Analysis

The data analysis focused upon the 11 students who were interviewed after instruction. There were two stages to the data analysis process. During the first stage detailed case studies of three students were prepared. These students were given the pseudonyms Bill, Sue and Tom. During the second stage, the analytical framework developed for the case studies of Bill, Sue and Tom was extended to the other eight students. These two stages are discussed separately following the flow chart (Figure 3.1) that summarizes the methods of data collection and analysis.

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----------------------------------
-  100 FIRST YEAR CHEMISTRY      -
-  STUDENTS GIVEN WRITTEN        -
-  INSTRUMENT.                   -
----------------------------------
               :
               :
               :
----------------------------------
-  11 REPRESENTATIVE STUDENTS    -
-  CHOSEN FOR CLINICAL INTERVIEWS-
-                                -
-  NO RANDOM SELECTION.          -
----------------------------------
               :
               :
               :
----------------------------------
-  3 CASE STUDIES OF STUDENTS    -
-  REPRESENTATIVE OF THE         -
-  11 STUDENTS INTERVIEWED.      -
----------------------------------
               :
               :
               :
----------------------------------
-  COMPARISON OF THE 3 CASE      -
-  STUDIES WITH THE REMAINING    -
-  8 STUDENTS IN SMALLER SAMPLE  -
----------------------------------
```

Figure 3.1: A Flow Chart of the Methods and Data Analysis Post-test.

Stage 1: The Case Studies of Bill, Sue and Tom

The literature review in chapter 2 highlighted eight issues that seemed relevant to my study. All of the 11 students chosen for clinical interviews addressed a majority of these issues in a satisfactory manner. Bill, Sue and Tom were chosen for inclusion in in-depth analysis because they were articulate in explaining their thought processes and represented the range of abilities found in the 11 students. In the early stages of data analysis, the 11 students naturally separated into three groups; those who were near the goal conceptions for each of the issues, those who retained naive conceptions in spite of instruction, and those students who appeared to be in a transitional state somewhere between goal and naive conceptions. Bill, Tom and Sue are representative of students in these three categories.

In the development of the case studies, emphasis was placed upon development of a coherent framework which would provide a sensible and consistent explanation of Bill, Sue and Tom's responses to the written instrument and the clinical interviews. The guidelines used to develop this framework were the categories of chemical knowledge, conservation reasoning and explanatory ideals, and the eight issues which emerged from the literature review in chapter 2. The central problem of these case studies lies in trying to determine where Bill, Sue and Tom stood on each of the eight issues.

During the analysis of Bill, Sue and Tom it became apparent that two of the issues from chapter 2 were not relevant to this data set. Additionally, two new issues not previously discussed in chapter 2 emerged as important elements of the three case studies. Specifically, the issue dealing with the properties of individual atoms and molecules and the issue of the form of student explanations were not pertinent to an understanding of the three case studies. However, the students' confusion over the kind of transformation they were observing and their notions of what would count as an adequate scientific explanation did emerge as unanticipated findings from the three case studies. Further details on these findings can be found in chapter 4.

Stage 2: How the Remaining Eight Students Were Analyzed

The three students chosen as the case studies for this paper were representative of other students in the sample. While all students were clinically interviewed, detailed case studies were not prepared as part of this dissertation. Rather, the comparisons between the three and the remaining eight were done by focusing upon the similarities in responses to the relevant issues identified in the three case studies. Students were categorized as holding either naive conceptions, goal conceptions or being in a transitional state for each of the issues. There is some commentary following each issue comparing the eight students to Bill, Sue and Tom.

Subsequent sections explain the selection of questions and give a brief example of the kind of responses generated from these questions. A copy of all the written instruments may be found in the Appendix.

Specific Descriptions of Data Collection/Analysis

Chemical Knowledge Questions

The literature review in chapter 2 indicated that chemical knowledge of structure and process in chemistry is difficult for the majority of first year chemistry students. In subsequent sections of chapter 2, I argued that chemical knowledge plays a role in the development of mass conservation during chemical changes and that chemical knowledge is a pre-requisite for the adoption of the chemist's explanatory ideal, the atomic molecular theory. From the literature review in chapter 2, three issues emerged from the discussion of chemical knowledge. These issues will be listed and the questions on the written instrument that address these issues will be reviewed with some commentary on the expected responses.

Issue: The Nature of Reactants and Products.

This issue was attacked directly on the written instrument and again during the clinical interview. Each of the demonstrations was accompanied by the same set of questions. The first question asked students to, "Make a list of all the substances that you believe to be involved in this change-and tell the role of each." Students were asked during the clinical interview, "What were they thinking" as they listed the reactants and products. I hoped that students would identify the chemical substances involved in the reactions they were describing. Students were not explicitly asked to write a balanced chemical equation. Some of the students did include equations as part of their explanations. By leaving the equation as an unstated option, I felt that I could get a better idea of the size of the system and components of the system that the students were evaluating.

Issues: The Properties of Atoms and Molecules and Mobility Across Levels.

My study was conducted at the phenomenological level of chemistry. Chemical changes were demonstrated and students were asked for their explanations. In this format, there were no specific instructions for students to talk about the atoms and molecules involved. For these issues, I was interested in the extent that students, without being guided, would disclose their understandings of atoms, molecules and their willingness to use atoms and molecules in their explanations without being told to do so. An example of such an open-ended question that provided students with an opportunity to shift across levels is, "How do you think the rust was made and what is it made of?" During the clinical interview I used the probe, "What were you thinking when you gave this response?" Even with these kinds of open-ended questions, there was an expectation that students would demonstrate a mobility from the phenomenological to the atomic-molecular level as class discussions had focused upon the interaction of surface atoms of iron and copper with oxygen gas molecules, etc.

Conservation Reasoning Questions

Two of the three demonstrations dealt with chemical changes that produced a removable coating on the surface of a metal: iron rusting and the oxidation of copper metal in air. The third demonstration focused upon the changes associated with the burning of a wood splint. For those chemical changes that produced a removable coating, students were asked to predict whether the substance with the coating would weigh more, less or the same as the original uncoated substance. Each question was evaluated in terms of the prediction, the explanation that followed and the students' chemical knowledge of reactants and products. These questions were analyzed from the perspectives suggested by the three conservation issues identified in chapter 2. Since the conservation issues were just different aspects of the same problem, specific questions were not designated for each of the issues. A brief synopsis of how these issues were addressed follows.

Issues: Conservation of Mass, the Boundaries of the System and the Nature of the Change Taking Place.

The questions about weight/mass were directed at the students' grasp of the law of conservation of mass and elements. For example, the responses of students to the question, "Will the rusty nail weigh more, less or the same as the original clean nail?" held interesting possibilities for conservation reasoning. For example, it is possible that the students in this study are ignoring important aspects of the system they are asked to describe, such as the presence and reactivity of oxygen gas. It is also possible that students are applying some form of conservation reasoning other than that associated with chemical conservation. Piaget has shown that conservation reasoning is complex and seems to develop incrementally with conservations of number, shape, volume and amount developing at different rates. This study identifies the kinds of conservation reasoning used by students even if it is not chemical conservation. Some plausible responses to the rusty nail question are given below.

A response that the coated nail will weigh "more" suggests that the student may hold the chemist's versions of the law of conservation. For example, if a student responded, "More, because the oxygen combined with the iron," this suggested that this student was chemically conserving mass. Yet, a response of "more" when coupled with an explanation that, "the rust coated the iron and coatings will always weigh more," suggested that the student was not chemically conserving mass.

A prediction that the rusty nail would weigh less than it did before rusting suggested that students were not conserving mass in a traditional chemical sense. Comparing the prediction with the explanation allowed me to conclude that these students were overlooking the substantative nature of oxygen gas. That is, the boundaries of the system these students were explaining included only the nail and the rust, but did not include any invisible gases.

An interesting response to interpret was that of "same." Students who responded that the rusty nail would weigh the same as the original clean nail were not conserving mass in the chemical sense and were most likely overlooking the role of oxygen gas as a reactant in this reaction. It is here, that the issue of the perceived type of transformation became relevant. A response of "same" could suggest an explanation of rusting as an elaborate version of a physical change of state. Changes of state conserve both mass and elements. Water freezing to ice does in fact conserve both mass and elements, but is not a chemical change.

The paper/pencil instrument also asked students to compare the mass of the nail after the rust is removed to the mass of the original clean nail. Given the nature of the question it was unlikely that any students would predict "more." For those students who predicted "less" or "the same," their prediction was evaluated in conjunction with their explanation. If a student responded, "less" they may have been conserving mass and elements, but for the wrong reasons. If a student really treats these types of chemical changes as changes of state, it is not illogical for them to state, "less." If you remove the surface layer from a freezing tray of ice cubes, the remaining water will weigh less.

On the other hand, if the response of "less" was accompanied with an explanation that included phrases such as "eaten away" and their list of reactants and products consisted of only everyday materials, I concluded that this student was ignoring mass conservation all together.

The most acceptable response following a "less" prediction was that the nail weighed less because some of the original nail was in the coating of rust. This suggested an understanding of chemical conservation of mass.

A response of "same" suggested that the nail was just covered with a coat of rust that somehow formed on the surface of the nail. This type of response suggested that the iron nail was not really a reactant in a chemical sense in this transformation.

After turning the page, students were then told that if the coating was removed, the remaining metal would weigh less, and were asked to explain this fact. Presumably, if a student held the chemist's theories, upon being told this information, they would conclude that the coating must include some of the iron from the nail. If the student was committed to a non-chemical system of only everyday materials, they would miss the significance of this new information.

All of the demonstrations were accompanied with questions similar to those interpreted above. Responses to these questions gave data from which patterns in the students' conservation reasoning could be derived.

Questions Directed at Explanatory Ideals

An explanatory ideal as described in chapter 2 is a complex mental structure. One assumption of this study is that both students and chemists have explanatory ideals. This does not mean that they are conscious of them. It remains problematical whether Aristotle could have written down or openly discussed his explanatory ideals. For these reasons, I decided to ask students about their explanatory preferences. By collecting data upon the types of explanations that students prefer, I felt that this would give us some insights into their explanatory ideals. My assumption is that students will choose or prefer an explanation that is in accord with their explanatory ideals.

The student evaluation sheet from the paper/pencil instrument proved to be a useful entrance to the students' explanatory preferences. Included in the interviews are student responses to a second instrument that was used only during the clinical interviews. Initially, this instrument was only to be used if the students did not respond to probes directed at their self-evaluations. Its use, however, provided for insightful commentary and was included in most of the interviews.

The Issues of Form and Content in Student Explanations.

Because the questions on the written instrument were open-ended, there were no specific questions directed just at form and content. The written questions that provided most of the information were those that asked the students to explain how the rust, etc. was formed. In addition to the questions dealing with the specific chemical changes, the students were asked to evaluate their own responses. At the conclusion of each demonstration, an additional questionnaire was distributed to each student. Each student was asked to make two personal judgments as to the acceptableness of their own responses. I hoped that by asking the students to evaluate their own answers, it would be possible to gain some insights into their explanatory preferences. During the clinical interviews, students were asked to clarify their written responses and were also given an additional instrument which asked the students to choose a balanced equation, a home-spun analogy or both as a means of making their explanations more acceptable to a scientifically trained adult. The sheet with the equations and the analogy was created for the sole purpose of stimulating conversation if the students were too self-conscious to discuss their own responses. I expected that the vast majority of the students would easily see through the two alternatives and unhesitantly choose the balanced chemical equation. Not so! Many of the B+/A students who participated in this study rather consistently chose the composite analogy.

These choices can be interpreted in three ways. First, by choosing the analogies, students may be indicating a need for something familiar when explaining scientific phenomena. Second, students may be demonstrating an unconscious need for something verbal. And third, by not choosing the analogy and shunning the equation, students may be stating that they really do not understand the equation.

It would be expected that an A-student who understood the equation would have no need for the analogy, as is the case for Tom whose case study follows in chapter 4. Responses from the students who were clinically interviewed suggest that many students chose the analogy for all three of the reasons cited above. A copy of this portion of the instrument can be found in the Appendix.

The information gained from these areas -- the written explanations of the specific changes, the evaluations, the preferred mode of explanation and the clinical interviews -- was used to make inferences on the form and content of student explanations. More will be said on this in chapter 4.

Summary of Chapter 3

Chapter 3 reviewed how students were selected and the methods of data collection and analysis. In summary, I would like to make the following points:

1. About 100 first year chemistry high school students were asked for their understandings of rusting, the oxidation of copper metal and the burning of wood. In this early stage of data collection students were asked to respond in writing to a questionnaire that accompanied a demonstration of each of these chemical changes. The questionnaire was structured in such a way that data could be gained about their chemical knowledge, conservation reasoning and their explanatory preferences. Specific questions accompanying each demonstration focused student responses in each of these areas. Students were

tested before and after instruction on chemical change, equation writing and stoichiometry. Responses on the written instrument indicated that all students entered in a naive state. I decided to focus attention upon student understandings after instruction and to ignore any pretest post-test comparisons.

2. To insure a cross-section of student thinking, 11 students were chosen for clinical interviews from three loosely defined grading categories, A/B students, B/C students and C/D students. No attempt was made for random selection and no claim is made for statistical significance. Thus, after the initial selection of students no effort was made to correlate achievement with response patterns outside of loose references to kinds of responses that the best students were giving. Each student was thought to be giving a good effort in the class and each student, regardless of their grade, was friendly and indicated a willingness to discuss their written responses in a clinical interview.

The clinical interviews lasted between 30 and 45 minutes. Students were asked to explain what they were thinking about as they responded to the written instrument.

For the clinical interviews, an additional instrument was constructed to aid in the clarification of the students' explanatory preferences.

3. Data analysis took place in two stages. In stage I, three students, Bill, Sue and Tom were selected for in-depth case studies from the 11 who were clinically interviewed. These students were representative of the thinking in the 11 students. The main task in this analysis was trying to determine where each of the students stood on the eight issues identified in the literature review in chapter 2. Not all of the issues were pertinent to my study and the data analysis uncovered two new issues not considered during the review of the literature.

In stage II, the key issues derived from the three case studies was extended to the remaining eight students who were clinically interviewed.

CHAPTER 4

RESULTS

Introduction

Chapter 4 will be an in-depth examination of the responses of three students that typify the students in this set. Bill, Sue and Tom were chosen because they represented a cross-section of student responses from the most naive to the most sophisticated in terms of their understanding of the chemical changes presented for their explanation.

Each case study will examine the student's responses from four perspectives. Patterns in their responses are used to discover the students' chemical knowledge, ability to chemically conserve, their explanatory preferences and their responses to new information. Statements of Bill's, Sue's and Tom's explanatory ideals will be made when the data warrants such inferences.

The case studies represent a compilation of information gained from the written exercise and the clinical interview. The progression in the case studies will be from Bill to Tom and ending with Sue. Sue was chosen to be last because analysis of her responses places her somewhere between Bill, who has a limited understanding of chemical change, and Tom, whose responses closely approach those of the chemist.

Tom, Sue and Bill are representative of the other eight students who earned above-average, average and below-average grades in chemistry.

The analysis of Bill, Sue and Tom addresses the issues raised in the literature review found in chapter 2. New issues are also brought to the forefront. The issues raised in these case studies will be used to assess the remaining eight students. Summary charts, together with a commentary, will presented on the students' chemical knowledge, conservation reasoning and explanatory preferences.

Case Study 1: Bill

Introduction

Bill was one of four students whose responses to the questions on the paper/pencil instrument indicated a much different approach to the explanation of chemical change than was presented during instruction. Bill talked freely during the clinical interview and was able to articulate his position better than the remaining three students. For this reason Bill was chosen to be one of the thee case studies.

This case study will begin by examining Bill's responses to a series of questions about rusting, the heating of copper and the burning of a wood splint. There are patterns in Bill's responses that indicate an erroneous but rational approach to explaining chemical change. These patterns yield insights into his chemical knowledge and his conservation reasoning.

Next, Bill's reflections and judgments upon his own answers will be considered. His written responses together with information gained from the clinical interview yield unique insights into Bill's explanatory preference.

Furthermore, Bill's responses suggest that the amount and nature of the chemical knowledge acquired by Bill is governed by three factors: his present chemical theories, his present level of conservation reasoning, and his explanatory preference. His ability to handle new information depends upon the interaction of chemical knowledge, conservation reasoning and his explanatory preference. Unfortunately, Bill's theories and his explanatory preference represent naive ways of thinking about chemical change.

This case study describes and analyzes the difficulties of a hardworking student who is having many problems learning the chemist's version of chemical change.

Bill's Explanation of A Rusty Nail

On the paper/pencil instrument Bill was asked to write down the reactants and products involved in this change. Bill listed iron and cold as the only reactants/products involved in a nail rusting. Bill says of the cold, "...the coldness reacts on it (nail)....plastic doesn't rust because coldness doesn't cause the same reaction."

Adding to this, Bill later states that, "...rusting is a breakdown of the iron because it (coldness) brings out the rusting....it (coldness) almost draws it (rust) out, like a magnet....like an attractor, it brings it (rust) out."

Bill shares his reasons for the importance of the cold.

Bill: ...if something is applied, different conditions....in a warm temperature, the nail won't rust....but in a cold temperature it will rust because it's kinda like the conditions around it are changing so itself must change.

I: ...so the cold...

Bill: ...it has an effect on it...it has a different temperature....different atmospheres...it brings out the elements that make it (nail) rust....

On the paper/pencil instrument, Bill predicts that the rusty nail will weigh the same as the original clean nail and gives the following explanation:

Bill: It would probably weigh the same because the iron nail just turned rusty and it didn't say whether anything was lost. It just said that it turned rusty. Nothing was lost.

This response prompted a question during the clinical interview portion of the study.

I: What were you thinking about?

Bill: To me, it (the nail) just changed form....cold isn't really a solid, it just changes the form of it (nail)....the cold brings out what was in the nail.

On the paper/pencil instrument, Bill makes a further prediction that the nail would weigh less after the rust is removed, "...because you are taking the rust away from it (the nail) and the rust comes from the iron and therefore rust contains iron."

When asked to comment upon this during the clinical interview Bill replies that:

Bill: ...the rust comes from the iron and therefore the rust contains iron.

I: What do you mean by that?

Bill: I meant that the rust is the iron.....

Explanation of the Heating of Copper

Bill lists on the paper/pencil instrument, "copper and heat" as the only substances involved in the heating of copper. Bill is asked about this during the clinical interview.

I: What role does the copper play?

Bill: ...it is the base for the reaction...the heat is the catalyst, if you just stick copper down, it won't burn...the heat is what causes the reaction...just like the nail, the coldness is the catalyst...it (the heat) causes the copper to shine...."

When asked about the black coating that forms on the copper, Bill responds:

I: ...so how do we end up with the black coating?

Bill: ...like when you combine the heat and the copper...its like the end product, the mixing of the two...mixing the heat and the copper caused the product of the black coating, I would say.

Bill has predicted on the paper/pencil instrument that the coated copper will weigh more than the original clean copper because there is a, "...black coating all over it (copper)."

Bill further predicts that if the coating is removed, "...it (copper) will weigh the same because all it did was turn it black. You could scrape it (black coating) off and you would have your original piece of copper."

Later on, in the paper/pencil instrument, Bill is given the information that if the coating is removed, the remaining copper will indeed weigh less. To this he responds:

Bill: (from paper/pencil instrument): Heat was applied to it (the copper) and it (the copper) lost weight from evaporation due to the application of heat.

During the interview, Bill is asked to clarify his statements on the coating.

Bill: When it (copper) burned you really didn't lose any fumes...the basic copper just remained, except the outer just turned color....it (the coating) was like a film...made up from the base weight of the copper.

In a concluding statement on the paper/pencil instrument Bill states,

Bill: The coating was made of copper....there was nothing else the coating could have been made of.

Explanation of a Burning Splint

The clinical interview with Bill ended before we were able to address his responses to the burning splint. Fortunately, Bill gives a pretty good set of written responses. We begin with Bill's prediction that the burned splint will weigh less than the original splint.

Bill: It (the splint) weighs less because the flame destroyed part of it. Matter was being destroyed.

When he is told that the burnt splint will indeed weigh less, Bill reconfirms his original thesis.

Bill: ...the flame destroyed the matter by consuming it. In the next response asking him to comment upon whether he thought a chemical reaction had taken place or not, Bill again states:

Yes, Because the matter is being destroyed and the product is smoke. Heat + splint = smoke. MATTER DESTROYED!!

How to Make Sense of Bill's Responses

The question arises, "What is there about the nature of Bill's explanations that accounts for these unexpected patterns in his responses?" I have noted that Bill is attracted to analogical thinking with an emphasis upon the familiar event. Bill's explanations of the rusting of a nail, the oxidation of the copper and the burning splint suggest three classes of familiar events. The first is that of organic growth/decay, the second is changes of state and the third is destruction by burning. A discussion of the plausibility of each of these classes will be take in turn.

Chemical Change as Organic Growth/Decay

There are segments of Bill's explanation of rusting that show interesting parallels to the type of explanation given by Aristotle and his followers, the Alchemists. In particular, it is Bill's use of heat and cold to promote chemical change that is reminiscent of the Alchemists whose theories of chemical change were the operant theories right up to the time of Dalton and the modern atomic theory.

From Bill's responses to rusting and the heating of copper, it appears that he is treating heat and cold in much the same way as the alchemists. The alchemists used heat to speed up the natural processes associated with "organic growth" in order to produce gold from baser metals. Heat was associated with nurturing. Nurturing was a process of varying environmental conditions to enhance the growth of living materials. From the time of Aristotle, nurturing was also thought to be related to the processes of chemical change. For Bill, nurturing and decay may be opposite ends of the growth continuum. Bill's responses suggest that by varying the environmental conditions the formation of rust may be enhanced. Whereas heat may enhance growth, cold may enhance decay. Bill has stated that, "the cold brings out what was in the nail." It is as if the nail can be made to decay into rust given the proper conditions. We should note that Bill has stated in the clinical interview that,

Bill: ...if something is applied, different conditions...in a warm temperature, the nail won't rust...but in a cold temperature it will rust....

I: ...so the cold...

Bill: ...it has an affect on it .... it has a different temperature...different atmospheres..it brings out the elements that make it (nail) rust....

Another aspect of Bill's responses that appears consistent with the alchemist's approach to chemical change is his almost blatant lack of concern for conservation of elements. At no time, in any response, does he ever indicate an awareness of the modern chemist to conserve elements.

As was stated above, I believe that Bill is attempting to explain these unfamiliar chemical changes by analogy to everyday changes with which he is familiar. Bill seems to have some familarity with the growth of living organic materials. Perhaps Bill is recalling information he learned in the Biology course he took the previous year.

Chemical Change as Intricate Physical Change

Another familiar process involves changes of state like the formation of ice on water and the evaporation of liquid water. A closer look at Bill's responses from this perspective proves quite interesting. There are segments of Bill's responses that read as if he were describing a change of state rather than a chemical change. This represents the only conservation reasoning pattern that emerges from discussions with Bill. As was stated earlier, conservation of physical entities represents a level of understanding that comes to some students only a short time before they attempt to learn the concepts of chemical conservation. Conservations associated with changes of state were difficult for students only a year or two younger than Bill. In Bill's chemistry course, changes of state are presented just before a discussion of chemical changes. It is not unrealistic to suggest that Bill is using his notions of changes of state to help him explain the chemical changes.

In changes of state, substances change appearance but not mass. Ten grams of water, when frozen, make ten grams of ice. If water starts to freeze and then some of the solid ice crystals are taken away, the remaining water will weigh less. Thinking in this way about Bill's explanation of rusting, it follows that if some iron is changed into rust and the rust is removed, the remaining iron will weigh less. This is precisely the prediction made by Bill. Bill states that the rusty nail will weigh the same as the original clean nail, because the rust is just iron. In the copper demonstration he states that the coating on the copper is just copper and that the copper looses weight by evaporation. As was stated earlier, Bill has no understanding of chemical conservation. Yet, his predictions on mass changes associated with the iron and copper demonstrations make some sense when interpreted as applications of his knowledge of changes of state.

The objective of this discussion on changes of state and the earlier discussion of organic growth/decay is to argue that even though Bill's responses are markedly different than those of the chemist and even from some of the other students interviewed, his responses demonstrate a sensible, consistent approach to describing change.

Burning and Dissolving: Both Destructions of Matter

Bill's description of the burning splint demonstrates his lack of chemical knowledge and of any laws of conservation. Bill overlooks the role of the invisible reactants and products and focuses upon the external manifestations of the change before him. When Bill states that burning destroys matter I am inclined, given his other explanations, to believe that he really means that the splint is destroyed and not just rearranged into carbon dioxide and water vapor.

In chapter 2, Driver detailed accounts of students who thought that dissolving actually destroyed the sugar when placed in a container of water. For many students, dissolved sugar did actually cease to exist. Also recall Driver's suggestion that understanding dissolving depended upon an understanding of the atomicity of matter, an understanding that Bill presently lacks, and an ability to imagine the reversibility of the dissolving process. Bill shares a "prototypic view" of chemical change with his focus upon the external manifestations of the change involved. Like the students in Driver's study, Bill grossly underestimates the size of the system before him. Without an understanding of the role of invisible gases like oxygen, carbon dioxide and water vapor, the dawn of chemical conservation for Bill does not appear to be imminent.

How Bill Evaluates His Own Responses

One might think that a student with such unusual theories of chemical change would feel somewhat lost in this course. Such is not the case for Bill. Following each demonstration, Bill was asked to critique his answers. He consistently indicated that his explanations would be similar to those of a scientifically trained adult. Bill also indicated that he was satisfied with his explanations and that they made sense to him. In other words, here is a student who gives incorrect answers but thinks they are right. He is satisfied with his explanations and they make sense to him. Situations such as this pose some real problems for the teacher and also yield some insights into how complicated the learning process can be.

This section will review Bill's reflections on his own responses. This review will yield insights into why Bill is satisfied with his answers when they are obviously much different from those a chemist would give. This particular set of responses will lead to a statement of Bill's explanatory preferences and ultimately to a statement about Bill's explanatory ideals.

In the clinical interview, Bill shares some insights as to why he responded the way he did. During the clinical interview, students were shown a balanced chemical equation and a verbal, homespun analogy. They were asked if either of these two would make their explanations more acceptable to a scientifically trained adult. This instrument was designed to uncover the students' explanatory preferences.

After answering questions about the formation of rust on a nail, Bill stated his belief that his responses were essentially correct and that he was personally satisfied with them. He was asked about this in the clinical interview.

I: what is it about your answers that make sense to you?

Bill: ...even though some of my answers are not those of a trained adult, I feel even with my observations from my point of view that they make sense to me....

I: ...what exactly do you think that I would want in your answer?

Bill: If it had more terms, if it had a more scientific outlook...if I had like the closing line, something outstanding that would make it (rusting) different than other reactions.

Bill is next shown the alternative descriptions.

Bill: I think both of them...I think that in order to understand a reaction you have to break it down into the ferric and the oxide...you also have to have a written explanation because rusting is a breakdown of the iron...the coldness draws it out (rust) like a magnet....

In this next exchange Bill relies upon the analogy to make sense of unfamiliar chemical change. In explaining why his description of the heating of copper makes sense to him, Bill states:

Bill: ...this is not a very hard experiment and I could see exactly what was going on....it's very obvious because in everyday life...when you burn wood in heat, you get fire out of it, and it's like the wood breaks down and for me it's even more like a gas stove ...in everyday life I see these things....I've had experience with heat.

I: You talk of experiences of everyday life, were they helpful to you?

Bill: ...I base my assumption on those, I compared the fire to what happened to that (stove) to this (the heated copper)....

I: Do you often try to look for everyday analogies...

Bill: I remember the things from everyday life...I recall it when it comes down to scientific work....year after year things come along and things would change.

When Bill is shown the equation and the composite analogy, he again gives his choices with the following explanation:

Bill: ...number 1 and number 2 (both the equation and the analogy)...both help...besides having the formula, you need the explanation, some things are left unanswered in the formula....

I: What don't you like about 1 (the equation)?

Bill: It doesn't tell you that the copper weighs less because the copper has been burned away....you are just saying that you are combining the copper and the bunsen burner but you aren't saying that it weighs less....

Analogy as the Preferred Explanation

This section consolidates much of the information given above into a more concise description of how Bill formulates his responses when asked for an explanation of a chemical change. In doing this, Bill's explanatory preferences will become evident. Recall the argument that the preferred explanation is a preference for one type of explanation. The patterns in Bill's responses suggest that his preferred explanation is the analogy with familiar events. The preferred explanation becomes a general statement of what counts as an adequate explanation in chemistry.

It is interesting that Bill's explanations of chemical phenomena share some similarities to those given by Aristotle. Toulmin has argued that Aristotle explained unfamiliar chemical changes in terms of the familiar changes associated with organic growth. This approach to explaining the interactions of inanimate atoms and molecules in terms of the processes associated with living materials is a key characteristic of Aristotle's explanations and forms the basis of his preferred explanation. Although there are elements of Bill's explanations that resemble Aristotle's predilection with organic growth, the most common characteristic of both their explanations is the common practice of explaining the unfamiliar chemical change in terms of the familiar event.

The modern chemist's approach to scientific explanation contrasts with that of Aristotle and Bill. Modern chemistry explains phenomena through reference to subsystems. This is an example of reductionism. The modern chemist explains the changes associated with rusting by reference to interactions between atoms and molecules. Atoms and molecules form the basis of the modern chemist's preferred explanation. The atomic-molecular theory becomes the chemist's explanatory ideal.

Bill's responses suggest that it is doubtful that he even thinks of atoms and molecules when asked for an explanation at the phenomenological level of chemistry. It seems safe to say that Bill's explanatory ideal is not the atomic-molecular theory.

Yet, a problem remains in adequately describing Bill's explanatory ideals. I believe that at this time, Bill lacks an explanatory ideal for chemical changes. An explanatory ideal is a statement of a consistent explanatory preference. Bill has no statement of things considered more simple and self-explanatory as the modern chemist does. This lack of a developed explanatory ideal can be used to explain why Bill's choice of analogies appear to have an ad-hoc quality about them. Without a developed explanatory ideal, each chemical change has a different analogical counterpart. Although Bill prefers the familiar event as did Aristotle, Bill lacks a fully developed explanatory ideal. Aristotle, unlike Bill, found in the familiar changes about him a reoccurring theme in the life cycles of plants and animals. Bill has not yet found such a pattern in chemical changes.

In summary, Bill is satisfied with his responses because they are derived form everyday experiences. The familiar event makes sense to Bill. His statements about the importance of analogy in his explanations lend insights into Bill's theories of chemistry, his method of classifying changes and ultimately about his preferred explanation.

How Bill Handles New Information: Reinforcement Among the Areas of Understanding

An important theoretical premise of this dissertation is that understanding the nature of Bill's problems requires an understanding of his chemical knowledge, his level of conservation reasoning and his explanatory preference. An outcome of this premise is that in order to help Bill gain the chemist's understandings of chemical change, one cannot "just" change his specific knowledge or "just" his theories or "just" his explanatory preference. Changing Bill's understanding in one area, say his explanatory preference, will not be sufficient to help him generate acceptable explanations. Bill must be taught new specific knowledge and shown how theories like those associated with conservation organize these specific knowledge. After gaining some confidence using his new specific knowledge and theories, he will begin to develop an explanatory preference consistent with his other knowledge and theories.

I would next like to show how these areas interact and mutually reinforce one another. This will be done by examining how Bill handles new information. By showing how Bill handles new information, information that was meant to jar and reorient his thinking, the relationship among the areas will become evident.

The new information on the written exercise consisted of giving the student the correct response after asking for a prediction of mass change. For example, the student was asked whether the nail would weigh more, less or the same as the original clean nail after the rust was removed. The student then turned the page and was told that the nail would indeed weigh less after the rust was removed. Presumably, if the student had responded, "more" or "the same," this new information would hopefully cause them to rethink their explanation. Near the end of the clinical interview, students were shown the paper with the balanced equation and the composite analogy formulated from the responses of the students. This constituted new information to the student. It was expected that given these options in the presence of the instructor, the students would again rethink their earlier responses and select the response that made the most sense to them after reviewing all the questions pertaining to the specific chemical change. It was anticipated that the students would all choose the balanced equation as the equations had been discussed during the presentation of the material during instruction on chemical change.

During the clinical interview Bill was shown a balanced chemical equation for the chemical change he observed and a composite analogy. He was asked if these might make his explanations more presentable to the scientist. I will briefly review a series of responses in which Bill demonstrates his interest in the analogy as the preferred explanation.

I: (After the rusting exercise) What do you like about 2 (the analogy)?

Bill: Well, 2 (the analogy) gives examples of other kinds of breakdowns...they all have something in common ...each of them, the fungus and the heat, something brings them out....

I: (After the copper exercise in which Bill indicates that, "some things are left unanswered in the formula.") What don't you like about 1 -- the equation?

Bill: ..it doesn't say that the copper weighs less because the copper has been burned away....you are just saying that you are combining the copper and the bunsen burner....

Although several points can be made about Bill's responses, the most significant one for this discussion is the ease with which Bill dismisses the information contained in the chemical equation. Bill has just finished commenting upon his responses to the iron and copper exercise. He is shown the chemical equation with the expectation that subsequent responses will include reference to this equation and the information contained within it. In particular, it was expected that Bill would comment upon the role of oxygen gas as a reactant in both the iron and the copper reactions. He does not. In fact, Bill completely dismisses the role of oxygen as a reactant in the copper reaction and replaces the oxygen with the bunsen burner. I believe that Bill does this because his preferred explanation consists of analogies with familiar events. Bill's familiar events center around things that can be detected by his senses, like the bunsen burner. Although it was not pursued during the clinical interview, I believe that when Bill referred to the bunsen burner, he was referring to the flame or the heat from the burner.

Additionally, Bill's lack of specific knowledge of invisible gases and his lack of a chemical conservation theory make it impossible for him to see the significance of the equation. His chemical theories are drawn from familiar events. He can readily explain the changes before him through reference to these naive theories. Bill openly states that he finds the composite analogy an attractive addition to his analogy based explanation. His explanatory preference for the analogy is reinforced when he finds yet another analogy before him. There is little need to adopt atoms, molecules or equations when his theories of heat and cold are reinforced by the composite analogy. The oxygen gas written before him undergoes a metamorphosis into the bunsen burner. It is as if the invisible oxygen gas is indeed invisible even though written upon the paper before him.

In another example, Bill is shown the balanced equation for the formation of rust from iron and oxygen gas and a composite analogy. He chooses both of these as important additions to his explanation. In one breath, he states that the equation helps him understand the reaction, but in the next breath, he dismisses the information in the equation and states that the analogy is important because of its content. The analogy helps Bill's understanding of rusting and reinforces his commitment to those things that are readily detectable by his senses as, "...the coldness draws it (the rust) out." Again oxygen gas is displaced by "cold" as a key participant in the formation of rust.

Summary of Bill's Case Study

This case study has tried to show that Bill's lack of specific knowledge does not prevent him from responding in ways that show a consistent, sensible approach to chemical change. In fact, it is not so much Bill's lack of the chemical knowledge that proves interesting, but rather, it is that Bill has developed a chemistry without atoms or molecules.

Bill's approach to chemical change becomes easier to understand after reviewing his explanatory preferences. Bill's responses showed similarities with those given by Aristotle and the alchemists. Another perspective suggests he is treating chemical change as an intricate version of changes of state. Given this line of reasoning, some of Bill's mass predictions make sense. However, applying conservation reasoning appropriated to physical changes precludes Bill from conserving elements or mass on a consistent basis in chemical transformations. In fact, Bill never demonstrated an understanding of chemical conservation. It is believed that whatever conservation reasoning Bill does possess belongs to a lower level of physical conservations.

In order to make Bill's theories comprehensible, an argument was presented that Bill's explanatory preference was for analogies based upon a familiar event. In the clinical interview, Bill even stated that he searches his memory for analogies to help him explain the unfamiliar change. Unfortunately for Bill, the analogy becomes not an "aid" to explanation but "the" explanation itself.

Bill has and will continue to have problems with learning the chemist's versions of chemical change. When he was presented with new information that was meant to reorient his thinking into a more conventional mode, Bill consistently dismisses this information as a matter of differing vocabulary, and sticks with his familiar theories.

Bill's reaction to new information suggests that there is reinforcement among his chemical knowledge, conservation reasoning and his explanatory ideals.

At the end of chapter 2, I derived a list of eight issues pertinent to my study from the literature on chemical knowledge, conservation reasoning and explanatory ideals. These issues become the organizing structure in the analysis of Bill's case study. The results indicate that two of the issues were not relevant to understanding Bill's chemical explanations. Additionally, one new issue did emerge. The following commentary summarizes the key issues underlying Bill's responses.

Chemical Knowledge Issues

ISSUE: The properties of atoms and molecules.

One finding of the Ben-Zvi et. al. study was that students often attributed properties, like state, to individual atoms and molecules. In the Ben-Zvi et. al.

study, the questions were directed at student understandings of atoms, molecules and chemical changes at the atomic-molecular level. The questions in my study were directed at the phenomenological level with some expectation that students would respond in ways that would give some insight into their understandings at the atomic-molecular level. Such was not the case. Due to the kinds of responses given by Bill, this was not issue in his case study. Bill shows no interest in atoms and molecules. He gives no indication that he believes the nail or the copper are composed of atoms. Bill never once used the words, "atom" or "molecule" in either his written or verbal commentary. It is quite probable that the whole concept of atoms and molecules holds no explanatory power for Bill.

ISSUE: The nature of reactants and products in chemical changes.

Bill regularly substitutes everyday materials for chemical substances as reactants/products. Bill also treats heat and cold as material substances capable of participating in chemical changes. This dramatically effects Bill's ability to conserve mass -- an issue that will be reviewed shortly. Bill's responses suggest that he has no understanding of what happens in a chemical reaction. Because he lacks a working knowledge of atoms and molecules, he is unable to properly represent a chemical transformation as one in which the atoms of existing substances rearrange to form new substances. Bill treats chemical reactions at the phenomenological level as either intricate physical changes or quasi-chemical transformations akin to cooking.

ISSUE: Mobility across the three levels of chemistry.

Bill's lack of knowledge at the atomic-molecular level prevents Bill from making the transition between the phenomenological and atomic-molecular levels of chemistry. Thus, all of Bill's explanations focus upon the visible manifestations, such as the nail turning rusty, rather than the interactions of the atoms that compose the rust. As I noted above, it is probable that atoms, either as a physical entity or as an explanatory concept, do not exist within Bill's scientific framework. In Bill's case there can be no mobility across levels which do not exist.

Conservation Reasoning Issues

ISSUES: The Conservation of mass and the boundaries of the system.

These issues were derived in chapter 2 from the studies of Piaget/Inhelder and Driver respectively. In Bill's case study, these issues appear to be closely related and will be discussed together.

One source of Bill's problems with chemical conservation seems to be derived from his errors in attributing to non-matter properties of matter such as mass. Bill's use of heat and cold only make it easier for him to avoid mass conservation. Bill never seems to wonder where the mass comes from during the heating of the copper, nor is he concerned about the increased mass of the rusty nail. Judging from his responses, the reaction of cold with the nail made the rust which increases the weight.

From a conservation standpoint, the boundaries of Bill's system end with the visible reactants and products. Bill regularly fails to attribute important physical and chemical properties to gases such as mass and the ability to participate in chemical reactions. Bill's problems may be deeper than Driver's study anticipated. Bill's problems with mass conservation may be more than just a failure to consider the substantive nature of gases. When the wood splint burns away, Bill's responses suggest that the products have left the domain of matter, which include gases, and have entered the domain of non-matter.

ISSUE: The nature of the change taking place.

Bill's responses suggest that there may be some confusion in his mind over the kind of transformation that is taking place. When Bill's predictions are examined from the perspectives of organic growth/decay and changes of state, his responses seem to make sense given this interpretation of the change before him. His best attempts at conservation reasoning seem to be limited to those instances where he sees an analogy to a physical change.

Explanatory Preferences Issues

ISSUE: The form of the student responses.

It is interesting that in spite of all Bill's problems in explaining chemical change, the form of his responses is not a major issue. Bill's explanations contain neither the word substitutions nor the theologies used by the younger students in Solomon's cited in chapter 2. Bill's explanations are based upon analogies with familiar events, which according to Solomon are precursors to acceptable scientific explanations. Bill's explanations are based upon phenomenon considered by him to be more simple and self-explanatory. In this sense, Bill's explanations contain the form of acceptable scientific explanations as outlined by Toulmin in chapter 2.

ISSUE: The content of students' preferred explanations.

While the form of Bill's explanations may be adequate, the content is not. Bill has created a chemistry without atoms. An acceptable explanation for Bill is one that is based upon an analogy relating the scientific phenomena to something he already knows.

The use of analogies, similes, metaphors and models in scientific explanation can be treated as a useful step in the development of a scientific explanation. In some cases, analogies actually pinpoint the underlying mechanism in a complex system. Such might be the case of explaining the workings of an intricate piece of machinery through reference to the workings of a bicycle. The analogies used by Bill in this study do not focus upon the underlying mechanism, but upon surface similarities between the familiar and the unfamiliar. For example, the heat from the stove effects in the changes associated with cooking, while in a similar fashion, the heat from the bunsen burner effects the formation of the black coating on the surface of the clean copper.

Bill's use of the familiar event to explain chemical changes represents a consistent pattern in his explanations. The analogy with familiar event becomes Bill's explanatory preference.

An Additional Issue Raised from Bill's Case Study

ISSUE: Student perceptions of the nature of scientific explanations.

The studies reviewed in chapter 2 did not address the issue of student perceptions of scientific explanations. This is an issue related to topic of explanatory preference in much the same way that reactants/products and the reaction mechanism were related to the topic of chemical knowledge; i.e. different perspectives of the same topic.

Bill's perception of the nature of scientific explanations represents a barrier to changing the content of his responses. Bill seems aware that a chemist would use atoms and molecules, but he lacks the chemical knowledge of the atomic-molecular theory to put together this kind of an answer. Bill regards the chemist's superior knowledge to lie in the chemist's ability to use technical vocabulary. Bill has stated on the paper/pencil instrument that he would need, "A more scientifically phrased explanation...." to make his responses more acceptable to the scientist. For Bill, a scientific explanation in one the includes "big words" like those found in the chemistry text. Interestingly, Bill never defines what the content of these explanations might be.

Rather his view seems to be that scientists have the ability to talk fancy.

Case Study 2: Tom

Introduction

Tom can be described as one who shares not only the chemist's theories of chemical change but the chemist's explanatory ideal as well. It would be unfair to characterize Tom as the hypothetical A-student who gets everything right all of the time. In fact, Tom had some interesting problems with mass conservation on the paper/pencil exercise. The resolution of these problems will form the main force of my argument that chemical knowledge, conservation reasoning and explanatory ideals interact to yield Tom's final solution. First, however, Tom's responses to specific chemical changes will be reviewed.

A Review of Tom's Responses to the Three Demonstrations

The Rusty Nail

On the paper/pencil instrument, Tom is asked to list the substances he believes are involved in the formation of rust. Tom lists iron and oxygen. He also writes an equation showing the formation of ferrous oxide. To a later question, Tom writes that, "Rust is ferrous oxide, a by-product of the reaction of iron and oxygen." Tom then rewrites the equation, indicating both reactants and products.

Tom: Fe + O_2 -----> FeO The ferrous ions-iron-and the oxygen ions form together to make a new substance. This is a characteristic of a chemical reaction.

Tom was asked about these responses during the clinical interview.

I: What were you thinking about?

Tom: It's (the rust) the product of a simple chemical reaction....

On the paper/pencil instrument, Tom states that, "oxygen in the water along with its acids help the reaction of rust along."

I: What role do you feel the oxygen plays...

Tom: The oxygen from the water takes place with the ferrous to form ferric oxide and then you have hydrogen gas given off...

I: ...and what if the nail was outside in the air?

Tom: The oxygen would come from the air...it has to come from somewhere....

The Oxidation of Copper Metal

In the copper demonstration, Tom lists copper and oxygen gas as reactants with heat acting as a catalyst. Tom is asked about this in the interview, I: Is there anything else you would like to add?

Tom: ...and cupric oxide, it's a product...

Tom then explains why the remaining copper will weigh less after the black coating is removed by writing the following equation.

Tom: As the Cu + O_2 ------> CuO the copper ions were changed. The CuO was taken away, and in (doing) so, part of the copper particles (were also taken away).

In the clinical interview, Tom reaffirms his belief that copper makes up part of the coating.

Tom: ...the copper ions formed cupric oxide which is the coating, so it (the remaining copper) has to weigh less.

The Burning of a Wood Splint

In the burning splint demonstration, Tom also correctly predicts that the wood splint will weigh less after it is burned because,

Tom: ...some of the carbon on the wood is used up as CO_2...part of the ions that make up the wood combine with O_2 in the reaction and go up as a gas.

Tom's Self-Evaluation of His Responses

At the end of each demonstration, Tom was asked to critique his responses. Tom consistently states that he feels that his responses would be similar to those of a scientifically trained adult and that he was satisfied with them. A common response was, (following the rusty nail exercise), "...I know the reaction and I am happy.....I can show it in an equation....I feel I am sufficiently knowledgeable to be able to talk about this on a reasonably learned level to a chemist."

Following these written exercises, Tom was asked about these statements during the clinical interview.

I: Why do your answers make sense to you?

Tom: ...because when I write down the chemical equation, I can basically see what is going on and the change in the atoms...I can tell the reactants and products....

This confirms another similar statement made earlier in the clinical interview:

I: Why is the equation so important?

Tom: I think that it scientifically tells you what is going on...that's what we learned and that's (the equation) what I wanted to know...so I would be able to explain what is going on....

Tom is then given an option of adding the composite analogy to his answer to "make it more acceptable" to the teacher. Tom rejects the analogy by stating,

Tom: ....the chemical equation would be a lot better because you are really not explaining what is going on in the second part....

I: Is there anything that you don't like about it (the analogy)?

Tom: It's not really chemically sound...the rust "eats the nail," you know that is not chemically sound, you are not really stating what is going on....

I: Why do you feel that "the acid eats the nail," is not chemically sound?

Tom: ...a chemist can't say, "something eats up" ...it's nice to have the synonym when you start the chapter but you want a scientifically sound basis like working with a chemical equation.

Tom remains steadfast in his commitment to the equation. During questioning of his responses on the copper demonstration, he again rejects the analogy by stating, "it's kind of vague, because you say that the copper is burnt away...well, like how...where is it going and what is it doing?"

How Tom Handles New Information: Reinforcement Among the Three Areas with Emphasis on Tom's Conservation Reasoning

Tom's responses have been examined from the standpoint of his chemical knowledge and his notions of an adequate explanation. Tom's preferred explanation is similar to that of the chemist. Understanding in the areas of chemical knowledge, conservation reasoning and explanatory ideals do not exist in isolation but reinforce one another. One way to test this possible reinforcement is to see how the student responds to new information. In discussions with Tom, a situation arose in which there was a conflict between alternative interpretations of the Law of Conservation. This situation will be described. Tom's responses will show how his chemical knowledge, conservation reasoning and explanatory ideals reinforce one another to resolve his conflict.

The most interesting aspect of Tom's theories of chemistry involve his notion of conservation of mass. Twice on the paper/pencil instrument, Tom incorrectly predicted the weight changes associated with rusting and the heating of copper. In both instances, Tom predicted that the rusty nail and the coated copper would weigh less than the original clean piece of metal. These rather atypical responses present a situation that strongly suggests that Tom's understanding at the three levels does not exist in isolation. The following discussion will focus upon this relationship.

Tom's responses on the paper/pencil instrument were examined. Tom predicts that the rusty nail will weigh less than the clean nail because, "A reaction has occurred where properties of the nail are lost. It (the nail) is different. The nail has new properties, a new weight."

Initially, it appeared that Tom has misapplied his correct understanding that chemical reactions produce new substances. He has substituted this understanding of chemical reactions for the operant one governing the conservation of mass. In the clinical interview, however, we find out that the true source of confusion for Tom lies with his interpretation of the Law of Conservation of Mass.

I: Why did you say that it (rusty nail) weighs less?

Tom: ...part of the Fe atoms have changed, they have formed ferric oxide...it seems that some of them will be gone...some of the atoms have changed even though there is no loss of matter, there should be no weight change.....

These are a strange set of statements. In one breath, some of the nail is gone and in another there is no loss of matter. For a student that holds a strong commitment to the Law of Conservation of Mass, he has destroyed matter in one breath and transmuted matter in the next. Tom quickly adds, "I got confused on that one." It is possible that the source of Tom's confusion lies in a pre-chemical belief that rust somehow eats the nail, making the nail weigh less.

Tom then adds, "....either it (the rusty nail) should weigh the same or less, because of the Law of Conservation."

I: What does the law tell you?

Tom: ...that matter can't be made or destroyed, it can only change form...

I: And how did you interpret that with regards to a nail rusting?

Tom: ...the ferric oxide is changed, but in a chemical reaction...either it will weigh the same or less..

Tom demonstrates that he knows the verbal statement of the Law of Conservation and the he knows what happens in chemical reactions. But, he is still confused and spends the next few minutes changing his mind as he struggles for an explanation that accommodates the Law of Conservation. As the discussion is becoming bogged-down, questioning is directed at Tom's responses to the copper demonstration as he makes the same incorrect weight predictions in this demonstration as in the iron nail exercise. It is here that we find that Tom's problems arise because of a dual understanding of the Law of Conservation.

In the copper demonstration, Tom writes that the coated copper will weigh less than the original clean copper because, "a chemical reaction has changed the copper ions, so they are a different weight?"

I: What were you thinking about there?

Tom: ...like I said before, when you have energy activating...it seems that some of them (copper particles) will be burned off, but you still have the Law of Conservation...they have to be conserved...

Again, Tom is in a state of mental disequilibration. In other instances he demonstrates that he is aware of the role of oxygen gas in both the iron and the copper reactions. Yet, at this point he gets hung-up with the visible reactants. This is where the mental conflict arises. Because he shares the chemist's notion that physical observations must have a theoretical basis, he searches for one, and that causes more problems for Tom. This shows that Tom has not totally abandoned the chemist's explanatory preference. He holds that acceptable explanations appeal to a commonly accepted scientific theory.

I: How does the Law of Conservation apply to the heating of copper?

This question was asked in the previous exercise and Tom skirted the issue. Now he does not.

Tom: The copper ions still have to be there because the total amount of matter has to the there...but when you add this (the copper) into the energy...the Law of Matter and Energy, they interact (matter and energy)...so it seems that the copper should be expended in this reaction??? (a questioning tone).

Tom is convinced that an acceptable explanation must include a scientific law or theory. In this case, it is the Law of Conservation. Tom's problem is that he has learned two versions of the Law of Conservation. One is best applied to physics; the total amount of matter and energy in the universe is constant because matter and energy can be interconverted. While the other is more appropriate for the everyday workings of the chemist; matter cannot be created or destroyed, only rearranged. Here, Tom struggles between two competing theories.

I: Why are you so torn? Is there anything you would like to know?

Tom: A reasonable explanation.

I: If I were to tell you that the coated copper actually weighs more, what would that do for you?

Tom: ....(pause)..I would say that when the copper and the oxygen interact, there is something made there.

I: How would that take into account the Law of Conservation?

Tom: Well, oxygen ions are taken in...and you are forming a new substance. The oxygen is being combined so you will have more...I can understand this more...

Tom reaffirms this by his statement that, "the coating is the product of the two (copper and oxygen)."

This last piece of discourse brings out some interesting aspects of how Tom thinks about chemistry. Tom asks for, "a reasonable explanation," instead, he is given only one small bit of information (the coated copper weighs more). From this single bit of information, Tom synthesizes a whole explanation that brings into account all of the corollaries of the Law of Conservation. This is significant in that this is characteristic of a chemist's thinking. This, more than any other aspect of Tom's responses demonstrate how his understanding in all three areas, chemical knowledge, conservation reasoning and explanatory ideals, reinforce one another.

In a sense, the type of chemical knowledge Tom was given was somehow anticipated. It is amazing that so little a bit as "it weighs more," allows him to generate a complete explanation. It is as if Tom actually was waiting, with two complete theoretical frameworks intact, for either the words "more" or "less." This suggests the power of developed structures for conservation reasoning and explanatory ideals to discriminate between pieces of chemical knowledge. Tom has stated that the homespun analogies provide him with little significant information. Tom's theories alert him to the significance of the information given him.

In Tom's case, there is a tightness of fit among his chemical knowledge, conservation reasoning and explanatory ideals. One cannot help but believe that since the chemical knowledge fit into Tom's notions of conservation and that these understandings fit his explanatory ideal, that there is a lot of reinforcement among these areas. On the other hand, given this reinforcement, one would expect Tom's responses to reflect a growing confidence in the atomic-molecular theory as a tool for explanation. This explanatory ideal dictates the conditions of an adequate explanation, the atomic-molecular theory, as Tom's explanatory ideal pushes the search for explanations of chemical change that are reductionist. As all three areas of understanding are highly developed, it would be surprising to ever see Tom select a homespun analogy as his choice for an adequate explanation. Even when he is confused, it is over which interpretation of the Law of Conservation is most appropriate. He does not resort to ad-hoc theories as a band-aid remedy for his confusion. Tom knows what does and does not count as an adequate explanation in chemistry.

Summary Of Tom's Case Study

Tom was shown to hold considerable amounts of specific knowledge. He held a working knowledge of many of the terms associated with chemical change. Tom correctly identified and used reactants and products most of the time in the three exercises. He was also attuned to the existence of invisible reactants like oxygen gas and carbon dioxide.

Tom utilized the atomic-molecular theory in all of his explanations. He seemed at ease explaining chemical changes through reference to the interactions of atoms and molecules. Tom successfully wrote balanced equations as part of his explanations. He was aware of both the form and the content of an acceptable scientific explanation. It became apparent that Tom really thought like a chemist. His approach to explanations of chemical changes was reductionist. That is, he explained larger systems in terms of smaller subsystems of atoms and molecules. He also tried to explain the mass changes associated with the changes observed through reference to a commonly accepted chemical theory, the Law of Conservation. Tom rejected opportunities to supplement his explanations with homespun analogies. Tom's preferred explanations were similar to that of the chemist. His consistent preference for the atomic-molecular theory suggests this theory as his explanatory ideal.

Tom's commitment to the laws of conservation provided some difficulties in his explanation of the mass changes associated with the nail and the copper exercise. Analysis of these difficulties showed the extent of Tom's understanding of the theories of chemistry and their ability to discriminate between significant and insignificant data. Given one small piece of information, Tom was able to abandon one framework of thought and to adopt another. In this case, Tom eliminated the physicist's version of the Law of Conservation in favor of the chemist's version. This example was used to argue that Tom's understandings at the levels of chemical knowledge, conservation reasoning and explanatory ideals interacted with and reinforced his commitment to his understanding in these areas. Given this perspective, I anticipate Tom will continue to use the chemist's theories and explanatory ideals in future explanations of chemical change.

As with Bill, this case study will conclude with an analysis of how Tom's responses address the issues derived in chapter 2.

Chemical Knowledge Issues

ISSUE: The properties of atoms and molecules.

Like Bill, Tom gives no specific information on the properties of atoms and molecules although his responses do suggest that atoms are indestructible and can combine with other atoms to form compounds with new properties. The properties of atoms and molecules is not a major issue in this case study.

ISSUE: The nature of reactants and products in chemical changes.

Tom is very much into chemical substances. In contrast to Bill, Tom uses chemical substances to explain chemical changes and Tom believes that chemical substances are composed of atoms and molecules. Tom's responses indicate a mobility across the levels of chemistry. His explanations are based upon the atomic-molecular theory. He seems confident that he can explain any of the changes before him through reference to changes at the atomic-molecular level.

ISSUE: Mobility across the three levels of chemistry.

Tom's responses are reductionist in nature. Acceptable explanations in chemistry are characterized by reference to subsystems of atoms and molecules and the theories that govern their interactions. Tom explains chemical changes at the phenomenological level through reference to a subsystem of that level. For Tom, the changes in the iron and the copper are best explained through reference to the subsystem of atoms and molecules that interact during the course of these changes.

Conservation Reasoning Issues

ISSUES: Conservation of mass and the boundaries of the system.

Tom's chemical knowledge extends into the area conservation reasoning. Tom's use of conservation reasoning applies to all situations encountered by the chemist. Tom is aware of the concepts of reactants and products. In the responses cited above, Tom consistently conserves elements where they ought to be conserved by writing essentially correct chemical equations. It is interesting that he writes equations at all. The students were asked to describe the change they observed. There was no specific instruction to write the chemical equation. Tom's interest in the chemical equation will be discussed in a subsequent section where he evaluates his own responses.

Tom, far better than Bill, grasps the size of the system before him. As part of Tom's commitment to the Law of Conservation, he introduces invisible reactants where appropriate. Oxygen, gas and carbon dioxide play roles of reactants and products in all three demonstrations and are used to account for mass changes accompanying the chemical transformation.

Earlier in this commentary, Tom made some statements about the role of oxygen in the formation of rust. His first comments about the iron taking the place of the hydrogen suggest that he is treating the rusting of the nail as a single displacement reaction. This would seem to contradict his earlier equation that formed rust by a synthesis reaction. Yet, the important point for this discussion is that Tom finds a way to conserve elements in a way that is consistent with accepted chemical theory. When given an alternative to the instance where iron rusts when wet, Tom states that, "The oxygen would come from the air." Apparently, Tom is secure enough in his theories to search for oxygen, be it from the water which he knows to be a chemical component of water or from the air which contains oxygen as an invisible reactant.

ISSUE: The nature of the change taking place.

Like Bill, Tom has some difficulty in conserving mass in chemical transformations. To preserve conservation, Tom occasionally applies conservation reasoning patterns more appropriate to a nuclear system. That is, he interprets the change as a nuclear one where substances can be transmutated into new substances. Both Bill and Tom's explanations were shown to make sense given their respective perceptions of the change before them. Unlike Bill, however, Tom's superior chemical knowledge and explanatory ideals draw him back to traditional chemical theory upon receiving the new information that the coated copper will indeed weigh more than the original clean copper. Aside from this momentary lapse, Tom consistently affirms that chemical changes have taken place.

Explanatory Preference Issues

ISSUE: The form of student responses.

As with Bill, form is not an issue in the analysis of Tom's responses. While form is not an issue, there is a difference between the form of Bill's and Tom's responses. Toulmin's and Solomon's criteria for explanations of good form include explanations based upon analogy. In Toulmin's case, analogies have good form because they relate the unfamiliar to the familiar. For Solomon, analogies are the precursors of explanations based upon scientific theory. Bill was shown to rely upon analogies with familiar events as the basis of his explanations. Tom, however, utilizes the atomic-molecular theory as the basis of his explanations. Both Bill and Tom's explanations share good form. Tom's, however, are more acceptable than Bill's because the content of his are based upon the atomic-molecular theory which is the focus of the next issue.

ISSUE: The content of student responses.

One of the important aspects of Tom's responses, regardless of the errors in chemical knowledge, is that Tom is aware of the content of an adequate explanation. Tom states that analogies are helpful, but do not carry the same weight as the chemical equation. I take Tom's interest in the chemical equation to be indicative of his commitment to the atomic-molecular theory as his preferred explanation. At first, the clinical interviews were not to include the paper with the analogies. It was expected that almost every student would choose the equation over the analogy. As it turned out, Tom was in a minority of students that actually preferred the equation over the analogy. Tom's consistent choice of the equation over the analogy is significant in that the chemist would do the same. An equation is more than just a fancy way of stating an analogy. Equations are the symbolic representations of interactions of atoms and molecules.

ISSUE: Student perceptions of the nature of scientific explanations.

Tom consistently rejects the homespun analogy as a legitimate explanation. In some ways, Tom's viewpoint is like that portrayed by Toulmin. Toulmin states that in modern chemistry, acceptable explanations most often explain familiar events in terms of relatively unfamiliar interactions between invisible and inanimate atoms and molecules. Strict reliance upon an analogy to explain chemical changes would result in errors similar to those Aristotle made when he used familiar life cycles to explain more complex chemical changes. Analogies cling to the familiar. Analogies are, for Tom, at best an aid to understanding rather than a legitimate explanation in and of themselves. Statements such as these show Tom and the chemist to prefer similar kinds of explanations. Tom believes that adequate explanations consist of explanations that are based upon the atomic-molecular theory.

The patterns in Tom's responses suggest that he has acquired the chemist's explanatory ideal for chemical change. One of my assumptions is that a consistent pattern in explanatory preference would be taken as a statement of an explanatory ideal. The singular pattern that emerges from reviewing Tom's responses is his commitment to the atomic-molecular theory. When asked for an explanation, Tom refers to those things that he finds more simple or self-evident. For Tom, those things more simple are found in the atomic-molecular theory.

Case Study 3: Sue

Introduction

Sue was chosen to be interviewed because she seemed representative of students whose understanding of chemical change lie somewhere between those of Bill and Tom. Sue is a student in transition from naive to mature thinking. A contributing factor in her selection was her willingness to discuss her responses in a free and open manner. The basis of the interview was Sue's responses to the paper/pencil instrument administered to about 100 General Chemistry students. This case study will show that the objective of the teacher was only met in part for Sue. Further, this discussion will argue that in spite of some evidence that might suggest differently, Sue's responses represent a rational and consistent approach to the explaining of chemical change.

I will follow the same pattern of analysis with Sue as I have done with Bob and Tom. I will begin by reviewing her explanations of the three demonstrations. Commentary will follow upon the patterns that seem evident within these responses. Subsequent analysis will examine Sue's reflections upon these responses and finally, her approach to new information.

Sue's Responses to the Demonstrations

To understand Sue's theories of chemistry, it is necessary to examine her theories of specific chemical changes. Sue's responses on the nature of rusting, heating copper and burning wood will be examined.

I: How has your understanding of rusting changed? (since instruction)

Sue: I know the products and reactants and how they react.

Sue indicated on the paper/pencil instrument that rust was, "made from the reaction of Fe, O_2 and H_2O together." In another question taken from the copper demonstration, Sue indicates that the black coating on the surface of the copper is made of, "Cu and O_2 coming in contact with the heat." In other statements, she cites Cu, O_2 and CuO as reactants and products. Sue mislabels the reactants as products, but aside from this error, she used only chemical substances as reactants and products, and she has conserved elements.

When asked to make predictions about the weight of the visible reactants (the nail, the piece of copper and the wood splint), Sue correctly accounts for the weight changes in every instance. For example, Sue states that the rusty nail will weigh more than the original clean nail, "because, the rust is an extra film on the nail, made up of the substances above (Fe, O_2 and H_2O), which do weigh something." In the Copper demonstration, Sue explains that the copper will weigh less after the black coating is removed because, "some of the elements in the copper had to be used in the reaction....it (the coating) was made in the chemical change." Responses like these indicate that Sue recognizes the importance of conserving mass. (Note. By "elements in the copper,"' it is assumed that Sue is referring to the atoms that make up the copper. This was the case for other students who made this remark.)

At the beginning of the paper/pencil instrument she states that in chemical reactions, "...a substance has changed to create a different substance. You cannot change it back into the starting substance."

Many times throughout the paper/pencil exercise, Sue demonstrates a commitment to this. When asked about the heating of copper, Sue states that a chemical change occurred as, "there was a color change and a new substance was formed."

During instruction, the students were taught the common visible characteristics of chemical change. Sue often demonstrates that she has learned how to use the manifestations to correctly identify chemical changes. In her responses to the burning splint exercise, she states that the splint at the end will weigh less because, "The wood was no longer wood after it was burned...a new substance was formed...the ashes from the wood."

The above responses are similar to those given by Tom. Sue has some idea of where chemistry begins and ends and appears to follow the chemist's rules on conservation. Yet at other times, on the paper/pencil instrument, and during the clinical interview which followed the written exercise, Sue gave some unexpected explanations as to how and why these chemical changes took place.

I: Why is oxygen necessary? (for rusting)

Sue: ....long pause....I don't know except that it is important, water alone cannot corrode metal, it can't eat it away....so something has to be with it and oxygen is the only thing I thought of that can be involved.

(In explaining why the nail would weigh less after the rust is removed, Sue gives the following explanation.)

Sue: I knew all these things like the oxygen could make something that could eat away....like a cake batter, you mix all these things together and it makes something ...well if the cake batter was put on a piece of paper ...after you take it (batter) off, that paper is thinner and it looks like something is off it...and when you take the rust off of the nail, it's like part of the nail went with it.

When Sue is asked to compare the weight of the copper with the original copper after the cupric oxide coating is removed, she correctly predicts less.

Sue: ....less, because the coating was produced and is like a lid on a jar....a covering, and if you take it (the lid) off, it (the jar) obviously weighs less.

Sue was also asked to explain how a wood splint burns. On the paper/pencil, she explains that the wood splint weighs less after it is burned because, "it disintegrates and goes 'bye-bye.' It's gone in the form of ashes or nothing."

Sue further states that wood pulls the fire and that oxygen keeps the fire going. In the clinical interview she comments upon this statement.

Sue: ...something has to be there to keep the fire going....that fuels the fire and the oxygen is like sparks ...be like a magnet to the fire....bringing it to the wood.

Later in the same interview, Sue uses this analogy to explain why a match will weight less after burning, "when you look at a match and it's burning, you see less and less of it, it's getting smaller...when you use a candle stick, you eventually have to get a new one 'cause it gets burned away."

Sue's Evaluation of Her Own Responses

How can the existence of these two sets of dissimilar responses be explained? Considering the extent of Sue's responses, it is not easy to dismiss either set. Examination of her specific knowledge and theories does not lend much insight into why she responds in ways that are so polar. To get a better understanding of this dilemma her reflections upon these two sets of responses will be reviewed. This will lead into a discussion of Sue's explanatory preferences.

After the written responses on the paper/pencil instrument, Sue was asked to evaluate her own answers. Sue indicated on the iron nail and the burning splint demonstrations that her answers made sense to her even though she was aware that they might not be entirely correct. Again, during the clinical interview, Sue was asked to evaluate her own answers. Sue was shown the paper containing a balanced chemical equation and a composite analogy describing the change. From these discussions it becomes apparent that she is aware of the shortcomings of her responses and makes the following declaration:

I: Would either of these two descriptions (the balanced chemical equation or a verbal analogy) make your answer more acceptable to me?

Sue: ...I bet half of the people in the class would take this one (points to the analogy) but I don't think that a group of scientists were in the room, I think that the formulas would be accepted the most.

I: Why?

Sue: Because the second one (the analogy) is like for people who don't know how much of what element are involved so they are just trying their best to think of how it works, like we're (the students in the room) are doing ....like we are doing on these papers....the scientists would know how much of what, and I think that they could just look at the formula.

In subsequent demonstrations, Sue also states that the formal explanation is important to her.

Heating Copper

I: ...so the formulas are important to you?

Sue: Yea, then I would feel more like a chemist...I'd feel more secure about my answers...when I think of formulas, I think of chemists....smart people.

In the paper/pencil exercise, Sue is asked to write down what it would take to make her answers more acceptable to the chemist. Here she writes, "It would take knowing exactly what elements were involved and the roles of those things. As you would say, 'more knowledge'." Lacking this specific knowledge, Sue does what comes naturally and tries to make sense of the phenomena confronting her by searching for an analogy. When asked about this during the clinical interview Sue confirms this natural tendency to simplify the complex.

I: How did you come up with this cake thing?

Sue: I just thought of it...you try to think of examples of things...for a better understanding...it just popped into my mind.

I: Do you do this a lot? (look for examples)

Sue: Yeah, cause I don't understand things a lot ....so I have to do it a lot.

During the clinical interview, when asked what it would take to make her explanations more acceptable to the chemist, she consistently chose both the equation and the analogy.

I: Is there anything that you don't like about either one of these? (points to both the equation and the analogy)

Sue: No. I like the example...I think it was good about growing old, you lose some of the things you had while you were still growing...like the match, when it is real young, it's got everything and it burns real bright but when it gets old the flame goes down and it loses some of its umph then it burns out.

Sue: A Student in Transition

The other case studies examined how Bill and Tom handled new information that is explicitly chemical in nature. As in the other case studies, the new information consisted of the sheet with the equation and the homespun analogy. This sheet was presented to the student near the end of the clinical interviews on each of the demonstrations. This technique was helpful in extending the understanding of their explanatory preference. Both Bill and Tom utilized a consistent approach to new information. Bill ignored the significance of the information while Tom used the information to construct a scientifically acceptable explanation. This information was used to argue that there is a continuous interplay or reinforcement between the levels of specific knowledge, chemical theory and explanatory preference which eventually generates the responses that we read in the case studies. When this format is continued with Sue, there is no consistency in her handling of new information. My conclusion is that Sue has not yet settled into a preferred explanation. Sue is a student who is making the transition from naive to mature thinking about chemical changes. I will begin by examining her responses to questions about rusting. Then, I will review her evaluations of her own responses. That will lead into how Sue handles new information.

In this segment I am asking Sue about the formation of rust. She initially gives an explanation that is decidedly non-chemical. Rather than accepting her answer as given, I asked for further clarification. It is at this point that Sue reverts back to a chemical explanation based around the interaction of atoms and molecules. Sue is not given new information at this point but is explaining her thinking on the written exercise. This exchange suggests that her understanding in the area of chemical knowledge are sufficient enough to push her into a chemical explanation and, for the moment, abandon the analogy. This dialogue further suggests that Sue hasn't completely settled the question of her preferred explanation.

Sue states on the paper/pencil instrument that rust is made from the reaction of iron, oxygen, gas and water. She comments upon this statement by adding, "...some chemicals just don't go together and create what you want them to!"

I: What did you mean by, "Some things just don't go together?"

Sue: When you put things together you want them to...you know, make something pleasant...these when they went together...they didn't react good...like magnets don't react, they couldn't form something that was beneficial... instead they reacted in such a way that caused a disturbance...and when they were used together they formed the rust on the nail....

I: So what exactly is rust?

Sue: ...it's a reaction when these elements get together..

I: Is rust a something?

Sue: It can either be a verb or a noun....rust is rust like on a car...or it can be corrosion.

I: What is the noun rust...what is in it...if I take a piece off my car?

Sue: It's the metal eaten away quote-unquote, it's the mixture of the elements...

I: so rust is eaten away metal?

Sue: so to speak...

I: What do you mean, "So to speak?"

Sue: Well it's eaten away metal...but then there has to be something there...because rust a something different than the metal, it's a different compound....it's not even made out of the same stuff.

I: It's not made from the same stuff?

Sue: Well it is made from the metal, so there still has to be something there from the metal...

I: So what is the rust?

Sue: There is some metal.....rust is iron after it is reacted with oxygen and the moisture and anything else there is...

This is an interesting dialogue. At one point Sue uses terms like "eaten away" to describe rust and rusting. Yet, in this dialogue, Sue demonstrates enough understanding of the chemistry to stick with a chemical explanation that draws upon the interactions of chemical substances to produce new substances. She is not as confident in her response as was Tom. Yet, Sue does not give up on a chemical explanation.

Sue has indicated that she felt that her responses to the burning splint exercise would be much different than those given by chemist. Interestingly, she also states that regardless of this fact, her answers make sense to her.

I: Why do your answers make sense to you?

Sue: Well, this time I have a better picture of what is going on with the burning of a splint than with the heating of copper...

I: Now what would it take to make your answer a little better for me?

Sue: ...pause...just the formula cause I don't think I had a good enough explanation this time...the one about the candle picture...if I could write that out and then have the formula, then you would be happy.

This commentary seems to indicate that Sue feels a need for some kind of explanation beyond the equation. The equation only specifies the reactants and products and does not actually explain the transformation. It is interesting, that Sue, like Bill never really talks about atoms combining and molecules breaking apart as an explanatory device. While Sue does talk about chemical substances on several occasions, it is doubtful if Sue has a functional knowledge of atoms and molecules. Everyday analogies fill this void in her understanding.

Analogy as a Barrier to Chemical Thinking

Sue's analogies suggest an interesting relationship between the chemist's preferred explanation and her personal preferred explanation. Sue appears to search for analogies after she uses up her chemical theories and specific knowledge. When Sue intimated that students need analogies to help them understand until they learn more of the specific knowledge and chemical theories, she may have spoken with a wisdom beyond her years. Sue may very well be describing a general approach to scientific explanation.

Analogies are used to cement Sue's previous reasoning. In both the rust and the copper exercises, she introduces essentially correct reactants and products before she brings in her analogies. This approach suggests that both her conservation reasoning and her explanatory ideals are changing her explanatory preference from one that focuses upon analogy to one that focuses upon the interactions of atoms and molecules. While Sue has some of the chemist's chemical knowledge and conservation reasoning, she is not as secure as Tom who can openly state that these analogies really do not contain anything of interest for anyone who understands chemistry like the chemist does.

Sue has stated that students, like her, need the analogy to make personal sense of the changes before her.

In the burning splint exercise, the splint shrivels as the flame burns away its outward appearance. Sue is caught by the visual characteristics of the splint burning and the analogy to people growing old. Sue is caught up in a prototypic viewpoint (Driver) and resolves this by using analogies to explain the phenomena. The problem is that Sue's analogies focus upon the surface similarities between the chemical change and the analogy rather than upon some underlying chemical theory. For example, once Sue focuses upon the shriveled splint, she ignores the significance of the oxygen and the carbon dioxide as identified in the chemical equation.

Summary of Sue's Case Study

An understanding of Sue's explanations comes from her placement in this discussion. Sue's responses show similarities to those given by both Bill and Tom. Within this context, Sue appears to be somewhere between the two in her understanding of chemical change. I have tried to present Sue as an example of a student in transition from naive ways of thinking to the scientific ways of thinking found in the chemist. Being in transition presents mental struggles that often have Sue waffling between these two modes of explanation. In fact, all of the issues identified during Bill's case study also apply to Sue even though some may apply to a lesser degree. As with Bill and Tom, I would like to analyze Sue's position with respect to chemical knowledge, conservation reasoning and her explanatory preferences by contrasting Sue's responses with the issues raised in chapter 2.

<u>Chemical Knowledge Issues</u>

ISSUE: The Properties of atoms and molecules.

Sue's responses don't yield any information about her conceptions of atoms and molecules. In fact, Sue is like Bill in that she never once uses the words "atom" or "molecule" in any of her written or verbal discussions. Sue sometimes uses the word "elements" in a way that suggests that she may mean "atoms." For example, Sue explains why the nail will weigh less after the rust is removed by stating, "some of the elements of Fe may have been given off as a result of the reaction with H_2O. Those elements helped form the rust plus when the rust was scraped off, the weight of those elements went with it."

It is possible that Sue really means atoms when she states elements. Yet, at this time, there is no information available on this matter.

ISSUE: The nature of reactants and products.

Sue has acquired much more chemical knowledge than Bill. Her understanding of the atomic-molecular theory and how it applies to chemical change is much deeper than Bill's. Sue explanations are sprinkled with bits and pieces of correct chemical knowledge. Her lists of reactants and products include both correctly represented chemical substances like Fe, H_2O and O_2 and everyday materials like rust. She also properly assigns energy, in the form of heat, a catalytic role in these chemical changes. She also seems to understand that chemistry makes new substances with new properties.

Like Bill, however, her explanations indicate that she, too, has problems shifting her thinking from the phenomenological to the atomic-molecular level of chemistry. Sue never demonstrates a working knowledge of atoms and molecules. Sue is interesting in that she can introduce chemical substances into her explanations at the phenomenological level but reverts to the use of analogies as a substitute for an atomic-molecular explanation. Whenever Sue really tries to "get down into" the change, she invariably settles for an analogical explanation because she lacks an understanding of the atomic-molecular level of chemistry.

Combining Sue's written responses with those given in the clinical interview yields a puzzling situation. Unlike Bill and Tom whose clinical interviews built upon their responses on the paper/pencil instrument, Sue's interview presents another set of responses much different than those given in the written part of the study. Her written responses suggest a student who holds quite a bit of the correct chemical knowledge associated with chemical change. In her responses to the iron and the copper exercises, Sue identifies reactants and products and she introduces the invisible reactant oxygen gas where appropriate. Her responses are reductionist in nature. Sue appears to use chemical substances to explain the changes before her. In this sense she is similar to Tom whose responses centered upon the atomic-molecular theory.

On a related aspect of Sue's understanding of chemical knowledge that is not formally addressed by either Bill or Tom, is her notion of how reactants actually form products in chemical reactions. Sue holds some rather unusual ideas of the reaction mechanism. It is here that the word, "reacts" takes on a decidedly private meaning for Sue. Whereas the chemist thinks in terms of the interaction of atoms and molecules where bonds are broken and new bonds formed, Sue sees chemical reactions taking place because of the reactants, "just don't go together and create what you want them to!!!"

For Sue, elements take on almost human qualities. Iron, water and oxygen don't "like: one another and consequently don't "get along" and thus react to form an undesirable product, rust.

Conservation Reasoning Issues

ISSUES: The conservation of mass and the boundaries of the system.

Sue's responses suggest that she may hold a partial commitment to the conservation laws as they apply to chemistry. Sue is able to conserve mass in both the iron and the copper demonstrations. Her written explanations do not include balanced equations as did Tom's. Yet, Sue can state that the rusty nail will weigh more because the rust is made up of iron, oxygen gas and water. In contrast to Bill, Sue does not substitute non-matter like heat or cold for chemical substances in her explanations of the mass changes of the three chemical changes. In response to questions on the copper exercise, Sue has written that, "Some of the elements in the copper had to be used in the reaction causing there to be less elements, therefore, weighing less."

In the clinical interview, however, Sue's responses seem more like those of Bill than Tom. She readily falls into forms of explanation that focus upon homespun analogies rather than atoms and molecules. A chemistry of cake batter, jar lids and magnets would appear to preclude Sue from ever sharing in the chemist's notions of chemical change. At times Sue appears to have forgotten the chemist's rules which govern mass conservation.

ISSUE: The nature of the change taking place.

Sue does not explicitly discuss the Law of Conservation, yet, some of her responses suggest that she is aware of its applications in chemistry. Like Bill, even Sue's analogical explanations do show a tendency to conserve mass in an incorrect but logical manner. It is here that the content of Sue's analogies becomes interesting. In the iron and copper exercises she is able to chemically conserve the mass. For example, Sue stated that the rust was composed of iron, oxygen and water and that it is not just changed metal as Bill has suggested but actually a different compound. Yet, Sue also has used a cake batter analogy to explain why the nail would weigh less after the rust is removed. Sue's choice and use of analogy suggests that there remains some confusion over the kind of transformation taking place. Sue's cake batter analogy focused upon the cake batter coats the surface of the wax paper and when the cake if lifted off, some of the wax will also be removed making the remaining paper weigh less. Scraping like erosion is a physical change. By using this physical change analogy, Sue was able to conserve mass in a nonchemical but logically consistent manner.

When faced with the problem of conserving mass during burning, Sue is not up to the task. She seems aware that a chemical change did occur but ignores the possibility of invisible products like CO_2. For Sue, burning destroys matter leaving only ash behind. She is reminded of how candles burn apparently down to nothing and must be replaced. Sue is like Bill in two respects, she does not conserve mass when she chooses a chemical analogy like burning for the change she is trying to explain and she underestimates the size of the system she is trying to explain.

It is interesting that Sue appears to be somewhere between Bill and Tom in her ability to conserve mass. When Sue is trying to think chemically, she can sometimes conserve mass by accounting for some of the reactants in the products. When she is thinking analogically, she can still conserve mass in a way the is consistent with her perception of the change when that analogy is to a physical change.

Explanatory Preference Issues

ISSUES: The form and content of the student's responses.

Sue explicitly states that she searches for analogies to familiar events because the familiar removes the sense of puzzlement. As discussed in chapter 2, Toulmin identifies this approach to explanation as having its origin with Aristotle whose explanations were characterized by the reference to the familiar event. Solomon has suggested that similes, analogies and metaphors can be considered the forerunners of scientific explanations. I would argue that Sue's explanations, like Bill's, have good form but lack the content of scientifically acceptable explanations. For example, Sue is unable to distinguish between good and bad analogies. Old people appear shriveled-up. So do the remains of the match. The similarity in surface appearances is not much of an aid in explaining the underlying chemical changes associated with the burning of a piece of wood. This analogy does not help Sue with reactants and products nor does it direct her conservation reasoning to chemically conserve mass or elements.

To understand how Sue could give two seemingly different explanations, her responses were scrutinized from the perspective of her explanatory preferences. Sue's explanatory preferences lie in some middle ground between a completely naive response and one that a chemist might give. Sue, unlike Bill and Tom, does not have a single explanatory preference. She appears to be testing the intellectual waters. Her statements suggest that she is moving away from analogical explanations towards those that are based upon accepted chemical theory. Yet, Sue never completely abandons the analogy as a preferred explanation. She is, however, aware of the chemist's preferred explanation. Like Bill and Tom, Sue's explanations are of the good form as identified by Toulmin and Solomon. And, like Bill, it is the content of these explanations that causes Sue problems. I speculate that Sue would abandon the analogy as a preferred explanation if she had more positive experiences using the equations.

Sue's perception of the nature of scientific explanations is closer to that of Tom than Bill. Sue's commentary on the difference between student and chemist explanations indicate that unlike Bill, she is aware that scientific explanations include more than fancy words.

ISSUE: Student perceptions of the nature of scientific explanations.

As in the case of both Bill and Tom, this new issue appears to be relevant to and understanding of Sue's responses. The interesting difference between Sue and Bill lies in their perceptions of scientific explanations. Whereas Bill believes that scientific explanations use fancy words, Sue seems to recognize, unlike Bill, that fancy talk would not be acceptable to the chemist. She translates this to mean that responses acceptable to the chemist include formulas, equations and use some chemical terms. Yet, Sue does not feel comfortable with just the equations, for she is a student. Students use analogies because, "they don't know how much of what elements are involved...." Sue has also stated in the written exercises that she would need more specific knowledge to present a more acceptable explanation. Sue seems to be saying that students have to make do with analogies because they lack the chemical knowledge of the chemist.

After instruction that was meant to teach the chemist's theories and the chemist's explanatory ideals, that is, to help the students think more like chemists, Sue still sees herself as a student. She refers to the scientists who have knowledge of elements and the students, like her, who are "trying their best to think of how it (demonstration) works." Chemists have their ways of looking at the world and students have another. Chemists have formulas and equations (and theories etc.) that students do not. Chemists have all sorts of specific knowledge about rusting, copper and burning that Sue feels that she does not have.

On the positive side, Sue is aware of the importance of formulas and equations even though she feels she needs more understanding of these concepts. That cannot be said of all students, even after six weeks of instruction.

Conclusion

In conclusion, Sue's case study demonstrates that it is not an easy task for students to give scientifically acceptable explanations. Sue does possess quite a bit of chemical knowledge, yet her ability to utilize that knowledge to chemically conserve mass is problematic. In some areas Sue seems to have enough specific knowledge and chemical theory to pull off an acceptable explanation. Yet, she remains unsure of her explanations and reverts back into analogical explanations quite readily. After a near perfect written explanation for the oxidation of copper in air, Sue stated that she felt a need for the analogy. These types of responses suggested that Sue is having problems in areas apart from that of chemical theory. Sue is struggling over her choice of explanation. To fully understand Sue's responses we needed to conceptualize her as being a student in transition.

Summary of the Three Case Studies

The first part of chapter 4 documents how Bill, Sue and Tom explain chemical changes. These three students represent the range of students found in this study.

The focus of analysis was the set of issues raised in chapter 2 after reviewing a body of prior research. Of the eight issues raised in chapter 2, six were relevant to understanding the responses given by the students in this study. The two issues that did not emerge as issues by my data were Issue 1, the properties of atoms and molecules and Issue 7, the form of student explanations. Bill and Sue never talk about atoms/molecules on their own. When asked open-ended questions about chemical changes neither of these students choose to explain them using atoms/ molecules. Atoms/molecules hold no explanatory power for these students and thus little can be said in regards to this issue. The responses of all three students, even if not chemically correct, all had good form as detailed by Solomon and Toulmin in chapter 2. The remaining discussions will focus only upon those issues pertinent to this data set.

The detailed analysis of Bill, Sue and Tom raised several issues pertaining to the kinds of understanding needed for an adequate explanation of chemical changes. The following issues pertaining to chemical knowledge, conservation reasoning, and explanatory ideals as they relate to the students' ability to acquire new knowledge are identified and are summarized in Table 4.1. Table 4.1 contrasts misconceptions with scientific conceptions for each issue. Commentary will follow the chart comparing the responses of Bill, Sue and Tom.

Table 4.1: Issues Underlying Bill's, Sue's and Tom's Explanations of Chemical Change.

ISSUE	CHEMICAL KNOWLEDGE MISCONCEPTION	SCIENTIFIC CONCEPTION
Properties of atoms and molecules.	Student responses indicate that students who use words like atoms/molecules are merely responding to questions directed at this level rather than a commitment to their existence.	
The nature of reactants and products.	Everyday materials/ catalysts/non-matter etc. may be reactants/products in chemical changes.	Only elements and compounds may be reactants and products.

Table 4.1, Cont'd.

Mobility across the three levels of chemistry.	Knowledge of the atomic/molecular level is not necessary to explain chemical changes.	The chemist can explain chemical changes at all three levels.
	CONSERVATION REASONING	
Conservation of mass.	The properties of matter like mass are attributed to non-matter like heat and cold. Gases, because they are invisible, are not substantive and need not be considered in mass predictions.	The total mass of the reactants must equal the total mass of the products and can only be accounted for by chemical substances. Invisible reactants/products must be used to account for mass changes.
Confusion over the kind of transformation.	If a physical change analogy is chosen, the mass prediction is consistent with the choice of explanation.	Chemical changes conserve mass even though there is a loss of identity of the reacting substance
	EXPLANATORY PREFERENCES	
The form of scientific explanations.	Good form as defined by Solomon and Toulmin involves using familiar to explain the unfamiliar. Bill, Sue and Tom all gave explanations of good form. Form is not an issue in the responses of these students.	

Table 4.1, Cont'd.

The content of scientific explanations.	Explanations based upon analogy with everyday events are acceptable.	Scientific explanations are based upon the atomic/molecular theory.
Perception of the nature of explanations.	Scientists use fancy words to explain scientific phenomena.	Scientific explanations focus upon the interactions of atoms and molecules.

Chemical Knowledge

Looking at the students' understanding of chemical knowledge, there appears a simple progression from Bill to Sue to Tom. Bill has little or no understanding of the atomic-molecular theory. Bill gives no indication in any of his commentary that iron, copper or wood are composed of atoms or molecules. In similar fashion, Bill also ignores the accepted conventions for representing atoms, molecules and energy in chemical equations. Tom, on the other hand, seems quite comfortable with the atomic- molecular theory. Tom uses atoms and molecules to explain the observable changes at the macroscopic level. Tom talks about the interactions of atoms and molecules and even writes chemical equations as part of his explanations. While there is no direct evidence of specific understandings of structure and process as in the Ben-Zvi et. al. study reviewed in chapter 2, it seems safe to say the Tom believes in the existence of atoms and molecules to the extent that he sees them as useful in explaining the changes before him. Such cannot be said for Bill.

Sue's understanding of the atomic-molecular theory lies somewhere between that of Bill and Tom. In some instances, Sue can write a balanced chemical equation as part of her explanation. In others, atoms and molecules are replaced by homespun analogies of cake batter and people growing old. Sue seems to be a student in transition. More will be said about Sue in a subsequent section.

<u>ISSUE:</u> <u>The Nature of Reactants/Products</u>

In comparing the three case studies, there is a difference in what each student considers to be legitimate reactants and products. There is a progression from Bill who uses only everyday materials to Sue who uses a mixture of chemical substances and everyday materials to Tom who only uses chemical substances. The focus of this study did not allow for the collection of new data on the properties of individual atoms and molecules as did Ben-Zvi et. al. with the exception of the indestructibility and immutability of atoms. Both Bill and Sue show a willingness to destroy matter as is seen in their explanations of burning.

Whereas the chemist recognizes only three kinds of transformations: physical, chemical and nuclear, what kinds of transformations exist in the students' minds? Bill's mechanism of change and Toms's are quite different. Tom consistently recognized only those of the chemist. Bill seems to utilize destructions, organic transformations and changes of state as his categories of change. Recall Bill's statement that he understood burning because of his familarity with other "breakdowns."

ISSUE: Mobility Across Levels

One characteristic of a chemist's approach to scientific explanations is the ability to explain chemical changes at the phenomenological and the atomic-molecular levels. Neither Bill nor Sue demonstrated an ability to explain chemical changes at the atomic/molecular level. In fact, neither Bill nor Sue ever used the words "atoms" or "molecules" in any of their explanations. Tom, however, indicated a willingness to use atoms and molecules.

Conservation Reasoning

ISSUE: Conservation of Mass

Mass conservation during chemical changes is a complex topic. Underlying chemical conservation is the insight that mass is a property of all matter and remains constant during all but nuclear transformations. Chemical conservation imposes an additional constraint in that chemical knowledge is intertwined with conservation reasoning. Thus, to correctly chemically conserve mass requires both the insight of conservation and a great deal of chemical knowledge.

Bill's explanations of the three changes provided for some interesting speculation as to how the products, as he saw them, were formed. I have argued that to make sense of Bill's mass predictions several different conceptualizations may be applied. Each of these focuses upon Bill's consistent choice of everyday materials for reactants and products. A property of physical changes, like heating or a change of state, is that the material is the same before and after the process. A quasiscientific approach suggested by Bill's responses was that heat and cold can just change one material into another. For example, cold can change iron into rust. This could represent a physical transformation, like cooling water will form ice. Another possibility suggested by Bill's responses was that such a usage of heat/cold play more of a catalytic role as found in organic changes such as cooking where heating transforms a gooey egg into something edible.

Two significant and interrelated misconceptions emerge from the students' responses. The first deals with the tendency of students to attribute properties of matter like mass and the ability to participate in chemical reactions to non-matter like heat and cold.

Bill has compensated for his lack of chemical knowledge by using heat/cold to account for some of the mass that is gained/lost during chemical transformations. Even Tom uses heat energy to account for the mass lost during the oxidation of copper.

The second misconception emerges as result of the failure of students to attribute mass to gases and the ability of gases because they are invisible to participate in chemical reactions. Bill and to some extent Sue have consistently overlooked the role of invisible reactants and products in explaining the mass changes associated with chemical transformations. Heating copper to blackened copper represents from the chemist's perspective a violation of the rules for mass conservation as does burning wood into nothing.

Tom consistently demonstrates an understanding of the chemical conservation rules. His commitment to chemical conservation is so well refined that he looks for certain kinds of information related to the mass changes associated with chemical transformations. Such information seeking could only be dictated when the student has a thorough understanding of the conservation laws.

The Issue of Conservation Reasoning Apart from Chemical Conservation

As stated in chapter 2, Driver makes the point that just because a student is not chemically conserving, that does not necessarily mean that the student is not applying some kind of conservation reasoning. The case studies of Bill and Sue show this to be a point well taken. There is no doubt that Bill cannot chemically conserve. He does not have enough chemical knowledge to do so. Yet, if his predictions are examined in the following way, "Given a physical change perspective, do Bill's predictions make sense?" it becomes possible to argue that Bill is trying to conserve mass, albeit for an incorrect system. For example, Bill seems committed to the conservation rules only when the changes remind him of physical changes. Changes that require an understanding of chemical conservation are either ignored or somehow undergo metamorphoses into a physical change. Using this convoluted type of reasoning is a way to tease out the conservation reasoning patterns from the chemical knowledge to which they are integrally tied. Further analysis using this line of reasoning is presented during the analysis of the eight other students who were clinically interviewed.

Explanatory Preference/Explanatory Ideals

Asking these three students about their preferred explanations produced a fascinating set of responses. The students' explanatory preferences followed a pattern similar to that found in the previous sections. Bill consistently preferred the analogical or non-chemical type of explanation that we can refer to as a naive explanation. Given Bill's lack of chemical knowledge, his preference for everyday analogies make sense. It is hard to imagine Bill preferring a chemical explanation when he understands so little of the atomic-molecular theory.

Tom's preference consisted in explanations based upon the atomic-molecular theory with its emphasis upon the chemical equation. Sue vacillated in her preference between the analogy and the chemical equation.

The Issues of Form and Content

On the surface, Bill's understanding of the three areas of chemistry seems hopelessly muddled. Yet, there are some aspects of Bill's responses that are worth a closer look. In some ways, Bill's responses are similar to those given by Tom. Bill's responses share the same form as Tom's. Bill and Tom both explain chemical change through reference to things considered to be more simple. In this respect, Bill and Tom are in a sense equally scientific. The difference between Bill and Tom lies in what each considers to be more simple or self-explanatory, that is, their explanatory ideals. In this sense, the differences between Bill and Tom lie more in the content than in the form of their explanations. In this way the differences between Bill and Tom are similar to the differences between Aristotle and the modern chemist.

Bill's explanatory preferences suggest that his explanatory ideals for chemical change consist of everyday events and not the atomic-molecular theory. The events of everyday life shape the theories that Bill uses in his explanations of chemical change. Everyday events generate the facts and theories considered by Bill to be more simple or self-explanatory than the event to be explained. This naive explanatory ideal greatly influences Bill's ability to organize and handle new information.

Unfortunately, there is a problem in the explicit identification of Bill's explanatory ideals. Toulmin had the luxury of analyzing the explanations of one of the greatest minds in all of recorded history. From Toulmin's perspective, Aristotle consistently explained chemical changes through reference to the life cycles of plants and animals. Bill's theories of chemical change are not so clearly defined. Although Bill's explanatory preference lies with the familiar analogy, there is no single analogy to which he consistently appeals. It is doubtful that Bill even has a fully developed explanatory ideal at this time. An attempt to infer a statement of Bill's explanatory ideals at this time is unwarranted by the data.

Tom has consistently demonstrated that he prefers explanations that utilize the atomic-molecular theory. His responses are reductionist and more importantly, Tom seems to understand that his kinds of explanations would truly be acceptable to the chemist. Tom's explanatory ideal for chemical change is the atomic-molecular theory. Tom is secure enough with this explanatory ideal that when he is presented with new information, he looks for information that is explicitly within the domain of the atomic-molecular theory. Recall that Tom was given a single bit of information on the mass changes associated with the oxidation of copper metal. From this minute piece of information, Tom was able to reconstruct a complete explanation in harmony with the chemical knowledge and those aspect of chemical conservation associated with this change. Bill and Sue, on the other hand, have demonstrated that they will ignore information that is explicitly chemical in nature unless it can be related to an everyday event.

ISSUE: Perceptions of the Nature of Scientific Explanations

Bill and Tom hold quite different perspectives on what scientific explanations should look like. Bill feels that scientific explanations should include big words or sound scientific. In contrast to Bill, Tom eschews fancy words for an explanation that is based upon the interactions of atoms and molecules. Sue seems to understand that scientific explanations should be based upon the atomic-molecular theory but still feels that the scientist holds some special knowledge that students would find difficult to comprehend.

Summary of the Eleven Students Who Were Clinically Interviewed

Introduction

In this section the responses of these remaining eight students will be scrutinized more closely. While each student does have his or her own idiosyncrasies, there were several response patterns that allow for some grouping in the categories of chemical knowledge, conservation reasoning and explanatory preference.

The case studies of Tom, Sue and Bill provided a detailed understanding of these students' chemical knowledge, conservation reasoning and explanatory preferences. These case studies produced six issues pertinent to the understanding of how students explain chemical changes. This section will show how several of those issues reveal commonalities among the remaining eight students. Unlike the three case studies which presented a detailed analysis, this section will provide a rough assessment of the kinds of thinking used by the students in my study. In order to make my points, a table has been constructed showing the similar patterns of student thinking. See chapter 3 for the questions used.

I will begin the combined analysis by listing the six issues derived from the three case studies and noting which students hold naive conceptions, goal conceptions or seem to be in a transitional state with regards to their understanding of these issues. Following Table 4.2, each issue will be examined individually. Appropriate, examples will be taken from the responses of the eight students who were clinically interviewed.

Table 4.2: Breakdown of Students in Various States of Understanding

ISSUE	NAIVE CONCEPTION (2 of 3)	GOAL CONCEPTION (3 of 3)	TRANSITION (2 of 3 Goal)
Nature of reactants/ products.	Bill, Mary Peter, Jen, Phil	Rob, Jill, Tom, John	Sue, Cathy
Mobility across levels.	Bill, Peter, Jen, Mary	Tom	Sue, Phil, Cathy, Rob, Jill, John
Mass conservation.	Bill, Mary, Peter, Jen	Rob, Jill, Tom	Sue Cathy, Phil, John
Confusion over kind of transformation.	Bill, Mary, Peter, Jen, Sue, Phil, John	Tom	Cathy, Rob, Jill
Content of student explanations.	Bill, Mary, Peter, Jen	Tom	Sue, Phil, Cathy, Rob, John, Jill
Student perceptions of the nature scientific explanations.	All of the remaining students.	Tom	

Analysis of Chemical Knowledge Issues

ISSUE 1: The Nature of Reactants and Products Used in Chemical Changes

An important finding in the three case studies was that students had a variety of ideas of what could or could not be a reactant and product. The composite analysis of the 11 shows that almost an even breakdown of students in each of the three categories.

The Naive Students

The main characteristic of the naive students was their affinity for everyday materials and their use of non-matter as reactants and products. Peter, like Bill, is a naive student and his responses will be reviewed below.

A short excerpt from his explanation of rusting during the clinical interview shows that like Bill, Peter has very little understanding of chemical substances and their role in explaining chemical change. Peter has listed iron, water, salt and oxygen gas with water and the salt mixing which will slowly weaken the nail which gets eaten away. Later he states that, "Rust is made of decomposed metal that is considerably weak." Peter is asked about rusting in the clinical interview to which he responds:

Peter: ...when rust happens, when you take a piece of metal, when it gets eaten away, it gets thinner...you can scrape the stuff, the rust off...it's really very basic.

For the copper demonstration, Peter lists copper and fire as reactants and ignores the products. Later he states, "The temperature is strong enough so that it removes the unstable outer coating (of copper) and coats the copper with unstability."

<u>The Transitional Students</u>

There are two students, Sue and Cathy, who appear to be transitional students as they often give only a partial listing of the correct chemical substances in their explanations of chemical change. This is reflected in their responses to the burning splint demonstration. The content of their responses seems to focus upon the visible remains of the splint (the ash) and ignore the invisible gases produced during the chemical reaction. Cathy is like Sue in that she tries to explain chemical changes using chemical substances. In both the nail and copper demonstrations, Cathy correctly identifies most of the reactants and products. In her explanation of copper demonstration, she lists the following as reactant/products.

Cu - reactant
O_2 - reactant
fire- catalyst

Even though she never lists a product, she later writes, "The Cu reacted with the oxygen gas and a new substance was created. Since that new substance was made of both Cu and O_2, when you removed it, you were actually removing part of the copper."

For the burning splint demonstration, she gives a partial listing of reactants/products.

fire-catalyst
oxygen-reactant
wood splint-reactant
ashes-product

Unlike the copper explanation where further responses intimate the product, cupric oxide, in this explanation Cathy completely overlooks the carbon dioxide as a product and gives a reasonable but incorrect explanation for the lost mass. This will be reviewed under Issue 4.

The Goal Conception Students

The remaining three students are like Tom in that all consistently list only chemical substances for reactants/ products and most often they are the correct chemical substances. The following short dialogue is taken from the clinical interview with Jill in which she answers questions directed at her chemical knowledge of rusting.

Jill has stated that iron and oxygen gas react to form rust, which she properly identifies as ferric oxide.

I: When you think of rusting...what do you think about?

Jill: ...it's going to be an oxidation, with the iron combining with the oxygen to form the rust...

For students like Tom and Jill, chemical changes involve only material substances. Energy plays a catalytic role and does not replace atoms and molecules as reactants and products in chemical reactions.

ISSUE 2: Mobility Across the Three Levels of Chemistry

The willingness of students to explain chemical changes at the atomic-molecular level was an interesting aspect of the students' chemical knowledge and is related to the students' ability to use chemical substances in their explanations of chemical change. Students who regularly substitute everyday materials and non-matter for chemical substances never discuss chemistry at the level of individual atoms and molecules.

Table 4.2 is useful in identifying these students. The three students on the table with Bill are alike in that these students give no indication that chemical substances are composed of atoms or molecules. In varying degrees, this group of students seems to have created a chemistry without atoms. Mary is an example of a naive student. She never uses the word "atoms." In place of atoms, she uses the word "chemicals." The following excerpt is taken from the portion of her clinical interview where she is explaining how rust is formed.

Mary: When rust forms on the nail, it has to form with some of the chemicals. The sodium chloride and stuff, the water...have to form with the chemicals of the nail, with heat or something and form the rust.

Later, she is asked why she stated that the rusty nail would weigh the same as the original clean nail and responds in the following manner.

Mary: ...cause the chemicals of the nail, when they reacted...

Of the remaining students, only Tom showed a willingness to leave the phenomenological level and try to discuss the changes at the atomic-molecular level. Even the students who used only chemical substances in their explanations seemed content to talk about the changes to the copper and iron etc. without reference to the atoms that make up these substances. Responses given by the students in this group indicate that all members have some knowledge of the atomic-molecular theory. It is surprising that only Tom would, without direction, discuss these changes at the atomic-molecular level. This lack of initiative suggests that these students really do lack an understanding of the nature of scientific explanations, a topic that will be discussed in Issue 6.

Analysis of Issues Dealing with Conservation Reasoning

This analysis focused upon students' understanding of chemical conservation. Two issues emerged from the case studies, mass conservation and the use of inappropriate conservation reasoning to explain chemical transformations. Both of these issues are related to the students' chemical knowledge and demonstrate the overlap between chemical knowledge and conservation reasoning. The students who exhibited non-conservation reasoning are the same students who earlier demonstrated a proclivity to substitute everyday materials for chemical substances in their explanations of chemical change.

ISSUE 3: Mass Conservation

Primary interest was upon students' ability to accurately predict and explain the mass changes associated with chemical changes in which there was an invisible reactant/product. In the three demonstrations, the reactants/products were all gasses. Two aspects of mass conservation emerged from the three case studies. The first is the use of non-matter and/or matter-energy interconversion to account for some of the mass gained/lost during the transformations and the second is the tendency of students to ignore the substantive nature of invisible gases in chemical transformations.

Four of the 11 students regularly misconceived the role of oxygen gas in these chemical changes. All four students included oxygen gas in their list of reactants/ products. The inclusion of oxygen gas as a reactant leads to the expectation that oxygen would be used to account for the mass changes. Such was not the case. During the clinical interviews it became apparent that oxygen gas did not play an interactive role in these reactions. A common trend among these students is the belief that oxygen gas is necessary only to support combustion. The following excerpts from Mary's case study illustrate how the naive students used oxygen gas.

The Naive Students

Mary is an example of a naive student. On the written instrument, Mary lists O_2, heat and fire as reactants in the copper demonstration. She lists no products. She writes of each:

> O_2 - permits the flame
> heat - permits the change in the copper
> fire - turns it (the copper) black with a coating

In her explanation of rusting, she states that water, Ag and sodium chloride react to form the rust. Later in the clinical interview she remembers that oxygen gas is somehow involved. This brief excerpt indicates the role of oxygen gas in rusting.

I: Why do you now include oxygen gas in rust?

Mary: You have to have oxygen to light a match...to make things happen...for movement...you need oxygen to make things alive, like in reactions...

I: Why do you say that?

Mary: We need it (oxygen) for the chemicals to react...and to live, and it (the nail) needs it (oxygen) to react.

This is an interesting comparison between the need for oxygen to live and the need of oxygen for a chemical reaction. Perhaps Mary is thinking of the common expression that a candle flame will "die out" if oxygen is removed.

The Transitional Students

The students who were listed as transitional vacillated in their use of the invisible gas oxygen to account for the mass changes accompanying the three chemical changes. Phil is listed as a transitional student. Phil is like Sue in that he tries to explain chemical changes using material substances. He also, like Sue, still makes mistakes in his application of this chemical knowledge. This short commentary is helpful in showing that Phil, like Sue, only partially understands the role of oxygen as reactant rather than just a requirement for burning.

I: Can you think of any other substances? (that are involved in the heating of copper metal besides the copper)

Phil: ....oxygen....that's needed to burn...

I: Why didn't you put that down before?

Phil: Probably didn't think about it.

Later in the interview.

I: What did you think this black coating was?

Phil: The copper and part of the oxygen...

I: Do you think the oxygen goes into it (the coating)?

Phil: Yeah....no, no, no....that's not right...just the burnt copper...

This commentary shows Phil to be similar Sue in that Phil appears to be acquiring chemical knowledge in bits and pieces.

ISSUE 4: Confusion Over the Kind of Transformation

It is not the students' inability to chemically conserve that is interesting, but rather, how these students attempt to conserve mass without using chemistry! The point is that there are times that students appear to be trying to conserve mass. There are several instances of students whose reasoning makes sense and might well be considered correct if they weren't being asked to chemically conserve mass. I felt it would be interesting to follow Driver's suggestion and look for conservation reasoning within the students' perceived system.

In the summary of the three case studies, I suggested that Bill and to some extent, Sue, seemed to have different notions of the reaction mechanism than the chemist. This is related to the different categories of change as perceived by the student. The chemist recognizes only three: physical, chemical and nuclear. Each has their own rules governing transformations of that type. The students in this study have demonstrated that they categorize changes differently than the chemist. Instead of an interactive mechanism where bonds are broken and reformed between atoms and molecules, these students have different perceptions of how reactants become products.

The Naive Students

Seven students either used both everyday materials and some chemical substances or only everyday materials as reactants and products. For some of the students, products can be made in ways similar to changes of state like evaporation in which the products are for the student merely new forms of the original material. For others, the rust and the black coating are formed through quasi-chemical mechanisms. The essential characteristic of the quasi-chemical mechanism is that reactants somehow disappear and the products somehow appear because that's what happens when chemicals are mixed together.

Peter and Mary are examples of naive students. These students explain chemical changes as if they were only more complex versions of physical changes. The similarities between Peter and Bill are highlighted in this excerpt from Peter's clinical interview on rusting.

I: (Why does the nail weigh less after the rust is removed?) Where does this mass go?

Peter: What happens is that...some of the gases in there (the nail) are released and it is weakened, and it is easier to erode when it is weakened...like the wind or any friction is going to take it (mass) away in that weakened state...I was thinking of a nail is use in the environment.

Another response comes from Mary who appears to still struggle with physical conservation and like Bill and Peter appears to treat chemical change as an intricate form of physical change. In this next excerpt it becomes evident that Mary does not yet grasp the significance of chemical conservation.

I: (Mary has stated that the wood splint "turns to ash, compacting it into smaller quantities.) What were you thinking?

Mary: ...it was like smaller...but compacting is not the right word cause it like burnt up...if is was compacted it would weigh the same but look smaller.

I: Why did you put down compacting before?

Mary: ...because it looked smaller.

Transitional Students

Cathy, Rob, and Jill are transitional students. These students are inconsistent in their ability to chemically conserve mass. Even though these students consistently listed only chemical substances for reactants and products, some of their mass predictions suggested physical rather than chemical transformation.

Rob is an example of a transitional student. Rob gave an interesting non-chemical explanation of how carbon dioxide was produced during burning. As with the other students, Rob's prediction that the splint will weigh less after burning is consistent with his explanation. Rob treats burning as if it were physical change similar to evaporation. Rob knew that plants take in carbon dioxide during photosynthesis. He also had learned that burning wood produces carbon dioxide gas. Rob stated that burning somehow broke down the wood so that the trapped carbon dioxide, absorbed during photosynthesis, could escape into the air. In this way he accounted for all of the lost mass during burning. Although he did not give this analogy, it is possible that for Rob, burning is like opening a bottle of soda pop. Removing the cap, allows the carbon dioxide bubbles up and escapes.

Cathy is an example of a student who misinterprets burning as a nuclear transformation in which mass is lost in the form of heat and light energy. Cathy lists oxygen, and wood as reactants, fire as a catalyst and ashes as the products of burning. She predicts that the splint at the end will weigh less than it did before burning. The following segment is taken from her written responses.

> As the wood burned, it crumbled into ashes. This was a chemical change. The burning wood lost weight as it gave off light and heat.

Responses like this were commonly found among the naive and transitional students. In conclusion, I would say that most of the 11 students demonstrate an ability to conserve mass in an incorrect but logical way that demonstrates some commitment to conservation of mass. By far the most common conservation reasoning patterns seemed to focus upon physical or nuclear systems rather than chemical systems.

Analysis of Explanatory Preference

ISSUE 5: Form and Content in Student Explanations

In chapter 2, both Toulmin and Solomon were reviewed. Explanations of good form explained the phenomena through reference to laws or theories founded upon other phenomena considered to be more self-explanatory. There I argued that an acceptable explanation of why a giraffe has a long neck would use the Theory of Evolution as its basis. In chemistry, acceptable explanations use the atomic-molecular theory. Using Toulmin's example of Aristotle's matter theory, I also argued that Aristotle's explanations of chemical change, although not presently acceptable in light of the atomic-molecular theory, were nevertheless explanations of good form. In that sense, Aristotle's explanations represented an acceptable scientific explanation at that time in history. It was not that Aristotle lacked the proper form of modern scientific explanations, but rather, he lacked the proper content.

Solomon found that students of different ages gave different kinds of explanations to scientific phenomena. Younger students gave explanations that lacked good form because their explanations either restated the question only in different terms or they gave what Solomon terms a "that's just the ways things are" kind of explanation.

Solomon treated explanations based upon simile, analogy or metaphor as being quasi-scientific. If the simile/analogy/ metaphor drew the student to some key aspect of the scientific theory, then this kind of explanation exhibited good form.

In this study, all 11 students gave explanations of good form. By that I mean that none of the 11 students explained chemical change in ways that suggested they were merely utilizing Solomon's first two kinds of explanations. Rather, explanations based upon simile, analogy, metaphor and model were common to four of the 11 with explanations based upon chemical theory being used by the other seven students in at least two demonstrations.

The content of the similes, analogies, models and metaphors (SAMMs) proved to be a stumbling block for the students who used them. In every instance, the chosen analogies focused upon superficial characteristics of the phenomenon and could not be considered acceptable explanations. The problem with such a tactic is that analogies at the phenomenological level are not useful in promoting understanding because the similarities remain at the phenomenological level. The objective of chemical analogies is to help link the observable phenomenon to the atomic-molecular level. Use of the solar system model represents an acceptable transition to explaining atomic structure. Unfortunately, the SAMMs selected by the students were of everyday events: cake batter, putting on a coat and the burning of a candle to mention a few. There was little consistency or pattern in the content of the students' SAMMs. It appeared that the students used whatever SAMM popped into their heads first.

The Explanatory Preferences of the Eleven Students

The Naive Students

Three of the students were like Bill. They demonstrated a strong preference for analogies with everyday events. These four students also had the least amount of chemical knowledge. These students seem to typify the idea that it is difficult to prefer what you don't understand. The excerpts taken from the case studies of Peter and Mary presented earlier in this section demonstrate the preoccupation of these students with everyday analogies. Peter compared rusting with erosion and Mary used compacting as a means to explain burning. The following commentary is taken from Jen's case study. Her response suggests that the black material on the surface of the copper is like a "coat." When on, the copper will weigh more. When removed, the copper will weigh the same because none of the copper is in the coating. "The black just covered the copper, otherwise you couldn't get it off. The coating is just on the original piece, it didn't sink into the copper."

An Example of a Transitional Student

Solomon has suggested that analogies can be considered the precursors of scientific explanations. The problem with the analogies used by the students in my data set, however, is that the majority of the students have utilized analogies which focused upon the surface similarities of the chemical transformations. Throughout this discussion, Cathy has been cast as a transitional student. In contrast with the other students, Cathy used the analogy in ways that indicated she was on the brink of understanding the goal conception. The following excerpt is taken from her clinical interview on the oxidation of copper.

I: What were you thinking about? (Cathy wrote that copper and oxygen reacted in the presence of fire.)

Cathy: It is like the nail...a displacement or synthesis reaction....if I could figure out if it was a synthesis...then the copper and the oxygen combined to make the coating...

With Cathy there is no cake batter, no burning up into nothing, no erosion, no compacting and no eating away. Rather, her analogy draws from the fact that chemical reactions can be categorized into only a few different types based similarities among reactants and products. By using an analogy closer to the phenomenon she was trying to explain, Cathy went beyond the surface similarities and gives a very good attempt at a scientifically acceptable explanation.

The rest of the transitional students seemed unsure of themselves and waffled between the analogy and the atomic-molecular theory as their explanatory preference. Even students with the most chemical knowledge and conservation reasoning consistently indicated a preference for the homespun analogy on the written instrument used during the clinical interviews.

Only Tom out of the 11 students is listed as a goal conception student on this issue. Only Tom would openly state that the set of analogies listed would not be an acceptable part of a scientific explanation.

ISSUE 6: Students' Perception of the Nature of Scientific Explanations

This issue emerged from the three case studies as an unanticipated finding. This issue is an aspect of the larger topic of explanatory preference. At one point during the clinical interviews the students were asked whether a balanced equation, a homespun analogy or both would make their explanations more acceptable to a chemist.

The analogies were constructed in a non-scientific manner and were drawn from typical student responses. These questions represented a measure of the commitment to the analogy and gave a better indication of the student's perceptions of scientific explanations.

It was somewhat frustrating that after instruction that was meant to help students learn and use the atomic-molecular theory, only Tom consistently used the atomic-molecular theory in his written explanations. Only Tom consistently chose the balanced equation during the clinical interview. All of the other ten students indicated that the everyday analogies helped them understand the phenomena before them. The very fact that ten of the 11 students chose analogies to make their explanations more acceptable to the chemist is further indication that these students have misconceptions about the nature of scientific explanations. These students do not perceive the atomic-molecular theory as providing the content for acceptable scientific explanations. They mistakenly perceive that scientific explanations include "fancy words" much in the sense of Bill's closing line.

Another problem for these students was the misconception that the verbal analogy was needed to compliment the symbolic equation. This idea was best described by Peter. Peter seems to recognize that the equation would be important to the chemist but lacks the chemical knowledge important to comprehend the information conveyed in the equation. The chemist understands the meaning of symbols in an equation, Peter only knows that equations make an explanation look scientific. In the clinical interview, Peter is shown both the analogy and the equation. The following is taken from his responses to the burning splint demonstration.

> This (the equation) doesn't explain anything really, it tells what is going on but it doesn't explain it. Number 2 (the analogy) this explains it (burning) but doesn't really tell what's going on. Number 1 (the equation) tells just the chemical equation but doesn't tell anything is being burned...you would have to know some chemistry....both of these when combined could provide just an excellent explanation.... combining the chemistry and the words.

In conclusion, the issue of how students perceive scientific explanations is one that carries over into the area of chemical knowledge and ultimately will dictate the willingness of students to work at acquiring additional chemical knowledge. This conclusion is suggested by some additional data collected during this study. On a topic related to the students' indecision over the appropriate content for scientific explanations, students were asked if they were satisfied with their own explanations. A surprising number of the students who possessed large amounts of chemical knowledge indicated that they were not satisfied with their explanations. Additionally, another sub-group emerged from the students with the least amount of chemical knowledge. This group indicated they were satisfied with their responses regardless of how a chemist might evaluate them. I believe that these findings are somehow related to the students' uncertainty over the nature of scientific explanations. The issue should become a focal point for future research.

Chapter 4 Summary

The purpose of chapter 4 was to document the chemical knowledge, conservation reasoning and the explanatory preferences used by high school chemistry students as they explained three chemical changes. Chapter 4 also investigated the interrelationship among these three areas of understanding. Of the 100 students who were originally given the paper/pencil instrument, 11 were chosen for clinical interviews. Three of these 11, Bill, Sue and Tom were singled out for in-depth analysis. Analysis consisted of figuring out where each student stood on a series of eight issues identified during the literature review in chapter 2. Analysis showed that my data did not address two of these issues. However, two other issues not discussed in the literature did emerge as relevant to understanding the responses of the students in my study. The response patterns of Bill, Sue and Tom were common to the other eight students.

The issues and misconceptions presented in the heart of chapter 4 will be condensed into a summary statements of the various findings associated with the students' chemical knowledge, conservation reasoning and explanatory preferences. Two additional points will be made on the interrelationship among the three areas.

Chemical Knowledge

ISSUE 1: The Nature of Reactants and Products.

Students regularly substituted everyday materials like air, corrosion, fire, smoke and ash for chemical substances in their explanations of chemical changes. More often than not, elements that were listed in the reactants did not appear in the products.

ISSUE 2: Mobility Across Levels.

The use of everyday analogies inhibits smooth transitions between the phenomenological and the atomic-molecular levels of chemistry as identified by Ben-Zvi et. al. Everyday analogies keep the student focused upon aspects of the transformation that are not significant for the explanation of that change. Too often, the students' attention becomes fixed at the phenomenological level. Several students never referred to atoms or molecules in any of the written or verbal commentary. The analogy about shriveling-up with age caused many students to focus upon the non-combustible ash portion of the wood splint rather than upon the fact the carbon dioxide is an invisible product.

Conservation Reasoning

ISSUE 1: Mass Conservation and Size of the System.

Mass conservation during chemical transformations poses a problem for most of the students in this study. Six students failed to account for some of the mass as reactants formed products. These students overlooked the substantive nature of gases. Even the best students had their moments of confusion over the questions directed at conservation reasoning. Yet, the best students were committed to mass conservation even though they lacked important bits of chemical knowledge. When given information about the mass, these students were able to account for it in a chemically acceptable manner by bringing into play their vast quantity of chemical knowledge.

ISSUE 2: The Application of Correct but Inappropriate Conservation Reasoning.

Close reading of student responses indicated that although these students were not chemically conserving mass, they were doing much more than just making up answers. Many of the students' explanations did make sense given the students' perception of the change. For students who perceive a transformation as being non-chemical, their explanations were more likely to conserve mass if they explained the transformation using a physical change analogy rather than a chemical change analogy. For example, students who treated rusting and the oxidation of copper as intricate forms of physical transformations like freezing or evaporation, were able to account for the mass in a way consistent with their perception of the change.

Explanatory Preference/Explanatory Ideals

Explanatory preferences are treated as a specific instance in harmony with a more general explanatory ideal. The students in this study demonstrated some consistent patterns in their explanatory preferences.

ISSUE 1: The Content of Student Explanations.

The most striking aspect of this analysis was the preponderance of analogical thinking. Three of the 11 students openly admitted that they sought out analogies with everyday events as a basis for understanding the observed transformation. These students indicated that they were satisfied with their analogical explanations and thought these explanations were essentially correct. Even the best students admitted that the analogy helped in their personal sense making of the chemical change.

ISSUE 2: Perceptions of Scientific Explanations.

There was an underlying feeling among most of the students that scientific explanations used big words. Students regularly used words like "reacts" and "chemicals" in their explanations. Yet, only a few demonstrated a chemist's understanding of what these words meant.

The Interrelationship Between the Three Areas

The major premise of this dissertation is that when students learn about chemical change, they are really acquiring understanding in three areas that must ultimately blend together before a student can explain chemical changes in manner that would be considered acceptable to the chemist. There are two points to be made to highlight

how these three areas are interrelated from a student's perspective.

Point 1: When the problems of learning about chemical change are assessed from the chemist's perspective, many aspects of conservation reasoning and explanatory preference can be consolidated into those of acquiring knowledge of the atomic-molecular theory. It is possible to argue that having acquired sufficient chemical knowledge, the ability to conserve mass using the atomic-molecular theory is almost a given. So too with explanatory preferences. Conventional wisdom dictates that it is hard to prefer what you don't understand. Given the chemist's understanding of the atomic-molecular theory it is easy to understand why explanations based upon the interactions of atoms and molecules is preferred to everyday analogies. But, to understate the point, high school students are not yet chemists!

Point 2: With high school students, my argument for the parallel but interrelated development of the three areas has relevance. I have shown that an understanding of the atomic-molecular theory is important for a thorough understanding of chemical conservation and the explanatory preferences of the chemist. It is difficult to conserve mass during burning if the student lacks knowledge of carbon dioxide gas. Likewise, it is difficult to prefer the balanced equation over an everyday analogy if the student lacks understanding of how symbols are used in chemical equations. Yet, the case studies have shown some students to attempt mass conservation lacking chemical knowledge and the case studies have also shown some students to prefer everyday analogies having demonstrated a pretty good understanding of the atomic-molecular theory.

Looking at chemistry from the students' perspective, that is, bottom-up, shows chemistry to be a lot more differentiated than hierarchial. By this I mean that students learn chemistry in each of the three areas in bits and pieces. Students gradually abandon their naive ways of thinking as they move towards the goal conceptions in each of the three areas. The new understanding is fragile and is constantly being tested against their existing theories. This accounts for the waffling between naive and goal conceptions exhibited by even the best students. The three-part model for learning explains why so few of the students can explain chemical changes in ways that would be acceptable to the chemist.

CHAPTER V

SUMMARY AND IMPLICATIONS

Chapter 5 consists of a summary of the first four chapters of this dissertation followed by sections focusing upon the implications of this research for curriculum and instruction, for classroom teaching and for further educational research at the level of educational theory.

Summary of Dissertation

The Problem and Theoretical Basis

The problem of understanding scientific concepts pervades all of science education. In an attempt to understand the nature of this problem, research in science education has begun to focus upon the specific misconceptions that appear to exist as "critical barriers" to understanding science (Hawkins, 1978).

The understanding of chemical change represents a critical barrier phenomenon. Cars rust and disintegrate; food left out of the refrigerator will decay; wood logs burn down to a handful of ash; copper and silver utensils tarnish and must be cleaned. These everyday changes involve chemistry and are best explained through reference to the interactions of atoms and molecules. In addition to these everyday kinds of chemical changes there are physical changes that share surface similarities to chemical changes. Lakes freeze over in the winter, water in a coffee kettle will boil away and Kool Aid disappears giving color and taste to a pitcher of water. In the chemist's eyes, these represent entirely different kinds of transformations. Explanations of these changes do not involve chemistry, yet they pose major hurdles for beginning chemistry students.

My study began by asking what kinds of understanding students must have to produce an explanation of chemical change that would be acceptable to the chemist. The underlying assumption was that students must acquire understanding in three distinct areas: (a) chemical knowledge, (b) conservation reasoning, and (c) explanatory ideals. To date, most studies within the student conception genre have focused upon the first two areas of understanding. I believe that explanatory ideals represent an important concomitant in the formulation an acceptable explanation for a student, and as such, represents an important and overlooked aspect of student learning. Each of these areas is reviewed separately.

Chemical Knowledge

Many students take and pass chemistry courses, often with high grades, without understanding the chemical concepts underlying the content. Recent studies by Yarroch (1985) and Ben-Zvi, Eylon and Silberstein (1982) on student understanding of equation balancing, the meaning of subscripts and the representation of atoms and molecules in the atomic and multiatomic state demonstrate the disparity between correct answers as given on written instruments and student understanding of the concepts underlying the correct answers. Ben-Zvi et. al. (1985) indicate that difficulties will occur when students are asked to conceptualize chemical changes on the atomic-molecular level and the phenomenological level almost simultaneously.

Problems exist when students attribute properties like color and state, evident at the macroscopic level, to the individual atoms and molecules. Yarroch suggests that the source of students` difficulties lies in that students understand equation balancing at two different levels: one that incorporates the usefulness of abstract symbols in chemical explanations and one that involves the mathematical manipulation of chemical symbols (p. 458).

Conservation Reasoning

In addition to chemical knowledge, students must acquire an understanding of chemical conservation. Initial interest in conservation reasoning is derived from Piaget's and Inhelder's work on students' abilities to conserve mass and substance (1941). Piaget/Inhelder have demonstrated that children not much younger than those participating in this study have problems in conserving mass and substance in relatively simple physical changes such as the dissolving of sugar in water. Given the complexity of chemical changes in comparison to dissolving, it is not surprising to find the difficulties with conservation revealed by the Driver (1986) study. Driver's work further indicates that for many students, the lines delineating chemical and physical change remain fuzzy, even after formal instruction in chemistry. Vestiges of physical change are found in student explanations of chemical change.

My study chose to analyze chemical conservation from the perspective of conservation of elements and mass as a means of differentiating among chemical, physical and nuclear changes.

Explanatory Ideals

Are chemical knowledge and conservation reasoning enough to produce an acceptable explanation? Driver (1986) suggests a missing element in acceptable explanations. Driver indicates that students will regularly abandon their chemical knowledge preferring explanations that utilize their intuitive notions of change based upon experience. Driver's final statement forms a springboard for the third theoretical aspect of my dissertation, explanatory ideals.

> The issue which need to be considered is not just whether students understand the theoretical ideas or models they are exposed to in teaching but whether they can use them or see them as useful and appropriate in interpreting actual events (emphasis added). (p.168)

It is important that students believe the chemical knowledge they apply will adequately address the problem confronting them. To do otherwise is merely an advanced form of rote learning. For a student to write a chemical equation just because equations look scientific suggests that the student has in some sense missed the point that chemical explanations include equations because equations represent a summary statement of the reactants, products and the law of conservation and as such are important to an explanation in chemistry. Learning the acceptable make-up or form of a chemical explanation represents another kind of knowledge the student should acquire in a chemistry course. Notions of acceptable explanations are called explanatory ideals.

Interest in explanatory ideals comes form the work of Toulmin (1972) and Posner, Strike, Hewson and Gertzog (1982). Toulmin outlined a conceptual model from a historical/philosophical perspective. As part of his argument, Toulmin analyzes how our notions of matter-theory have evolved since Aristotle. In his argument for conceptual change, explanatory ideals are introduced as "ideas about the Natural Order" that men consider to be "self explanatory" (p. 42). Drawing from Toulmin, Posner et. al. suggest that what Toulmin believed to be happening in the larger realm of history/philosophy of science could be applied to the mental processes associated with individual human learning. For Posner et. al., explanatory ideals belong to an individual's "conceptual ecology" which are current concepts with which the individual presently interprets the world. A persons' explanatory ideals influence the type of explanation, the content of that explanation and ultimately the degree of confidence and satisfaction that person will have in the explanation.

An additional assumption of my study is that explanatory preferences represent specific instances of an explanatory ideal.

The work of Solomon (1983) on the kinds of explanations given by children to scientific phenomena was also reviewed. Solomon identifies four kinds of explanations. The first two are decidedly non-scientific and deal with teleologies and explanations by word substitutions. The third involves the use of similes, metaphors, analogies and models as a basis for more detailed explanations that utilize accepted laws and theories as a basis for explanation. Explanations based upon accepted laws and theories formed the fourth and best kind of scientific explanations.

Issues Derived from the Literature

From the literature review in these three areas, eight issues emerged that appeared pertinent to my study.

Chemical Knowledge

ISSUE 1: The Properties of Atoms and Molecules.

ISSUE 2: The Nature of Reactants and Products in Chemical Changes.

ISSUE 3: The Mobility of Students Across the Levels of Chemistry.

Conservation Reasoning

ISSUE 1: Conservation of Mass.

ISSUE 2: The Boundaries of the System. What are the components of the system the students are describing.

ISSUE 3: The Nature of the Change Taking Place.

Explanatory Preferences

ISSUE 1: The Form of Student Explanations.

ISSUE 2: The Content of Student Explanations.

Methods

Subjects for this study were selected from a student population of 100 high school chemistry students. After instruction on chemical change, formula writing, equation balancing and stoichiometry all students were asked to explain three chemical changes (rusting, heating copper metal in air and burning a wood splint) using a paper/pencil instrument. At the end of each demonstration, students were asked to evaluate their own responses.

Following the paper/pencil exercise, 11 students were chosen for clinical interviews. Students were chosen from three categories: those whose work throughout the year placed them as above-average students, average students and below-average chemistry students.

Interviews lasted about one-half hour and were conducted during the course of the school day. During the interview, students were asked to describe what they were thinking when they wrote a given response. Students were asked why they were satisfied with their responses. An additional instrument was prepared for the clinical interview that asked the students whether the addition of a balanced chemical equation, a non-chemical home spun analogy or both would make their responses more acceptable to a scientifically trained adult.

From this smaller pool of 11 students, three were slated for in depth case studies which form the main portion of this dissertation. Analysis consisted of determining where the three students stood on each of the eight issues. Bill is representative of students who have retained their naive conceptions of chemical change in spite of instruction. Tom is representative of a goal conception student and Sue is characterized as a student in transition from naive to goal conception ways of thinking.

In summary, this study is part of a research genre suggested by Driver and Erickson (1983) who defend and support theories-in-action studies characterized by an:

> ...approach of probing student's knowledge-in-action through regularities in their responses to carefully constructed task situations....Clinical interviews with students which probe their predictions and interpretations can be useful in eliciting such aspects of student thinking. In studies of this kind students are presented with an event or physical system....and they are asked to make a prediction of the outcome.... (p. 45)

Results

The results were organized according to the issues identified in chapter 2. Of the eight issues, two were not pertinent to my study and the issue of boundary of the system was so closely related to students' abilities to conserve mass that this was dropped as a separate issue. From the detailed analysis of Bill, Sue and Tom, two additional issues emerged. These issues were not discussed in the studies reviewed in chapter 2. Thus, there was some realignment of the issues in chapter 4. These issues were found to be helpful in understanding the explanations of the remaining eight students. The issues pertinent to my study fall into the three domains of chemical knowledge, conservation reasoning and explanatory preferences. The reader is referred to chapter 4 for a more detailed analysis of these issues. These issues and my key findings are cited below.

Issues and Findings Supported by the Data

Chemical Knowledge

ISSUE 1: The Nature of Reactants and Products.

Key Finding: A majority of students regularly substituted everyday materials and energy for chemical substances in these chemical reactions.

ISSUE 2: The Mobility Across Levels.

Key Finding: Only one student, Tom, was able to consistently take his observations of chemical changes and give an explanation that was based upon the interaction of atoms and molecules. The rest of the students focused upon some visibly aspect of the change they were asked to explain.

Conservation Reasoning

ISSUE 1: Mass Conservation.

Key Finding: The students who were unable to conserve mass ignored both the existence and the substantive nature of gases.

ISSUE 2: Confusion Over the Kind of Transformation.

Key Finding: The most interesting aspect of the conservation reasoning used by the students in this sample was not their inability to chemically conserve mass, but rather, that their explanations actually made sense given their misinterpretation of the change as a physical change.

Explanatory Preferences

ISSUE 1: The Content of Student Explanations.

Key Finding: Students in this sample regularly demonstrated a preference for explanations based upon everyday analogies. The content of the analogies varied among students and depended upon whatever popped into the students' heads while observing the demonstration. Several students stated during the clinical interviews that they actively sought analogies to help them make sense of the phenomenon they were observing.

ISSUE 2: Student Perceptions of Scientific Explanations.

Key Finding: A majority of the students indicated that while analogies with everyday events were sufficient for their personal explanations, they felt that a chemist would want an explanation that "used fancy words," or "sounded scientific."

Implications

Introduction

The results of this research have shown that when students learn about chemical change they are really acquiring understanding in three areas: (a) chemical knowledge, (b) conservation reasoning and (c) explanatory ideals. This study has shown that the topic of chemical change is much more complex than most teachers and text book authors currently acknowledge. I believe that my results have demonstrated that the topic of chemical change is one that holds both instructional and curricular significance as first described by Anderson and Smith (1983) and again by Hollon and Anderson (1985).

The naive conceptions found in this study meet the requirements for instructional significance in that (a) they are believed by many students, (b) held with a deep conviction and cannot be easily abandoned, and (c) hold the promise of being changed with proper instruction. The students in this study regularly used common sense thinking in place of scientific concepts. Analogy to everyday phenomena proved a common basis for scientific explanations. Even the students who acquired a scientific vocabulary really never understood the scientific conception. There was no real need in these students to change their naive conceptions. For example, the use of the word "reaction" was regularly found in students explanations, yet these students demonstrated little understanding that reactions involve the interaction of atoms and molecules. A majority of the students had not abandoned their naive ways of thinking about chemical change as a result of the instruction. In fact, instruction had done little more than help the better students acquire a more scientific vocabulary. The misconception remained for most students that scientific explanations involved the ability to "talk fancy." It is for these reasons that I believe that this topic holds instructional significance.

The patterns in the students' responses in this study demonstrate that this topic also holds curricular significance. To hold curricular significance, the naive conceptions must strike at concepts fundamental to the discipline itself or the concepts must be fundamental to several topics within the discipline. Many of the naive conceptions with reactants/products, explanations of chemical changes and mass changes challenge the scientific understanding of atomic-molecular theory which pervades all of chemistry and part of biology and physics. The conservation reasoning patterns and explanatory preferences identified in this study also show that chemical change is a topic with curricular significance. The confusion over what kinds of explanations are acceptable for chemical change highlights a larger problem of how students explain all scientific phenomena.

The results of this dissertation hold implications for three areas of science education: (a) curriculum and instruction, (b) teacher education, and (c) the direction and kind of future research. Each of these will discussed in turn.

Implications at the Level of Curriculum and Instruction

The topic of chemical change is one that deserves additional attention from both textbook authors and teachers alike. Too often, both groups have treated this topic as elementary and as such, simple for students to master. This has not been the case for the students in this study. This suggests that for students to acquire the scientific conception of chemical change, both teachers and authors must begin to anticipate the deeper misconceptions that affect the students' thinking about chemical change.

Implications for the Curriculum

The misunderstandings surrounding the application of the Law of Conservation to chemical changes needs to addressed within the body of text material. It is not that most students did not make some attempt at conservation. What is important is that students were using different interpretations of the Law of Conservation than was intended by the text. Within this vain, the curricular significance of this topic dictates a need for textbook authors to consider their treatments of physical and chemical conservation. Chemical conservation should be presented within the context of conservation of elements and conservation of mass. The differences between physical, chemical and nuclear changes must be contrasted.

As a practicing teacher I have found that many of my students have benefited from a direct comparison of these kinds of changes in a manner similar to that described in chapter 2. The kind of conservation reasoning that is required to properly explain chemical changes is not adequately treated in most traditional science texts. Additional space must be allocated for helping students understand the differences between chemical, physical and nuclear changes from the chemist's perspective.

A complete understanding of chemical change requires more than the acquisition of chemical facts and the ability to chemically conserve elements and mass. Explanatory ideals must be given some time for development during an instructional unit. Explanatory ideals/explanatory preferences represent yet another area of a student's conceptual ecology that cannot be overlooked. Students should be helped to understand why some kinds of explanations are more preferable than others. The function of analogy must be addressed more directly. The atomic-molecular theory must be presented as the chemist's explanatory preference. In particular, students should be taught that while analogy, metaphor etc. play an important part in scientific explanations, there are some kinds of analogies that are better than others. Analogies, metaphors etc. that focus upon surface similarities such as the similarity between the burnt splint and a person shriveled with age are apt to lead the student away from the underlying scientific theory or law.

Authors must help teachers become aware of the common naive conceptions students bring to the chemistry classroom. These naive conceptions form the basis of explanations which focus upon analogies to everyday events. Explanations based upon analogy remain the students' preferred form of explanation. These problems must be addressed directly within the text books.

Implications for Classroom Teaching

The results of this study suggest that traditional teaching methods are ineffective in helping students learn this topic. Students began the topic of chemical change in a naive state. For the most part they have not abandoned their naive conceptions of chemical change. The difficulties experienced by the students in this study arose when naive conceptions clashed with scientific conception. This suggests that teaching strategies aimed directly helping students abandon their naive conceptions might prove helpful.

Thus, the next step is to devise teaching methods and materials that can address specific naive conceptions and to investigate their effectiveness. This process has already begun. Before I describe my attempts to implement new teaching methods in my own classroom, I would first like to outline a direction for teaching that holds the promise of helping students learn the topic of chemical change.

Conceptual change teaching is a rubric attached to methods of instruction meant to uncover, elucidate, confront and abandon naive conceptions followed by the adoption of the scientific conceptions. Conceptual change teaching is derived from a theoretical model of conceptual change outlined by Posner et. al. (1982). A typical format used by researchers who are experimenting with conceptual change teaching involves the following sequence:

1. Student conceptions are diagnosed. Often an exposing event, perhaps a demonstration, is used to elicit the students' entering conceptions. In this stage of instruction students are asked to clarify and debate the merits of their own ideas.
2. Student conceptions are challenged. Many researchers have used a discrepant event. A discrepant event is one that runs counter to

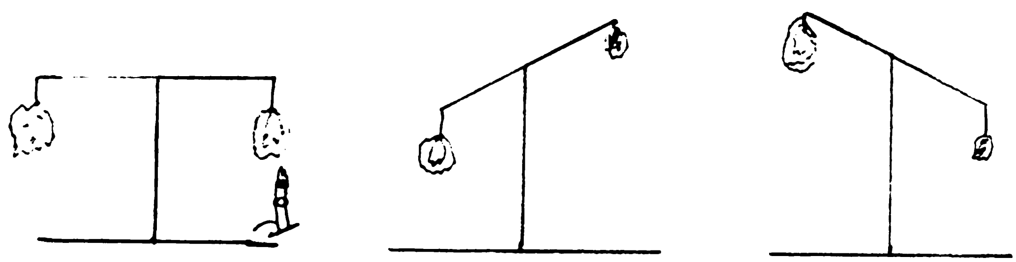
predictions made when using a naive conception. At this stage, naive conceptions are confronted and refuted. The scientific conception is presented in a form that satisfies the students' need to explain the discrepant event. The scientific explanation must be presented in a form that is intelligible and plausible to the student.

3. Students are given numerous opportunities to try out the explanatory power of the scientific conception on other events. This further helps the student challenge the naive conception as most students will waffle in their ability to use and thus accept the scientific conception.

A First Experience with Conceptual Change Teaching

During the 1985-1986 school year I introduced conceptual change teaching methods into a unit on chemical change in my ninth grade physical science classes. Four classes, (n=100) of physical science students were given a modified version of the written instrument used in this dissertation. These groups were taught in a manner consistent with conceptual change teaching as outlined by Ministrell, Nussbaum, Anderson and Smith. Students were given an exposing event, initial conceptions were recorded on the board, a discrepant event was presented followed by discussion, lectures were devised to address the naive conceptions, and students were given practice using the new conception.

As part of the discrepant event, steel wool is hung on both sides of a balance (see Figure 5.1). One side is heated with a bunsen burner. Students are asked to predict and explain the mass changes that accompany the heating of steel wool.



Common Prediction

Actual Result

Figure 5.1: Student Perceptions of Burning Steel Wool with a Bunsen Burner.

Most of the students predicted that the heated side would weigh less and rise. Typical explanations were: part of the iron would be burned away and heat expands the steel wool making it rise. After the demonstration students were astonished that the heated side weighed more. Several students in disbelief claimed that I somehow rigged the balance. It was even more incomprehensible that a gas like oxygen could make the steel wool weigh more. Only after the students observed the nodules of ferric oxide would they accept the alternative view provided by a few students that a new substance had been produced that could possibly account for the increased mass.

After instruction, over 25 percent of the ninth grade students demonstrated an understanding of chemical knowledge, conservation reasoning and explanatory preferences that would be acceptable to a chemist. Many more responded in ways that suggested a transitional state. The best ninth graders regularly chose chemical substances for reactants/products, introduced invisible gases when appropriate and indicated a preference for explanations based upon the atomic-molecular theory over non-chemical kinds of explanations.

These results with ninth graders are interesting and encouraging when contrasted with the results of 11th grade chemistry students using the same instrument. Out of 65 chemistry students, 10 demonstrated an understanding of chemical knowledge, conservation reasoning and explanatory preferences equivalent to Tom's in my study. An interesting comparison between the amount of knowledge in each of the three areas was found when comparing both groups. Even though the chemistry students had acquired much more chemical knowledge than the physical science students, their conservation reasoning and explanatory preferences were not much different than the ninth graders. For example, the same chemistry students who could list the reactants/products and write a balanced chemical equation would predict and justify mass changes ignoring the significance of the chemical knowledge they had written on the previous page. Additionally, these same students would indicate a personal preference for an everyday analogy over the same equation they had written only minutes before.

Implications for Teacher Education

It is evident from this discussion that traditional teaching techniques are not capable of promoting conceptual change in many students. At present, very few science teachers have been trained in or are even aware of conceptual change teaching techniques. Schools of education will need to include this approach as part of their methods courses for perspective science teachers. To reach the existing body of science teachers, workshops and inservice materials must be created that can inform and stimulate interest in conceptual change teaching.

It is not inconceivable that the same conceptual change techniques that are employed by the teacher to promote conceptual change within students must also be applied to the present body of practicing teachers. A recent experience with a fellow colleague suggests the truth of the above statement.

Another science teacher who is considered to be one of the best teachers in the school walked into my classroom one afternoon and saw a set of conceptual change materials on chemical conservation setting upon my desk. After a short inquiry as to their purpose he responded, "What's the big deal about mass conservation? I taught that topic to my students in Physical Science. There's no need to cover it again in Chemistry." Such responses suggest that conceptual change will occur first in the teacher and then in the student.

Implications for Additional Research at the Level of Educational Theory

This study has explored a set of chemical knowledge, conservation reasoning patterns and explanatory ideals associated with chemical change. This study has documented that each of these represent a distinct area in a student's conceptual ecology. None of these areas have been well-documented in the literature. The results of this study call for additional research in each of these areas. The discovery of explanatory ideals is particularly exciting and represents an unexplored area of a student's conceptual ecology. One potential area of interest would be in exploring the relationship between each of these areas. It is hypothesized that there exists an interactive relationship among chemical knowledge, conservation reasoning and explanatory ideals.

In the area of conservation reasoning more work needs to be done to understand how students make the transition from complex physical conservations, such as those associated with dissolving, to chemical changes. An unanticipated issue raised from my research that requires further study deals with the misapplication of physical conservation reasoning patterns to chemical transformations.

Additional work is needed in how students make the mental transition between their explanations at the phenomenological level to the atomic-molecular and multiatomic levels. The work of Eylon et. al. has shown the difficulties of students in making the transitions from the atomic-molecular to the multiatomic level. Another unanticipated finding of my study dealt with student perceptions of scientific explanations. I have not explored the relationship between mobility across the levels of chemistry and the students' perceptions of scientific explanations. It is possible that a better understanding of how reductionism is used in scientific explanations might help students make a more fluid transition between the phenomenological and the atomic-molecular levels of chemistry as outlined by Ben-Zvi et. al. in chapter 2. I leave these questions as directions for additional research.

APPENDIX

The Written Instrument

1. IN YOUR MIND, WHAT DOES IT MEAN TO SAY THAT A CHEMICAL REACTION HAS TAKEN PLACE-- WHAT DO WE MEAN BY 'REACTS'?

2. IF YOU WERE OBSERVING SOMETHING CHANGE, HOW WOULD YOU DECIDE IF A CHEMICAL REACTION WAS OCCURRING?

3. A. AN IRON NAIL RUSTS.
MAKE A LIST OF ALL THE SUBSTANCES THAT YOU BELIEVE ARE INVOLVED IN THIS CHANGE-AND TELL THE ROLE OF EACH.

(SUBSTANCES) (ROLE)

B. IF YOU COMPARED THE WEIGHT OF THE RUSTY NAIL TO THAT OF THE ORIGINAL CLEAN NAIL WOULD THE RUSTY NAIL WEIGH MORE/LESS/SAME AS THE ORIGINAL CLEAN NAIL?..............EXPLAIN YOUR ANSWER.

C. IF THE RUST WERE REMOVED FROM THE RUSTY NAIL DO YOU THINK THAT THE NAIL WOULD WEIGH MORE/LESS/ SAME AS THE ORIGINAL CLEAN NAIL? .... EXPLAIN YOUR ANSWER.

D. IF THE RUST IS REMOVED, THE NAIL WILL WEIGH LESS. WHAT DO YOU THINK HAPPENED TO MAKE THE NAIL LIGHTER?

E. HOW DO YOU THINK THE RUST WAS MADE AND WHAT IS IT MADE OF?

F. WHAT ROLE DO YOU THINK THAT THE WATER PLAYS IN THE RUSTING OF AN IRON NAIL?

G. IN YOUR OPINION, IS A CHEMICAL REACTION TAKING PLACE? ....

IF YOU SAID YES, EXPLAIN HOW THIS REACTION OCCURS. IF YOU ANSWERED NO, GIVE YOUR REASONS.

H. SOME STUDENTS STATED THAT THE NAIL CORRODES. IN YOUR MIND WHAT IS MEANT BY CORROSION?

I. THE RUSTY NAIL WEIGHS MORE THAN THE ORIGINAL CLEAN NAIL. WHAT DO YOU THINK HAPPENED TO MAKE THE NAIL GAIN IN WEIGHT?

TURN THE PAGE AND WAIT FOR THE NEXT PRESENTATION

4. A. I AM GOING TO PUT THIS PIECE OF COPPER METAL INTO SOLUTION X. DESCRIBE WHAT YOU OBSERVE.

B. IN YOUR OPINION IS A CHEMICAL REACTION TAKING PLACE? ....

IF YOUR ANSWER IS YES, HOW IS THE REACTION OCCURRING? IF YOUR ANSWER IS NO, GIVE YOUR REASONS.

C. MAKE A LIST OF ALL THE SUBSTANCES INVOLVED IN THIS CHANGE- AND DESCRIBE THE ROLE OF EACH.
(SUBSTANCE) (ROLE)

D. IF THE COATING IS REMOVED FROM THE COPPER, WILL THE REMAINING COPPER WEIGH MORE/LESS/SAME AS THE ORIGINAL CLEAN COPPER? .... EXPLAIN YOUR ANSWER.

E. DO YOU THINK THE COATED COPPER WEIGHS MORE/LESS/ SAME AS THE ORIGINAL CLEAN COPPER? .... EXPLAIN YOUR ANSWER.

TURN PAGE AND CONTINUE

F. IF THE COATING IS REMOVED FROM THE COPPER, THE REMAINING COPPER WILL WEIGH LESS. WHAT DO YOU THINK HAPPENED TO MAKE THE COPPER WEIGH LESS?

G. HOW DO YOU THINK THE COATING WAS MADE AND WHAT IS IT MADE OF?

H. THE COPPER WITH THE COATING ON IT WEIGHS MORE THAN THE ORIGINAL CLEAN COPPER. WHAT DO YOU THINK HAPPENED TO MAKE THE COATED COPPER WEIGH MORE?

5. A. I AM GOING TO LIGHT THIS WOOD MATCH. DESCRIBE WHAT YOU OBSERVE.

B. MAKE A LIST OF ALL THE SUBSTANCES YOU BELIEVE ARE INVOLVED IN THIS CHANGE AND TELL THE ROLE OF EACH.
(SUBSTANCES) (ROLE)

C. DOES THE MATCH AT THE END OF THIS DEMONSTRATION WEIGH MORE/LESS/SAME AS THE ORIGINAL MATCH? .... EXPLAIN YOUR ANSWER.

PLEASE TURN THE PAGE AND CONTINUE

D. THE MATCH AT THE END OF THE DEMONSTRATION WEIGHS LESS THAN THE ORIGINAL MATCH. WHY DO YOU THINK THIS IS SO?

E. IN YOUR OPINION DOES A CHEMICAL CHANGE TAKE PLACE? .... EXPLAIN YOUR ANSWER.

6. MANY OF THE STUDENTS USED THE TERM "CHEMICALS" IN THEIR DESCRIPTIONS OF THESE CHANGES. IN YOUR MIND, WHAT ARE "CHEMICALS?"

Portion of Written Instrument Dealing with Student Evaluations of Their Own Responses

1. Think back to the answers you just wrote down. How do you think your answers would compare to those that a scientifically trained adult might give? Circle the answer that best represents your feelings on this question.

    A. I can see many scientifically trained adults giving an answer just like mine. (The adult would say that I gave a correct answer.)

    B. My answer would share many of the same concepts as that of the adult even though my answers might be worded differently. (The adult would say that my answer was almost right.)

    C. My answer would be much different than that given by a scientifically trained adult.

Explain your selection below.

2. Now forget how your answers might compare with those of a scientifically trained adult and answer the following question as honestly as you can. In spite of what anyone else might say, how do you really feel about your answers?

    A. Right or wrong, my answers make sense to me.

    B. My answers don't make sense to me...I feel as if something important is missing.

    C. Even though I feel my answers are correct, I still am not satisfied with them because I'm not sure "why" they are correct.

Explain your selection below.

The Explanatory Preference Instrument

READ THESE TWO DESCRIPTIONS. WOULD EITHER OF THESE, ALONE OR TOGETHER, MAKE YOUR ANSWER MORE ACCEPTABLE TO THE SCIENTIFICALLY TRAINED ADULT? WHAT ARE YOUR IDEAS?

RUST ON AN IRON NAIL.

1.

2. Rusting is a breakdown of the iron. The rust eats the nail like acid eats u p metal or like a fungus eats the host. Thus, if you remove the rust, the remaining nail will weigh less than the original clean nail.

YOUR IDEAS:

HEATING COPPER METAL WITH THE BUNSEN BURNER.

1.

2. Heating the copper with the bunsen burner burns the outer coating of the cop per which turns black. The copper weighs less after the coating is removed because some of the copper has been burned away.

YOUR IDEAS:

BURNING OF A WOOD SPLINT

1.

2. When the match burns, it shrivels up.....kind of like growing old...it is worn out and no longer has the chemical and physical properties it used to have be cause they were burned up by the flame.

YOUR IDEAS:

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