A Study of How Precursor Key Concepts for Organic Chemistry Success Are Understood by General Chemistry Students

Patrick Gerard Meyer
Western Michigan University

Follow this and additional works at: https://scholarworks.wmich.edu/dissertations
Part of the Chemistry Commons, and the Science and Mathematics Education Commons

Recommended Citation
https://scholarworks.wmich.edu/dissertations/968

This Dissertation-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Dissertations by an authorized administrator of ScholarWorks at WMU. For more information, please contact maira.bundza@wmich.edu.
A STUDY OF HOW PRECURSOR KEY CONCEPTS FOR ORGANIC CHEMISTRY SUCCESS ARE UNDERSTOOD BY GENERAL CHEMISTRY STUDENTS

by

Patrick Gerard Meyer

A Dissertation
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy
Mallinson Institute for Science Education

Western Michigan University
Kalamazoo, Michigan
December 2005
This study examines college student understanding of key concepts that will support future organic chemistry success as determined by university instructors. During four one-hour individual interviews the sixteen subjects attempted to solve general chemistry problems. A think-aloud protocol was used along with a whiteboard where the students could draw and illustrate their ideas. The protocols for the interviews were adapted from the Covalent Structure and Bonding two-tiered multiple choice diagnostic instrument (Peterson, Treagust, & Garnett, 1989) and augmented by the Geometry and Polarity of Molecules single-tiered multiple choice instrument (Furió & Calatayud, 1996). The interviews were videotaped, transcribed, and coded for analysis to determine the subjects’ understanding of the key ideas. The subjects displayed many misconceptions that were summarized into nine assertions about student conceptualization of chemistry.

1. Many students misunderstand the location and nature of intermolecular forces.

2. Some think electronegativity differences among atoms in a molecule are sufficient to make the molecule polar, regardless of spatial arrangement.
3. Most know that higher phase change temperatures imply stronger intermolecular attractions, but many do not understand the difference between covalent molecular and covalent network substances.

4. Many have difficulty deciding whether a molecule is polar or non-polar, often confusing bilateral symmetry with spatial symmetry in all three dimensions.

5. Many cannot reliably draw correct Lewis structures due to carelessness and overuse of flawed algorithms.

6. Many are confused by how electrons can both repel one other and facilitate bonding between atoms via orbitals – this seems oxymoronic to them.

7. Many cannot explain why the atoms of certain elements do not follow the octet rule and some believe the octet rule alone can determine the shape of a molecule.

8. Most do know that electronegativity and polarity are not adequate to determine the shape of a molecule – but some apply the VSEPR theory in incorrect ways.

9. Students do not reason significantly differently when working with various representations of molecules such as ball-and-stick models, molecular formulas, and Lewis structures.

The study illuminated specific parts of the general chemistry curriculum that are particularly troublesome for students but necessary for their further achievement in chemistry. This information is important; it gives the discipline of chemistry education target areas to focus on for general chemistry pedagogical improvement efforts.
ACKNOWLEDGEMENTS

First, I would like to thank my parents, James and Barbara Meyer. They not only made it clear that supporting my education both inside and outside the classroom a very high priority, but more importantly that their love was independent of my achievements. I would also like to thank Frank Meyer for looking out for his kid brother in many ways.

Second, I would like to thank the members of my dissertation committee: William Cobern, Marcia Fetters, Heather Petcovic, and Elke Schoffers. You all have spent significant amounts of time with me and my papers to improve my academic thinking and writing – and I am the better for it. Debra Stoyanoff and William Merrow also have my gratitude for administrative support and technical support, respectively.

Third, I would like to mention Brian Nolan and Kimberly Jack. They thoughtfully listened and/or gave solid advice on a continual basis during the past years of planning, collecting data, and writing. Thank you both for your loyalty and sincerity.

Finally, I would like to thank my wonderful wife Cindy. She is my best friend. Her patience, helpfulness, and confidence in me have been invaluable throughout my studies. Mere words can neither explain nor quantify how grateful I am for her unfailing support in the years I have spent on my graduate work. Marrying her was the smartest thing I have ever done, and ever will do. I dedicate this work to her.

Patrick Gerard Meyer
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .......................................................................................................................... ii
LIST OF TABLES ........................................................................................................................................ vi
LIST OF FIGURES ..................................................................................................................................... vii

CHAPTER

I. INTRODUCTION ............................................................................................................................ 1
    Rationale for the Study ................................................................................................................ 2
    Societal Relevance of Chemistry .............................................................................................. 5
    Determining the Key Concepts to be Studied ........................................................................... 9

II. THE PROBLEM ............................................................................................................................. 12
    Statement of the Problem ........................................................................................................... 12
    Literature Review ....................................................................................................................... 14
        Key Concept One: Molecular Shape, Structure, & Polarity ................................. 16
        Key Concept Two: Bonding & Intermolecular Forces ................................................... 18
        Key Concept Three: Thermodynamics & Kinetics of Bonding ............................... 19
        Key Concept Four: Lewis Structures & Resonance ....................................................... 19
        Key Concept Five: Acid/Base Behavior ........................................................................... 23
        Key Concept Six: Electronegativity & Periodic Trends ................................................. 24
    Cognitive Science ....................................................................................................................... 26
    Definition of Terms ................................................................................................................... 27
    Limitations ................................................................................................................................. 29
CHAPTER

III. METHODOLOGY ........................................................................................................ 31
    General Method ....................................................................................................... 31
    Research Population ............................................................................................ 32
    Instrumentation ..................................................................................................... 33
    Protocol for Interviews ..................................................................................... 37
    Sample Population Description ........................................................................ 42
    Notation ................................................................................................................ 45
    Reliability of Interviews ..................................................................................... 46
    Researcher Bias .................................................................................................... 50

IV. DATA ANALYSIS .................................................................................................... 53
    Introduction ............................................................................................................ 53
    Definitions ............................................................................................................ 53
    Thematic Analysis ................................................................................................ 54
        Assertion 1 ........................................................................................................ 57
        Assertion 2 ........................................................................................................ 61
        Assertion 3 ........................................................................................................ 67
        Assertion 4 ........................................................................................................ 71
        Assertion 5 ........................................................................................................ 78
        Assertion 6 ........................................................................................................ 82
        Assertion 7 ........................................................................................................ 85

iv
<table>
<thead>
<tr>
<th>Table of Contents -- Continued</th>
</tr>
</thead>
</table>

**CHAPTER**

Assertion 8 ............................................................... 88
Assertion 9 ............................................................... 93
Field Observations ......................................................... 95
Textbook Proofing .......................................................... 98
Generalized Commentary .................................................. 99

V. CONCLUSION AND IMPLICATIONS ................................. 103

Subjects’ Patterns of Thinking ........................................... 103
How Students Go Astray in Learning Chemistry .................. 107
Comments on the Current State of Chemical Education ........ 113
Implications for Lecturers and Textbook Authors ................ 115
Strengths and Limitations ................................................ 118
Further Research .......................................................... 120

APPENDICES ................................................................ 122

A. Protocol Clearance From the Human Subjects Institutional Review Board .................................................. 122
B. Interview Diagnostics .................................................. 131
C. Interview Multiple-Choice Responses Tables .................. 143

BIBLIOGRAPHY .......................................................... 148
LIST OF TABLES

1. Frequencies of key concepts from instructor survey ....................................... 11
2. First semester subjects ..................................................................................... 43
3. Second semester subjects ............................................................................... 44
4. Gender, class year, and major counts of the subjects .................................... 44
5. Grouping of assertions under key concepts ..................................................... 57
6. Subject responses counts for assertion 1.......................................................... 58
7. Subject responses counts for assertion 2.......................................................... 61
8. Subject responses counts for assertion 3.......................................................... 68
9. Subject responses counts for assertion 4.......................................................... 71
10. Subject responses counts for assertion 5.......................................................... 78
11. Subject responses counts for assertion 6.......................................................... 82
12. Subject responses counts for assertion 7.......................................................... 85
13. Subject responses counts for assertion 8.......................................................... 89
14. Subject responses counts for assertion 9.......................................................... 94
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Incorrect pointing out of intermolecular forces for water</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>Structures for SiF₄, BF₃, and OF₂</td>
<td>63</td>
</tr>
<tr>
<td>3</td>
<td>Diatomic elements hydrogen and fluorine</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>Silicon carbide lattice</td>
<td>69</td>
</tr>
<tr>
<td>5</td>
<td>Hydrogen bonding of water molecules</td>
<td>69</td>
</tr>
<tr>
<td>6</td>
<td>Bilateral symmetry of H₂O and H₂S</td>
<td>73</td>
</tr>
<tr>
<td>7</td>
<td>Incorrect and correct spatial understanding of the polarity of SiF₄</td>
<td>76</td>
</tr>
<tr>
<td>8</td>
<td>Correct understanding of non-polar nature of BF₃</td>
<td>78</td>
</tr>
<tr>
<td>9</td>
<td>Lewis structure which notes original owner of electrons</td>
<td>80</td>
</tr>
<tr>
<td>10</td>
<td>Resonance of phenoxide ion</td>
<td>80</td>
</tr>
<tr>
<td>11</td>
<td>Two-dimensional and three-dimensional CH₄ structures</td>
<td>81</td>
</tr>
<tr>
<td>12</td>
<td>A typical salt of an amine and an arenediazonium salt</td>
<td>105</td>
</tr>
<tr>
<td>13</td>
<td>Lithium diisopropylamide</td>
<td>105</td>
</tr>
</tbody>
</table>
CHAPTER I
INTRODUCTION

Over the years organic chemistry has gained a fearsome reputation among college students as an academic hazing ritual, a rite of passage, and a “weed-out” course. In other words, it is seen as a “make-it-or-break-it” moment in the undergraduate curriculum of the prospective pre-med, health sciences, chemical engineering, science education, or chemistry major (Katz, 1996). This is not without good reason – failure rates (grade of D or below) exceed 30%, and continue to increase (Huddle, 2000). It is not unusual for students to repeat the course, or even take it several times in order to successfully earn credit.

Is the phenomenon of a relatively large proportion of students failing or repeating the course unavoidable, assuming standards are kept constant? Is a waste of time, talent, and tuition that could have been avoided (assuming that the student has some aptitude in the field and faithfully gives the course the necessary hours per week it deserves) had the student been better prepared before entering the course? When studying student performance in organic chemistry, we ought to consider the well known dictum from education psychology that the most important factor in determining how well a student will learn something is what he or she already knows (Ausubel, 1968). But we also need to realize that students tend to compartmentalize the things they learn. They tend to have “difficulty separating a concept or a process from the context in which it was initially presented” (McDermott, 1991, p. 306). In other words, they may have trouble applying a
concept they have learned in general chemistry to organic chemistry situations. Perhaps a richer understanding of a few key concepts will improve the chances of transference.

Since organic chemistry is typically not taken until the sophomore year in a science undergraduate sequence, college instructors cannot simply blame inadequate secondary science education for the quality of the student prior understanding when they enter the organic course sequence. Rather, we ought to reflect on the fact that the first-year general chemistry sequence gives an opportunity of two full semesters to prepare a solid foundation for student success in the following year. Perhaps this opportunity has not been well-structured so as to affect future organic chemistry success. If that is the case, then it ought not to be tolerated and efforts to change the existing situation are required.

Rationale for the Study

This study will build upon the research literature already present in chemical education. It will serve to enrich the ongoing discussion concerning what key concepts contribute to authentic learning of organic chemistry and how students understand these key concepts. The study will provide a descriptive study for the chemical education literature that curriculum designers and professors can reference in the future to not only boost student performance, but more importantly to deal with the two related issues of retention and attrition in the field of chemistry.

Retention has been a major concern in all of the “hard sciences” for decades, and chemistry is no exception. There is simply an enormous loss of people from those
professing an interest in a science or engineering career while still completing their secondary level education, to those finishing an undergraduate degree in such a major, to those entering graduate programs and finally earning a Ph.D. in science or engineering. This problem was a major concern as far back as 1970 even at a school with as powerful a recruiting advantage as Caltech. According to David Goodstein, who in the early 1990s served as provost at Caltech, the only reason the shortage of graduate students to satisfy the needs of research universities did not become critical was that students from other countries flocked to the United States for graduate work in the sciences (Tobias, 1990). Indeed, statistics show that the number of bachelor’s degrees in physics, chemistry, and geosciences awarded to U.S. citizens and permanent residents studying at U.S. institutions peaked at 22,000 per year in the early 1980s, falling to 17,000 per year by 1990 and never rising above 19,000 into the new millennium. Curiously enough, biology has not suffered this same decline – the same data collected for biology shows 36,000 graduates in 1989 and 62,000 in the year 2000 (NSF, 2003). This is evidence that we cannot simply blame the decline on the simple demographics of how many Americans and permanent residents were of traditional college age in those years. Excluding biology, the U.S. has slipped from third to thirteenth place internationally in terms of undergraduate completion of STEM (science, technology, engineering and mathematics) degrees since 1975 (NSF, 2003). The citizen and permanent resistant population of graduate students in science and engineering has done no better. From 1994 to 2001, there was a decline of 10% in the number of citizens and permanent residents doing graduate work in these fields, with a concomitant increase of 35% of international enrollment in the same (NSF, 2004).
There are serious concerns about what this phenomenon might do to the U.S. economy in the long run without a continued influx of skilled foreign labor. From 1990 through 2000, the production of Bachelor, Master, and doctoral level degrees in science and engineering rose by only an average of 2% annually, while job growth in these fields averaged 5% annually. (Crosby, 2004). Only the use of H-1B skilled worker visas has kept us from a real crisis. From 1990 through 2000, no less than 900,000 skilled foreign professionals entered the country via H-1B visas (OECD, 2002). And although the annual quota of H-1B’s was reduced from 195,000 to 65,000 in 2003 the wake of the recent recession of the early 2000s, demand from industry for skilled labor was so strong that the entire yearly quota in 2004 was filled on the first day of availability (October 1). This led Congress on November 22 to attach an amendment to HR 4818 (an omnibus spending bill) to exempt 20,000 additional skilled foreign workers from the quota for 2004. (CA, 2004).

In recent decades attrition has also been an issue of concern for students who are enrolled in science undergraduate courses. In the 1980s, less than half of those students intending to major in science and engineering fields completed that degree within five years. Of the college freshmen who switched out of science and engineering, 31% say the reason was that they found the course work too difficult, and a full 43% left because they found other fields more interesting (NSF, 1990). In the early 1990s, a study showed that 40% decline in the number of undergraduate science majors between the first and senior year of college (Didon, 1993, p. 336). More recent studies have shown that the situation has not improved. Fully 50% of students who enter college in SME (Science, Math, or Engineering) majors will change their major within two years (Change, 2002,
The author suspects that it is possible to reduce undergraduate attrition from chemistry through better pedagogy without compromising academic standards.

Societal Relevance of Chemistry

Chemical literacy is necessary in our society because many of the challenges that our 21st century civilization currently faces are chemical in nature. If our citizenry does not have it, they will be unable to carry out recommended or legislated “green” practices in the home, the farm, recreation areas, and the workplace. Protecting the environment from the ravages of acid rain, stopping the depletion of the ozone layer, and finding solutions to our fossil fuel dependency are all primarily chemistry-informed issues. Chemical literacy, therefore, is necessary for educated individuals to be able to appreciate and support endeavors to improve our quality of life and our planet’s environmental health. All high school and college graduates, regardless of track or major, ought to have studied at least some chemistry. It is the author’s opinion that a full year in high school, and if college-bound at least one semester in college combined with a semester of environmental science, would be sufficient for most people to achieve chemical literacy. If they have studied some chemistry, they will have a much better chance of understanding, interpreting, and critically evaluating stories of a scientific content they see in the written and visual media and have a greater chance of making informed voting decisions on issues with a scientific component. Such individuals will be able to evaluate daily choices and their import on our health, well-being, and environment.
There are many utilitarian reasons why devoting resources to the development of our chemistry talent is an excellent idea. As the 20th century progressed, chemistry in general, and organic chemistry in particular, became more entwined in our daily lives. The production of plastics, polymers, dyes, and synthetic rubber on which our modern society depends is a direct consequence of our better understanding of molecules acquired through organic chemistry. Our substantial accomplishments in the field of pharmacology, which have saved many lives and improved the health of countless others, can also be traced to the field of organic chemistry. Improving human and animal health through the use of pharmaceuticals, although often thought of as biological or medical issue, is really just as reliant on organic chemistry as it is on the life sciences.

Stepping back and generalizing a bit, studying chemistry can change the way a person faces all sorts of challenges in his or her life. Project 2061, Science for all Americans, perhaps said it best: “Scientific habits of mind can help people in every walk of life to deal sensibly with problems that often involve evidence, quantitative considerations, logical arguments, and uncertainty …” (AAAS, 1989, p.13). Our government’s own statements have also clearly identified a further reason: “twenty-first century economies will be based on how well nations use knowledge as a resource” (NSF, 1996, p. 1).

However, there are less obvious and more general reasons why chemistry education, and organic chemistry education in particular, is useful. Although traditionally (and sadly) chemistry has often been seen as a discipline of memorization of many abstract facts and algorithms, in fact it is a field of study that can give the student valuable experience in creative problem solving. This is quite different from simply
applying algorithms. Nor is it like solving kinematics/dynamics problems in physics, where the challenge is to define the system, identify which forces, masses, etc. are important, and find which mathematical relationships will produce a solution. Rather, solving organic chemistry problems requires a combination of logic, trial and error, and creativity or intuition. Possible answers must be evaluated for reasonableness, hidden assumptions must be discovered and evaluated, and a surprising amount of persistence may be required. The given information, or facts already known and the start of the problem needs to be carefully evaluated – with extraneous information put aside and pertinent facts identified. Some problems may need to be solved in a backwards (organic chemists would say retrosynthetic) fashion. Multiple pathways often lead to the same goal. In contrast to the mathematical perspective common in the physical sciences, often more than one explanation will fit the data, i.e. the problem either has more than one possible correct answer, or more information needs to be gathered. In other words, the organic chemistry student needs to learn to be both flexible and rigorous in the solving of difficult problems. These problem solving skills are often practiced in organic chemistry may be transferable to other fields, like medicine.

This process for solving organic chemistry problems bears a similarity to the procedures used in modern medicine by doctors trying to diagnose and treat the health conditions of their patients. In other words, there is an analogy between the work of the organic chemist and the work of the doctor of medicine. Here we see one of the reasons why medical schools in the United States, without exception, require basic proficiency in organic chemistry in the background of their applicants, and why these medical schools are so interested in organic chemistry performance. Certainly, many science courses are
helpful to the pre-med major – a correlation between overall science undergraduate GPA and performance in the preclinical phase of medical school is well known (Hall & Stocks, 1995). However, because of the nature of problem-solving in organic chemistry, it serves an important purpose in the preparation of a pre-med major. In a recent study of students who transferred out of pre-med programs, of those who mentioned low grades as a deciding factor, 78% named organic chemistry as the course that had affected their plans (Lovecchio & Dundes, 2002).

Additionally, organic chemistry requires the ability to organize a vast body of data into a logical pattern that can be brought into play almost immediately when the situation requires. The student does not have hours to consider and ponder in the middle of an exam, neither does the medical doctor have the luxury to consider and ponder a patient’s condition for hours during an emergency situation, or during a hectic, crowded time at a clinic. The vast amounts of knowledge needed by both the organic chemistry student and the medical doctor to complete their tasks must be accessible quickly – and this can be accomplished if mental structures have been built up in the person’s mind through careful practice. The careful practice needed to master organic chemistry is evidence of a solid work ethic, which is another important reason that medical schools are interested in organic chemistry performance. We also ought to consider that in medical school students will be expected to learn large amounts of material in relatively short times, in other words the rate of content gain expected of them is very high. If they fall behind it will be extremely difficult to catch up. Organic chemistry is a good undergraduate approximation to this experience, perhaps better than any other course offered in the pre-med curriculum. Put succinctly, success with proven success in
organic chemistry are more likely to earn highly competitive placement in preclinical programs.

Determining the Key Concepts to be Studied

It is necessary before performing this study to be able to answer the following question: what is an optimum foundation for future organic chemistry success? The author addressed this question by generating a small list of concepts that chemistry instructors feel ought to make up an adequate foundation for organic chemistry. If this small list of concepts forms both the framework and pedagogy for the first-year general chemistry curriculum, and influences decisions regarding the pedagogy, students may move away from the rote strategies of a novice. They may move toward the learning strategies of the expert, who is an independent learner who no longer needs a teacher “to hold his or her hand” when novel items are encountered. Of course, concentrating on a few key concepts does not necessarily result in the kind of deep conceptual understanding that would be so helpful later on. Students may try to understand the small number of key concepts in a rote and shallow fashion and fail to build skills in recognizing where a key concept might be applied to solve a problem. This would thwart the strategy of using the key concepts in the first place. In other words, the study’s prerequisite was to determine the consensus of local expert opinion as to which key concepts first-year general chemistry sequence needs to emphasize so as to provide the best foundation possible for future student success in organic chemistry. Because there is such a wide range of possible topics in the first year chemistry sequence, this is not a perfunctory
task. To determine the composition of such a foundation, one must differentiate what ideas are absolutely essential to future success and which are merely supplementary. A survey was chosen as the appropriate method to elicit and record the beliefs of experts, and the emphasis in designing the survey was discovering what concepts the instructors feel are most important for future success in organic chemistry. In other words, the task was to find out through surveys and interviews what concepts experts from a wide variety of colleges and universities think are key for future understanding and high performance in organic chemistry.

Key Chemistry Concepts from Pilot Study -- In a pilot study (WMU HSIRB Project Number 04-05-20, approved May 28, 2004) the author surveyed professionals who teach organic chemistry in Southern Michigan. Out of 19 attempts, 10 individuals were successfully surveyed. During a tabulation of the responses on these 10 surveys, a clear consensus about what key concepts ought to be learned before a student studies organic chemistry did emerge.
Table 1. Frequencies of key concepts from instructor survey

<table>
<thead>
<tr>
<th>Key Concepts</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Shape, Structure, &amp; Polarity</td>
<td>10</td>
</tr>
<tr>
<td>Bonding &amp; Intermolecular Forces</td>
<td>9</td>
</tr>
<tr>
<td>Thermodynamics &amp; Kinetics</td>
<td>8</td>
</tr>
<tr>
<td>Lewis Structures &amp; Resonance</td>
<td>7</td>
</tr>
<tr>
<td>Acid/Base Chemistry</td>
<td>7</td>
</tr>
<tr>
<td>Electronegativity and Periodic Trends</td>
<td>6</td>
</tr>
<tr>
<td>The Mole &amp; Stoichiometry</td>
<td>2</td>
</tr>
<tr>
<td>Solution Theory</td>
<td>2</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>1</td>
</tr>
<tr>
<td>Reduction &amp; Oxidation</td>
<td>1</td>
</tr>
</tbody>
</table>

The tabulation shows that there was a clear preference for a certain six key concepts, in order of popularity they are as follows:

1. Molecular Shape, Structure, & Polarity  
2. Bonding & Intermolecular Forces  
3. Thermodynamics, & Kinetics  
4. Lewis Structures & Resonance  
5. Acid/Base Behavior  
6. Electronegativity & Periodic Trends

For reasons that will be explained at the beginning of the methodology chapter of this dissertation, the research presented here focused on key concepts 1, 2, 4, and 6.
CHAPTER II

THE PROBLEM

Statement of the Problem

The issue investigated in this work is straightforward: how do general chemistry students understand the precursor key concepts that will serve to boost their performance later on in organic chemistry? In other words, this dissertation has one main goal. It is to investigate and characterize the subject’s current beliefs and proficiencies regarding the key concepts.

In order to investigate this question, it is necessary to find out what concepts commonly taught in general chemistry are most helpful in supporting later achievement in organic chemistry when learned in an authentic and deep manner. This was done through the use of an open-ended survey administered to a sample of organic chemistry instructors (see chapter one).

The approach taken in this dissertation can be characterized as primarily descriptive. The goal is to establish how students are interpreting the general chemistry instruction and materials to which they are exposed. This study will gather data to determine how well students are gaining the optimum foundation for later success in organic chemistry.
The author takes as a given that the rote learning common in chemistry is problematic, therefore this work will not gather evidence to support the claim that rote learning is a poor substitute for authentic conceptual development. This dissertation does not attempt to set up a controlled experiment to test the effectiveness of different methods of teaching, nor does it attempt to alter in any way the learning environment of the subjects under observation.

In the absence of an adequate conceptual foundation in preparation for organic chemistry, some students act as if they believe that organic chemistry is just one large mnemonic exercise, albeit one that can be of Herculean proportions, depending on the standards of the instructor. Unfortunately, research has shown that this common belief on the part of students is not a helpful one. Although the flashcard strategy will sometimes work for a while at the beginning of a student’s first organic chemistry course, the belief in this strategy’s appropriateness seems to stymie student performance in the long run (Bradley, Ulrich, Jones, & Jones, 2002). The weaknesses of rote learning have been clearly demonstrated in the literature (Bodner 1986), (Pendely, Bretz, & Novak, 1994), (Pungente & Badger, 2003).

As in any field, it is true that some rote learning is necessary for student success in organic chemistry – the author does not mean to suggest that there is no place for it in the discipline. Molecular nomenclature, for example, is a part of the curriculum that cannot be intuitively derived. In order to communicate accurately with others, every organic chemist must be using the same set of nomenclature rules. Students need through long practice, to master the complex yet logical nomenclature system used for organic molecules, which has its own rules of syntax and grammar just like any language does.
There is simply no room for individual construction of knowledge in nomenclature, because the rules are arbitrary, having been decided upon and amended periodically by meetings of the International Union of Pure and Applied Chemists (IUPAC). Certain periodic trends, like how many electrons a given element has in its outer shell, or the relative electronegativity of the elements is also a place where some rote learning is really necessary. Other things start out as being rote as well, such as the first rules for writing Lewis structures. What is important to realize though, is that claiming to understand organic chemistry just because one has learned the rules for nomenclature, periodic trends, etc. is like saying people can write elegant, logically constructed essay arguments just because they know the alphabet and some grammar rules! Certainly one must have mastered the alphabet and fundamental grammar rules in order to write well, but these are just stepping stones toward the ultimate goal, rather that the ultimate goal itself.

**Literature Review**

Success in organic chemistry requires a familiarity with a wide body of knowledge regarding the behavior of molecules in reactions. Indeed, often organic textbooks have review sections at the end of their chapters which contain lists of common reactions. This may mislead some students into thinking that if they just memorize the back pages of each chapter, then they have gained a working understanding of the material sufficient to earn passing grades on any exam the future might bring. The reality is sadly quite different. For example, a typical synthesis problem, in which students are allowed certain starting materials and all necessary reagents, cannot be completed just by
knowing the products of many reactions. The reasons are many: some reactions transform functional groups on the molecule that one would like to retain for a later step, some reaction intermediates will undergo structural rearrangements (e.g. inversion of chiral centers, and carbocations with their hydride or methyl shifts), and perhaps most importantly, there are many complicated ways that carbon skeletons composed of straight chains, branches, and rings can come together or break apart, depending on reaction conditions and what functional groups are already present. This means that synthesis problems require a familiarity with thinking about molecules in a way that considers their shape, their polarity, their solubility, and other characteristics. Synthesis problems also require an understanding of reaction mechanisms, which cannot all be memorized because there are so many different cases of them. Of course, nearly all of them follow from core concepts of how electrons are likely to move from one atom or bond to another atom or bond.

Perhaps the biggest strategic error students commit when they are involved in an organic chemistry sequence is sensing the difficulty of the task before them and trying to memorize results and algorithms. Students wrongly believe that doing so gives them a sufficient grasp of the field (Nakhleh, Lowry, & Mitchell, 1996). What they fail to see is that this technique only works when both the information to be mastered lies within the memory capacity of the student, and the material does not require deep conceptual frameworks. Unfortunately, perhaps due to a lack of challenging curriculum beforehand, many college students enter organic chemistry having never had the supremacy of the memorization tactic challenged. So, they rely on it and are shocked to find out that it is typically not very effective, especially in the second part of an organic sequence, as the
reactions and mechanisms continue to pile on, typically overwhelming the student’s capacity to retain in a fashion analogous to computer crash due to the overload of its Random Access Memory. Of course, the computer can only hold information in a disjointed, discrete series of zeros and ones – when a certain number of megabytes is reached, that is it. A human has no such strict, numerically defined upper limit.

Key Concept One: Molecular Shape, Structure, & Polarity

Since the essence of chemistry is the characteristics of atoms, ions, molecules, and how they combine or rearrange, the first two key concepts really are the foundation for all other learning. Chemistry students must know how molecules are put together from atoms, how the atoms are spatially arranged to form molecules, and how charge is distributed across molecules. They must also know how two atoms can come together to form a bond.

The fact that students often misunderstand the location of electrons means that they do not have a good understanding of molecular polarity, i.e. how charge is distributed throughout a molecule. Birk and Kurtz found that 16% of students studied after one semester of college chemistry and 14% of students studied after two semesters of chemistry may be aware that a polar bond forms between two atoms of significantly different electronegativites but think that if polar bonds exist in the molecule, then the molecule must be polar (Birk & Kurtz, 1999, p 127). The fact is that molecular shape in three dimensions must be considered. For example, molecules of carbon tetrachloride CCl₄ exist in a tetrahedron shape, with the chlorine atoms arranged at the corners of a tetrahedron which is centered on the carbon atom. Although it is true that each carbon-
chlorine bond is polar, it does not follow that the molecule itself is polar. The reason is
that all four polar bonds are “pulling against each other” at 109.5° angles, resulting in a
net sum of zero when the vectors are added.

Peterson, Treagust, and Garnett found that 46% of the 11th graders and 25% of the
12th graders they studied believed that the bonds an atom has with other atoms is the only
determiner of molecular shape. In other words, many students believe the presence of
non-bonding “lone-pair” electrons is irrelevant in determining molecular shape (Peterson,
Treagust, & Garnett, 1989, p 311). In fact, molecular shape is heavily influenced by the
presence of unbonded electron orbitals, and this occurs even in the most common cases –
the compound water $\text{H}_2\text{O}$ is a bent molecule, but if the lone-pair electrons on the oxygen
were irrelevant, then the water molecule would be linear just as $\text{CO}_2$ is, with a central
atom having two atoms arranged at 180° to it. However, the influence of electron pairs
can be misunderstood even when it is not ignored. Furió and Calatayud found that 22%
of first year university students studied confused electron-pair arrangement with the
molecular shape (Furió & Calatayud, 1996, p. 38). For example, some students have a
great deal of difficulty understanding why ammonia, $\text{NH}_3$, and methane, $\text{CH}_4$ have
different molecular shapes. Both have four electron pairs arranged around the central
atom, which can mislead students into thinking that both are tetrahedral, when in fact the
former is pyramidal. Although it is true that the lone pair in the $\text{NH}_3$ molecule takes up
more space than the bonded electron pairs do, resulting in a slight angular distortion from
a tetrahedron, this is not the primary reason why the molecular geometries are different.
Rather, the students may be overlooking the fact that electron domain geometry and
molecular geometry are different.
Key Concept Two: Bonding & Intermolecular Forces

The first two key concepts are ultimately referring to an understanding of what makes certain atoms form bonds with other atoms to form more complicated structures. What a bond really is, ultimately, is some combination of either an electron transfer followed by electrostatic attraction (an ionic bond) or some sort of sharing of electrons in an orbital held in common between two or more atoms (a covalent bond). Students may think of a bond as strictly one or the other, but even between two bonded atoms as different in electronegativity as fluorine and cesium, there will be some covalent character.

Many students also hold the misconception that the ionic bond can only form between the atoms that actually transferred electrons, but in fact a positive ion could form bonds with many different negative ions, and vice versa (Robinson, 1998). Peterson and Treagust found that 57% of 11th grade students and 39% of 12th grade students they studied have a problem predicting the location of the electrons in a bond between two atoms even after appropriate classroom exposure (Peterson, Treagust & Garnett, 1989, p. 309). Although electrons are only equally shared in bonds between atoms of the same element (e.g. diatomic hydrogen gas, H₂ or nitrogen gas, N₂) these students assume that the electrons will tend to be located exactly between two heteroatoms. To the contrary, unless the two atoms involved with the bond are of the same element, the electrons will be unequally shared, and spatially more often located nearer the more electronegative atom. This misconception may be encouraged by the fact that textbooks often initially teach Lewis structures (where the emphasis is just on electron accounting and not true
probablistic positioning of the electrons) and often address electron density and
 electronegativities in a later chapter. Students do not make the connection that the Lewis
structure was only part of the story (Taagepera, Arasasingham, Potter, Soroudi, & Lam,
2002).

Key Concept Three: Thermodynamics & Kinetics of Bonding

Key concept three was third in popularity among the organic chemistry
instructors. It is a fact that although many different bonding configurations are possible
between atoms and molecules, usually there are clear preferences in chemical reactions
for what will form. More thermodynamically stable (lower energy) compounds are much
more likely to be the product of reactions than higher energy compounds, and the kinetics
(rates) of reactions with lower energy reaction intermediates are favored over reactions
which require higher energy reaction intermediates. The timescale of the reaction must
be considered as well – some reactions that may be thermodynamically favored may have
unfavorable kinetics and therefore will not occur in the time frames that humans are used
to working in, but can in the large time frames to which a discipline like geology is
accustomed.

Key Concept Four: Lewis Structures & Resonance

Key concept four refers to one of the classic ways that molecules are often
represented on a piece of paper. Lewis structures were developed by Gilbert Lewis in the
1920s and consist of the elemental symbols of the atoms of the molecule connected by
pairs of dots (electrons) or short lines (sticks) which represent a bond between two atoms.
Lone pair electrons are also shown adjacent the appropriate atoms as a pair of dots. The word “resonance” means that many molecules cannot be accurately represented by one Lewis structure. This is because a single Lewis structure can show only purely single, double, or triple bonds between atoms, and can only show a lone pair of electrons in the possession of a single atom. In reality, the orbitals in which electrons find themselves sometimes allow bonds to exist that are of intermediate character, i.e. a bond order of one-and-a-half is between a single and double bond in its properties. Also, a lone pair of electrons may be in partial possession of more than one atom simultaneously. In other words, it’s not always as simple as atoms completely owning certain electrons. This resonance issue has traditionally been dealt with by drawing two or more Lewis structures for these molecules, understanding that the true nature of the molecule is some combination of these representations, and not even necessarily the arithmetic average of the representations. This means that the true character of the molecule may resemble one of the Lewis structures (the major contributor) more than the other Lewis structures (the minor contributors).

Lewis structures are problematic for students because there are many different mistakes which can be made in their construction. Sometimes we can lay the blame on the student: sometimes students draw in less than the correct number of bonds, leading to unfilled octets of the atoms, and often the formal charge calculations for each atom are omitted, which leads to a situation where high formal charges have not been minimized through the use of double and triple bonds (Pardo, 1989).

However, other problems may not necessarily be a consequence of a lack of adequate practice on the part of the student. Lewis structures are not necessarily as
logically consistent as one might initially assume – there are many rules which seem “made to be broken” and this may be the major difficulty for students. Even choosing the central atom may be difficult, and contrary to rule found in the literature, it is not even necessarily the single atom in a formula – consider nitrous oxide and disulfur monoxide, whose respective atomic arrangements are NNO and SSO, so the lone atom is not the central atom in the molecule (Ahman & Zakaria, 2000). Textbooks may oversimplify the situation, telling students that “the atom with the lowest affinity for electrons in the molecule or ion is the central atom” then explaining in the margin in a small font that atoms of chlorine, bromine, and iodine will be central in species combining oxygen and one of these halogens (Kotz & Purcell, 1991, p. 371). Unfortunately, even the exception to the rule given is not the whole story: consider species such as fulminate ion and sulfur nitrifluoride, whose respective atomic arrangements are CNO⁻ and NSF. The central atoms in these cases are not the ones with the lowest affinity for electrons in the molecule (Ahman & Zakaria, 2000). The other major problem may be that the octet rule (that states when drawing Lewis structures, make sure that all elements except hydrogen have eight valence electrons) and the rule of minimizing formal charge on atoms are sometimes in conflict with one another. In order to keep the octet rule intact, some structures need to be drawn as if only s- and p-orbitals were involved in the bonding at the expense of increasing formal charge on some of the atoms, while using the d-orbitals (which would require the central atom in the Lewis structure to be given an expanded octet of 10 or 12 electrons) often minimizes formal charge. Which rule should trump the other? Unfortunately, there is no clear answer to this question. We can’t just check the actual configuration of compounds against their Lewis structures to see which rule is
more important, because in some cases, Lewis structures that accurately predict the true molecular structure (defined as the true position of the atoms) use d-orbitals that are not filled with electrons in the actual molecule, and other Lewis structures that avoid using those d-orbitals fail to accurately predict the structure. This odd observation is a consequence of the fact that the Lewis structures are classical models that have been supplanted in modern chemistry by quantum mechanical analysis (Purser, 1999). In other words, electrons are now known to not be treatable merely as static particles (as a Lewis structure implies) but rather electrons have quantum wavelike properties. A simple example of this is diatomic oxygen, O₂. The Lewis structure would suggest that the molecule is composed completely of paired electrons, when in fact oxygen can be shown by experiment to be paramagnetic (meaning its atoms have unpaired electrons.) Two of the electrons in the molecule are held in an anti-bonding orbital, leaving an odd electron present on each atom – a result impossible to get from Lewis structures (Kotz & Purcell, 1991). Textbooks typically deal with the limitations of Lewis structures by introducing valence bond theory and molecular orbital theory, but for much of organic chemistry, Lewis structures coupled with VSEPR (Valence Shell Electron Pair Repulsion) theory are sufficient (Hurst, 2002).

With all of the problems and limitations of Lewis structures, one might legitimately ask: why are they used at all, and to what advantage? They are a form of structural drawing “shorthand” that can quickly and easily illustrate the bonding of the atoms in a molecule. Lewis structures are also good for electron “bookkeeping” most of the time, namely keeping track of how many electrons are in the orbitals of bonding
atoms, and whether a bond between two atoms in a molecule is single, double, triple, or some fractional bond order.

In recent years a new method of showing the distribution of electrons between the atoms of molecules has begun to supplement Lewis structures, namely the electron density distribution map (Shusterman & Shusterman 1997). This new kind of structure is beginning to appear in textbooks, though it is still not quite as common as Lewis structures, and probably will never fully replace them, since it is very difficult to draw a good electron density distribution map by hand. They are typically drawn using computer software such as the SPARTAN program, a product of Wavefunction, Incorporated. Perhaps their greatest advantage is that they encourage the student to think about electron density in a more holistic way, rather than in the all-or-nothing fashion that an unsophisticated use of Lewis Structures seems to encourage.

Key Concept Five: Acid/Base Behavior

Key concept five refers to the way that so many chemical reactions can be seen as one chemical species behaving as an acid and another behaving as a base. By the terms acid and base we do not mean here the traditional Arhennius definition of an acid being a substance that provides H+ in solution and a base being a substance that provides OH- in solution. Rather, we are talking about a broader definition. A major step toward this wider definition was taken by Brønsted and Lowry, who argued that any molecule that provided a proton was an acid, and that any molecule which accepted a proton was a base. This definition was reworked by Lewis to bring us to the definition most used by chemists today: a Lewis acid is a substance which can accept an electron pair, and a
Lewis base is a substance that can donate an electron pair. Many if not most organic reactions fall into this broadest definition, making an understanding of acids and bases very valuable for predicting organic reactions. The concept refers to the way that the charge distributions on two or more chemical species such as molecules or ions influence how they interact with each other during a chemical reaction. Both the mechanisms and final products of many reactions can be predicted with a relatively high degree of accuracy if the acid/base characteristics of the reactants are known. Chemical reactions tend to occur in predictable patterns time after time. However identifying the acidic and basic characteristics of chemical species, particularly when they get large and complicated with many functional groups, is by no means a trivial task.

Key Concept Six: Electronegativity & Periodic Trends

The sixth key concept was given a large boost by Linus Pauling in the 1930s (Pauling, 1932). He realized it was possible to directly measure with laboratory experiments the relative tendency of each kind of atom to attract an extra electron to itself. This number, called the electronegativity of the element, has a consistent value during chemical reactions, and an element's position on the periodic table has a very strong correlation to how electronegative that element is. Fluorine at the upper right of the table has the highest electronegativity, (meaning it has the greatest tendency to attract another electron to itself) and francium at the lower left has the smallest electronegativity, (meaning it has the smallest capability to attract another electron to itself.) The atom of an element like carbon that lies closer toward the middle of the periodic table has an ability to attract another electron that lies between these two extremes. Electronegativity
governs the way electrons are shared, given up, or accepted in reactions, so understanding it can be very powerful for later success. Although Pauling’s determinations of these values remained “state of the art” for a significant length of time, many scales which seek to supplant his scale have been published over the years, some of which could be just considered refinements of his techniques (Mulliken, 1934) and some of which were developed by using entirely different laboratory measurements, such as ionization energies (Allred & Rochow, 1958; Allen, 1989).

It needs to be stressed here, however, that electronegativity as it is traditionally understood is imprecise. Although Pauling decided from experimental dipole measurements that a difference of 1.7 in electronegativity values between two atoms (based on his scale) was the boundary indicating 50% ionic character in the bond (with a greater electronegativity difference between the atoms meaning predominantly ionic bonding character and a lesser electronegativity difference between the atoms meaning predominantly covalent bonding character) later work has shown that this is too facile an approach – although it is still commonly taught in general chemistry textbooks in this fashion (McMurry & Fay, 1995; Atkins & Jones, 1997; Brown, LeMay, & Bursten, 2003; Reger, Goode, & Mercer, 1997). A more sophisticated model, one that corresponds better to the thousands of compounds whose bonds have been studied suggests that the average of the electronegativities on the atoms in question needs to be also considered (Sproul, 2001). Perhaps the most important thing, though, is that even with these professional differences of opinion among chemists, any of the scales developed are sufficient for students get an idea of the potential polarity of a bond, and determine the nature of compounds whose bonds are strongly ionic or strongly covalent. But the fact remains
that the best prediction of relative polarity is hard to determine with an elementary approach just using electronegativities.

Cognitive Science

Learning theories implicitly or explicitly form part of the theoretical foundation for education research, this project being no exception. The theory of constructivism forms the philosophical foundation for this dissertation. Like most words in the education researcher’s lexicon, the word constructivism can be used in different ways and with different nuances among various authors. Several tenets of the theory are worthy of mention in the way the word is used in this work. First, knowledge is actively constructed in the minds of learners (von Glaserfeld, 1993). This means that learners are not passive recipients of the instruction they receive. There is always interpretation going on, which can lead to widely divergent concepts from what the instructor intended being built in the student’s mind. Second, the knowledge a person currently possesses is not what has been given to them by someone else, but rather is what they have constructed and pieced together themselves (Fosnot, 1989). Third, new knowledge is obtained and retained by integrating novel experiences into already built mental structures (Furth, 1981).

The key point here is that learning is an active process and is the result of students weighing current experience against the mental constructions built by past experience. The word experience itself has been defined as a sensation of the world which is outside of one’s own consciousness (Staver, 1998). This means that knowledge cannot be built
up by pure reason alone, wholly apart from experience. In other words, the philosophical foundation of this dissertation is incommensurable with Cartesian epistemology.

Definitions of Terms

This project will use a definition of chemistry which is holds fairly uniformly among various authors. It has remained essentially constant for decades. Compare the following excerpts. “Chemistry is the science dealing with the composition of materials and the changes in composition which these materials undergo” (Dull, Metcalfe, & Williams, 1958, p.2). Likewise, “chemistry is the study of materials and the changes they undergo” (Zumdahl, 1989, p.1). Another example states that chemistry is the study of the “composition, structure, and properties of substances and the changes they undergo” (Tzinopoulous, Metcalfe, Williams, & Kastka, 1993, p.3).

Chemistry is one of the four categories into which most natural scientific endeavor can be classified. It has relationships to, but can be taken separately from, biology (the study of life and its processes), physics (the study of motion and energy) and the earth sciences (the study of our planet: such things as weather, land, oceans, rocks, soils, etc.) (Toon & Ellis, 1973). The field of chemistry has provided much support for the other branches of scientific endeavor through the years, indeed, there are subspecialties in academe such as biochemistry and geochemistry.

The definition of organic chemistry developed in the 1770s as a consequence of the writings of the Swedish chemist Tobern Bergman who differentiated between substances derived from non-living sources like rocks and minerals (inorganic materials)
from those substances derived from living or once living materials (organic materials.)
The philosophy (or paradigm) of vitalism, the belief that somehow the organic materials
behave fundamentally differently from inorganic materials held sway for many years.
However, the synthesis of ammonium cyanate by Friedrich Woehler in 1828 gave an
equivalent example where an organic material could be obtained from inorganic starting materials.
This was the first relatively “hard-to-explain-away” published evidence that organic
materials perhaps were not really a set of compounds completely independent of
inorganic compounds. Vitalism did keep the chemists of the 19th century debating with
one another. Twenty years of further work that supported Woehler’s findings prompted
William Brande to confidently assert that “no definite line can be drawn between organic
and inorganic chemistry” and that “any distinction … must for the present be merely
considered a matter of practical convenience” (McMurry, 2000, p.2). Since the latter half
of that century, which saw vitalism utterly fade away, we have been in a period of anti-
vitalism in chemistry which displays “normal science” characteristics (Kuhn, 1970).

The modern definition of organic chemistry also holds fairly uniformly across
various authors. It has been called “the chemistry of carbon compounds” (Wade, 1991,
p.4), “the study of carbon compounds (McMurry, 2000, p.2), and “the chemistry of the
compounds of carbon” (Eğe, 2000, p.1). The most important thing we must remember,
though, is that “the same principles that explain the simplest inorganic compounds also
explain the most complex organic ones” (McMurry, 2000, p.2). There is no reason why
we cannot use the patterns of behavior of atoms, ions, and molecules, most of them first
discerned in simpler inorganic systems to help us understand organic chemistry
phenomena.
The term key concept for this chemistry education project refers to an overarching principle or idea, that when comprehended, allows a person to make correct inferences and interpretations of chemical phenomena in the way that an expert can and a novice cannot. It is not a pithy, one sentence clichéd scientific law or commandment; rather it is an intellectual construct that brings together many chemical observations by many chemists over many years into a logically coherent pattern which has both explaining and predictive power (Kuhn, 1970; Posner, Strike, Hewson, & Gertzog, 1982).

The term alternative conception, as used in this work, refers to a scientifically incorrect mental construct that a person has built about a chemistry concept. This term is sometimes used in place of misconception (although the two terms can be used interchangeably) because it acknowledges that significant mental effort may have been used by the person to build this naïve conception in an effort to organize his or her experiences (Abimbola, 1988; Gilbert & Swift, 1985).

Finally, the term cognition in this work refers to “the mental activity associated with understanding, processing, and communicating knowledge” (Myers, 1992, p. 286). It is the process used by people to attempt to solve problems, to reason, and to make the best decisions they can at that point with the information in their possession.

Limitations

The pilot study for this work involved faculty at a wide range of institutions: Carnegie Doctoral I Universities and smaller universities, private liberal arts colleges, and community colleges. However, all of the professors surveyed were working in
Southern Michigan. This is not as limiting as it may appear, however, due to the fact that as a professional class, professors are known to search around the nation for positions, and it is not unusual for internationals to be serving in Michigan institutions. This “mixing” is fairly thorough on a national level. It tends to homogenize American institutions of higher learning and provides a measure of face validity to the idea that the short list of key concepts generated from this project is generalizable.

Another limitation of this project is the reliance upon volunteers from the chemistry lecture sections solicited. This opens up the work to the criticism of a pervasive self-selection effect. Unfortunately, this cannot be avoided. To assure maximum participation in all four interviews in the short time available between the pertinent instruction of the key concepts and the end of the semester, a quick and wide net of solicitation needed to be cast. There was little time for a staggered randomized “small batches” type solicitation scheme such as randomly soliciting 5 or 10 students at a time from the class roster for participation until enough able and willing subjects were obtained. Even if the time were available for this procedure, the self-selection effect would still be present, so this method was not used. In its place one mass solicitation per semester was used, and random selection from all those interested and who had a class/work schedule complementary to that of the interviewer was performed to invite the actual participants.
CHAPTER III

METHODOLOGY

General Method

The method for collecting and interpreting data for this work consisted of three parts -- the first two were done concurrently and the third was done months afterward.

- Conduct individual student problem-solving sessions using a “think-aloud” protocol and one-on-one clinical interviews to see how well students have built these key concepts.
- Attend the subjects’ lectures and study their textbook as a check against alternative conceptions being directly reinforced.
- Use a thematic coding strategy to group student responses into categories for analysis.

According to the syllabus of CHEM 110, the course to be observed and the source of research subjects for this dissertation, key concept 5 is not dealt with in the course (it is addressed in the next offering in the sequence) and key concept 3 is only dealt with at the very end of the semester, right before final examinations. Because of this timing, it was deemed expedient to focus on key concepts 1, 2, 4, and 6 for the individual sessions with research subjects during this study.

As part of the research method, the textbook and instructional environment were examined to determine whether or not these were a source of faulty student ideas. This
was accomplished both through naturalistic observation of the lectures (that are the part of the subject’s learning environment which is structured by the instructor) and a careful study of their chemistry text. Certainly these are only a portion of the student’s learning environment, since studying and working problems both individually and collaboratively with others in the class can and does take place at all hours, making it impossible to observe directly and only available via self-reporting techniques which can sometimes be rather distorted and inaccurate. Nevertheless, this procedure is a necessary check when analyzing student misconceptions.

The largest and most important part of the method is to characterize how well the subjects actually have built new connections and cognitive structures to support these key concepts. This was done via individual video-recorded problem-solving sessions with subjects where think-aloud protocols are used in an attempt to describe the subjects’ current conceptions of the key chemistry concepts. The efforts to accomplish this provided the bulk of the data to collect and interpret.

Research Population

The data collection for this study took place at Western Michigan University, a Carnegie Division I doctoral institution. As of fall 2003, the student body of approximately 29,000 was 80% undergraduate, 90% in-state residency, and 6% internationals. The student gender distribution was 53% female and 47 % male. The student body was 85.3% Caucasian, 5.2% African-American, 1.7 % Hispanic, 1.4 % Asian/Pacific Islander, and 0.4 % Native American (WMU on-line, 2004).
The subjects were self-selected. Volunteers were solicited from one Fall section and one Winter section of CHEM 110 (a traditional first-year general chemistry course) and information was collected regarding their time availability during the week. Random selection was performed on the list of subjects who both expressed interest and had a class/work schedule complementary to that of the interviewer. Formal invitations to participate in the clinical interviews were then sent, and the first ten per semester that accepted the invitation were interviewed (See Appendix A).

The majority of the potential participants in this study were Caucasian, Midwestern USA students, and approximately 18-24 years of age. There were members of many ethnicities (African-American, Hispanic, Asian) and ages (typically a few students somewhat older that the others) present, but even lumped together into one group they comprised a minority of the population. In gender distribution the potential students were roughly equal, however a slight excess of females was apparent. They varied in the amount of previous college-level science experience, but the majority of them had only a fairly small amount or none at all. This is because general chemistry is usually taken in the first or second year of a student’s academic career, unless the student has dramatically changed the direction of his or her academic major during their college career. There were some students repeating the course in the potential participant pool.

Instrumentation

During the individual problem-solving sessions with the students, portions of two instruments previously published in the literature were used (Appendix B). The first is
the *Covalent Bonding and Structure* diagnostic instrument (Peterson, Treagust, & Garnett, 1989) which has already been used in published research by other authors (Birk & Kurtz, 1999). The instrument consists of multiple-choice two-tiered items. The first part of each item asks about chemistry subject matter content, while the second part asks the subject to choose from a list of reasons why he or she picked a certain answer to the first part. A two-tiered test was used to provide a common starting point across the many subjects who were each interviewed four times. In other words, the two-tiered test items provided a beginning script or a set of conversation starters that helped the investigator explore each subjects’ ideas about the key concepts. The instrument was a good choice for this because it induced the subject to not only explain what he or she thinks is correct, but also why he or she thinks it is correct – which is ultimately much more interesting from a research standpoint.

This approach was first justified in the mid 1980s with topics both chemical and biological (Treagust, 1986; Haslam & Treagust, 1987). Soon afterward some concerns were raised in the literature about the approach (Tamir, 1989). The primary one is that subjects may be influenced nearly as much by contextual clues from the questions as they are by their own thought processes, thus thwarting the intended goal the instrument, which is to characterize current student scientific conceptions. For example, Tamir found that the reasons secondary students gave for their answers to multiple choice questions were commonly not based on the science of the issue, but rather on pure (albeit often flawed) logic strategies (Tamir, 1989). For example, students may over-rely on certain key words rather than keeping their current conceptual understanding paramount (Yarroch, 1991). The validity of the approach is still being considered and has been found
problematic by some experts in the field, who speak of students being misled in choosing reasons for their answers by “tautologies, teleologies, and anthropomorphisms” (Griffard & Wandersee, 2001, p. 1050).

Another line of criticism is from Vermersh who argues that any interviewing, the dedicated purpose of which is to get current student conceptions out in the open, is suspect (Vermersh, 2000). He argues that any time questions starting with the word “Why?” are used, the subjects will tend to piece together concepts on the spot that they didn’t actually possess prior to piecing them together under the pressure of being interviewed. In other words, Vermersh argues that many of their ideas are merely another form of “pleasing the authority figure” behavior. He instead advocates for what he calls an explicitation interview. A proponent of Vermersh named Potvin has explained this strategy succinctly as “a type of interview that tries to stick as close as possible to the spontaneous evocations of the subject. It is through analysis of the verbalizations describing these evocations that the interviewer can understand and acknowledge the existence of certain habits of thought” (Potvin, 2005). Contrary to the way the two-tiered instrument is used in this dissertation as a sort of a conversation starter so that one can eventually ask why subjects make certain choices for the questions, Vermersh argues that the interviewer ought never to ask “why questions” or try to obtain justifications from subjects for previous statements made. Instead Vermersh argued that the interviewer should be trying to find out what the subject is thinking when situations are explored, rather than goading the subject into supporting earlier choices. According to Potvin, this “is a technique that spares the interviewer from triggering conceptions artificially, because conceptions very much look like justifications. Instead, the goal is to
obtain … any habit of mind, including conceptions, p-prims (DiSessa, 1993) core intuitions (Brown 1993) and intuitive rules (Stavey & Tirosh, 2000) that can be noted” (Potvin 2005). This argument is not aimed specifically at two-tiered instruments but more broadly at any sort of science concept elicitation clinical interview.

Nevertheless, the approach seems to have not stopped proliferating. To the contrary, a new two-tiered chemical education instrument concerning inorganic qualitative analysis was published and a new biological two-tiered study concerning breathing and respiration has been presented in recent years (Tan, Goh, Chia, & Treagust, 2002; Treagust & Mann, 2000). And the criticism of Vermersh and Potvin should be tempered by an understanding of how the reasons in the two-tiered questions were chosen. The reasons were obtained by “unstructured interviews, analyses of student-drawn concept maps, and open-ended pencil-and-paper test items.” (Peterson, Treagust, & Garnett, p.302). This means the reasons were originally gotten from the thoughts of students which were investigated in rather free and spontaneous ways.

The second instrument, the Geometry and Polarity of Molecules diagnostic, developed by Furió and Calatayud, has not been cited as often as the first but deals with many of the same topics. It is not a two-tiered instrument, but rather a set of 16 multiple choice questions. These are single tier (traditional) multiple-choice questions, with three or four possible answers given. Parts of it were used in two of the four interviews each subject participated in – the two interviews whose two key concepts are covered by the instrument.
Each interview lasted between 45 minutes and one hour, and the four interviews of a given subject were conducted in a period of five weeks or less, all during one academic semester.

Protocol for Interviews

The individual clinical interviews consisted of sessions of an hour or less in which the subjects were videotaped while attempting to work certain items and questions from the diagnostic instruments. The subjects were encouraged to “think out loud” during their efforts. They were required to use a marker and large whiteboard for any scratch work they did during the interview. This was to facilitate the videotaping of their efforts. They were allowed to use a Periodic Table throughout the sessions which was provided by the investigator. It included the elements’ names, symbols, atomic masses, and possible oxidation numbers. Probes were used when little or no commentary was given by the subject. Small hints were sometimes offered if it became obvious that the subject was making no headway on a certain item or question. All clinical interviews were carefully reviewed and transcribed. Subjects were be compensated by a $15 cash payment and were be encouraged by a bonus payment at the end of the series (an additional $15, to make $30 total payment for the last interview) to participate in all four consecutive clinical interviews. The items and questions used in the interviews were standardized among all the subjects, and were always given in the same order. However, if an interview ran up against the upper time limit of 60 minutes then the questions and
items at the end of the list were not used. This was rather atypical – usually there was
time to spare. The items and questions were used in the four interviews as follows:

1. Bonding – Peterson, Treagust, & Garnett items 4,7,11,12

2. Polarity – Peterson, Treagust, & Garnett items 3,6,9,14 with Furió & Calatayud
   questions 11-16

3. Lewis structures and Electronegativity – Peterson, Treagust, & Garnett items
   1,3,10,15

4. Molecular Shape – Peterson, Treagust, & Garnett items 2,5,8,13 with Furió &
   Calatayud questions 1-10

The first of the questions about bonding, Item 4 from Peterson, Treagust, &
Garnett, attempts to find out if students understand the relationship between melting
points or boiling points of substances and the strength of the bonds in the material. In the
reason section, item 4 differentiates between covalent molecular and covalent network
(continuous covalent lattice) materials. Item 7 similarly attempts to investigate the
relationship of phase (solid, liquid, or gas) at a certain temperature and the strength of the
intermolecular forces in materials, in this case water (H₂O) vs. hydrogen sulfide (H₂S).
The reason portion investigates whether or not the student can identify that the higher
polarity of water determines its higher strength of intermolecular forces. Item 11 gives
the characteristics of the produce ‘Vaseline’ and asks if the product would be a covalent
molecular or a covalent network (continuous covalent) substance. Choosing the correct
reason requires the student to identify that there are only weak intermolecular forces
present in this material and that therefore it easily moves to accommodate shape changes.
The false reasons talk about the bonds within the molecules actually breaking during
shape changes or the substance having a high viscosity because of a continuous covalent
network nature. The last item on the first interview, item 12, seeks to find out how students decide on the relative strength of intermolecular forces between similar compounds, in this case oxygen difluoride (OF$_2$) and carbon tetrafluoride (CF$_4$). The reason attempts to find out if students understand that the symmetric, non-polar characteristic of the latter is what keeps it from having the greater intermolecular forces.

In the second round of interviews, dealing with polarity, item 3 checks for understanding of the proper direction of the polarity of an oxygen-fluorine bond. The reason checks to see if the subject can identify that the shared electron pair in the bond lies on average closer to the fluorine, thus the polarity. The false answers focus on non-bonding electron pairs, the charge of the corresponding ions of these elements, and merely counting the number of valence electrons in the outer shell of each atom. Item 6 gives silicon tetrafluoride (SiF$_4$), oxygen difluoride (OF$_2$), and boron trifluoride (BF$_3$) and asks which of them is polar – this is to see if the subject can use symmetry as a disqualifier for polarity, and if the subject realizes that bilateral symmetry on a flat printed page is not sufficient for a molecule which needs three-dimensional spatial symmetry to be truly non-polar. The reasons use distractors such as the difference of the electronegativities of the atoms in the molecule or the mere presence of lone pairs. It must be kept in mind that lone pairs do not always signify a polar molecule, consider xenon tetrafluoride (XeF$_4$), which has two lone pairs of electrons on the central atom arranged at 180° to one another – that molecular is non-polar. Item 9 gives the Lewis structure for chlorine trifluoride (ClF$_3$) and asks if the molecule is polar – and it is. The second part of the question attempt to again see if the subject is merely basing this on electronegativity differences, if he or she thinks it is polar just because of polar bonds,
if the subject can correctly identify that the T-shaped arrangement results in an unequal spatial distribution of charge in the molecule. The last item of the second interview, item 14, mentions that sulfur dichloride has polar covalent bonds between the atoms and asks which would be assigned the partial positive charge – the sulfur or the chlorine. The reasons then try to find if the subject believes the assignment of the partial positive charge is due to charges of the ions of these elements, or the number of valence electrons, or the electronegativities of the elements involved.

The second interview also had a set of five single-tiered multiple-choice questions from Furió and Calatayud. These involved picking from a list of molecular formulas, Lewis structures, or ball-and-stick diagrams which choice was either polar or non-polar.

The third interview, which evaluated student understandings of Lewis structures and electronegativity, started with item 1. This item shows two different drawings of the hydrogen fluoride (HF) molecule -- one with the shared electron pair depicted equidistant from the two atoms, and the other showing the shared electron pair depicted closer to the fluorine atom. The reason seeks to find out if the subjects believe that electrons involved in covalent bonding must be centrally located, if the relative size of the atom is what counts, if non-bonding electrons influence the position of the bonding electrons, or if fluorine simply has a stronger attraction for the shared electron pair. Item 3 is included in the third interview even though it was also in the second interview. This is done as a longitudinal check to see if subjects are changing their answers as time goes on, possible due to either putting concepts together, the practice effect of being interviewed, or perhaps just by looking up things they were unsure about after the interview was over. Item 10 asks the subject whether the octet rule is used to determine the shape of a
molecule or the number of bonds an atom forms. The reasons are four potential wordings for the octet rule, including that “an atom forms covalent bonds through the sharing of electrons in order to have 8 electrons in the valence shell”, “the number of bonds formed equals the number of electrons in the outer shell”, that “the shape of the molecule is dependent of the number of shared electron pairs”, and that “the shape of the molecule is due to 4 electron pairs being located in tetrahedral positions.” The last item of the third interview, item 15, gives the molecular formula N₂Cl₄ and gives four candidate Lewis structures. In the reason section it explores the idea that it is nitrogen’s high electronegativity that requires double or triple bonds to always be present, that the structure is due to repulsion between all the electron pairs (both bonding and non-bonding), or that the shape is due to only the repulsions between the bonds present.

The fourth interview, covering molecular shape, starts with item 2 which asks what shape a molecule comprised of bromine and nitrogen would have. The reason seeks to find out if the subject considers the shape a consequence of nitrogen having three bonds with equal repulsion yielding a trigonal planar shape, or it the bonding and non-bonding electron pairs both contribute to make a tetrahedral shape, or if polarity of the bonds or electronegativity differences is the deciding factor. Item 5 asks if sulfur dichloride is V-shaped or bent. The reasons seek to find out if subjects think only non-bonding electron pairs, both bonding and non-bonding pairs, or just the high electronegativity of chlorine determines the shape. Item 8 gives three candidate structures for the COCl₂ molecule. The reason portion gives possible arguments via electronegativity, equal repulsion between bonding and non-bonding electrons, the stronger polarity of the carbon-oxygen double bond, or equal repulsion of the bonding
regions of the carbon only. The last item of the fourth interview, item 13, asked whether the “electron pair repulsion theory” was used to determine shape or polarity of a molecule. The reason portion supplied the possible ideas that it is non-bonding electrons that determine the polarity, or that the arrangement of bonding and non-bonding pairs is as such to minimize electron repulsion around the central atom, or that the number of polar bonds determines the polarity of the molecule, or finally that the repulsion between atoms determines shape.

The fourth interview also had a set of five single-tiered multiple-choice questions from Furió and Calatayud. These involved picking from a list of molecular formulas, Lewis structures, and ball-and-stick diagrams which choice had certain molecular geometries, such as tetrahedral or pyramidal.

Sample Population Description

In the first semester of data collection, 10 subjects were successfully brought into the study. Eight of these subjects completed all four interviews, while two only participated in the first interview and decided not to continue. While the exact cause of these subjects dropping out of the project remains undetermined, the investigator did note that subject 6A seemed very pressed for time in her schedule (she had changed the original appointment for the first interview twice) and subject 7A appeared intimidated by the process of the interview itself. This judgment is based on the fact that the subject was unable to make any direct eye contact whatsoever with the interviewer during the entire 45 minute first interview.

In the second semester of data collection, 9 subjects were successfully brought into the study. Eight of these subjects completed all four interviews, while one only
participated in the first interview and decided not to continue. While the exact cause of this subject dropping out of the project remains undetermined, the investigator did note that subject 9B, like 6A, seemed very pressed for time in her schedule -- extensive negotiation was necessary to make an appointment for the first interview. She also changed this time later on for another before successfully meeting.

Table 2. First semester subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Class Year</th>
<th>Major</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Female</td>
<td>sophomore</td>
<td>Physician’s assistant</td>
</tr>
<tr>
<td>2A</td>
<td>Male</td>
<td>Junior</td>
<td>Secondary ed.</td>
</tr>
<tr>
<td>3A</td>
<td>Male</td>
<td>Sophomore</td>
<td>Pre-med.</td>
</tr>
<tr>
<td>4A</td>
<td>Female</td>
<td>Sophomore</td>
<td>Pre-med.</td>
</tr>
<tr>
<td>5A</td>
<td>Male</td>
<td>Sophomore</td>
<td>Engineering</td>
</tr>
<tr>
<td>8A</td>
<td>Female</td>
<td>Senior</td>
<td>Psychology</td>
</tr>
<tr>
<td>9A</td>
<td>Female</td>
<td>Sophomore</td>
<td>Secondary ed.</td>
</tr>
<tr>
<td>10A</td>
<td>Female</td>
<td>Freshman</td>
<td>Engineering</td>
</tr>
</tbody>
</table>
Table 3. Second semester subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Class Year</th>
<th>Major</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>Female</td>
<td>First-year</td>
<td>Nursing</td>
</tr>
<tr>
<td>2B</td>
<td>Male</td>
<td>Sophomore</td>
<td>Physics</td>
</tr>
<tr>
<td>3B</td>
<td>Male</td>
<td>Sophomore</td>
<td>Environmental Sci.</td>
</tr>
<tr>
<td>4B</td>
<td>Female</td>
<td>Senior</td>
<td>Undeclared</td>
</tr>
<tr>
<td>5B</td>
<td>Male</td>
<td>Sophomore</td>
<td>Biochemistry</td>
</tr>
<tr>
<td>6B</td>
<td>Male</td>
<td>Sophomore</td>
<td>Biology</td>
</tr>
<tr>
<td>7B</td>
<td>Female</td>
<td>Senior</td>
<td>Biology</td>
</tr>
<tr>
<td>8B</td>
<td>Male</td>
<td>Sophomore</td>
<td>Engineering</td>
</tr>
</tbody>
</table>

Table 4. Gender, class year, and major counts of the subjects

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>8</td>
<td>2</td>
<td>10</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

In the first semester of data collection, of the subjects who completed all interviews, five were female and three were male. Their courses of study were: three for biomedicine (two pre-med and one physician’s assistant program), two secondary education (one biology and one earth science), two for engineering (one electrical and one aeronautical) and one psychology. There was one first-year student, five sophomores, one junior and one senior. One female first-year child psychology student
and one male sophomore physics student dropped out after the first interview. All subjects during the first semester were Caucasian and traditional undergraduate aged.

In the second semester of data collection, of the subjects who completed all interviews, three were female and five were male. Their courses of study were: two for biology, and one each for nursing, physics, environmental science, biochemistry, computer engineering, and undeclared. There was one first-year student, five sophomores, no juniors, and one transfer senior. One female sophomore dietetics student dropped out after the first interview. All the subjects were Caucasian, and eight of the nine were of traditional college age, and the ninth was between 30-35 years of age.

Notation

Each round of interviews dealt with particular topics, but there was some overlap between the interviews. Analysis of the videotapes of the interviews, coupled with a transcription and subsequent coding procedure, revealed certain trends in incorrect answers and misconceptions that several of the subjects displayed. These will be addressed in depth in the data analysis chapter under a group of nine assertions about subjects’ thinking. When making reference to a particular segment of an interview, a citation such as 9A2:33 will be used. This citation means the ninth subject, from the first semester, during the second interview, thirty-third minute, while the citation 5B4:51 would indicated the fifth subject, second semester, fourth interview, fifty-first minute.
Reliability of the Interviews

One important question that deserves being addressed whenever clinical interviews such as these are conducted is the following: how faithful was the subjects’ performance to the actual level of their understanding? In other words, did the conditions of the interviews either hamper the subjects from being able to demonstrate how much chemistry they understand, and did the interviewer somehow provide verbal or non-verbal feedback that boosted subjects’ performance beyond what they legitimately are capable of at this point in their academic careers? In effort to minimize these problems, the investigator has received years of formal training in qualitative interviewing methods at the graduate level, including conducting clinical interviews for two research projects prior to this one. He has also been trained and taught in a discovery learning paradigm in the last four years, one of the key strategies of which is the maintenance of a “poker face” when students are attempting to circumvent the inquiry process by getting direct feedback from the instructor.

Unfortunately, despite any prior training, there is some evidence to suggest that both of these confounding phenomenon occurred during the interviews of the first semester. For example, subject 8A seemed very nervous and frustrated throughout the set of four interviews whenever she could not answer something right away. The investigator was unable to put her at ease, even by the fourth interview. She appeared flustered, apologized several times for changing her answer while considering a question, and the presence of the interviewer seemed to make her socially embarrassed during these times. Subject 2A told the interviewer that he (the subject) believed that one of the
goals of the interview was to find the cognitive weaknesses of the subject, and then to emphasize that part of the interview. His exact words, while having trouble with a group of polarity questions were “You’ve found my weakness, and now you’re exploiting it.” (2A2:45). When a subject says this out loud, it raises the concern that the subject feels intellectually persecuted or ridiculed by the process, which could certainly affect the subject’s performance in a negative way. Subject 4A claimed that she sometimes became suspicious that she had given a wrong answer during the interviews because during those times she was questioned more persistently about why she thought the way she did then when she gave an answer she suspected was correct. She made the analogy to the behavior of a parent, explaining that when she was growing up, if she was doing something right, her parents didn’t bring it up. If she kept doing something wrong, they would keep talking with her about it. Subject 7B expressed a related idea during the third interview when she explained how it lowered her confidence in her chosen answer-and-reason pair when asked to draw a molecular Lewis structure on the whiteboard after picking. When the interviewer asked her why she assumed it was wrong after being asked to draw it, she explained “Because it has happened every other time” (7B3:35). Actually, she was mistaken (i.e. her initial answer-and-reason was correct) in the very case where she made this statement! It does make one wonder, though, if because of interviewer questioning and probing she may have been changing her choices on the diagnostic questions more than she otherwise would have just by having had the luxury of considering each item at her leisure and not being pressured by the presence of the interviewer as an “authority figure.”
In contrast, the presence of the interviewer and his interactions with the subject boosted the performance of subject 5A, based on his own comments. He explained during the fourth interview how he found the two-tiered questions much easier to answer if the interviewer read out loud the possible choices rather than if he (the subject) was only able to read the text. Subject 4B displayed a curious attitude that also raises concerns about her participation. She explained that she was very competitive, and wanted to be the best at everything, be it college grades, her retail sales job, her performance as a “dog mom” (responsible pet owner) and finally as a research subject for this project. Subject 4B seemed very interested in providing a very large amount of information and justification for her answers, so much, in fact, that she seemed uncomfortable taking time to think silently – she almost never stopped talking during the interview. This is problematic because many of the justifications subject 4B provided included partially or wholly incorrect facts that were given in a manner that seemed to the interviewer as if the subject was just “trying too hard” and was oversupporting her answers beyond her level of current chemistry conceptions – in other words, fabricating facts on the spot to appear more authoritative and productive as a research subject.

Another issue became obvious during the second round of interviews, in which a great number of very similar chemistry problems are posed in quick succession. Subjects noticed, particularly in the items 11, 12, and 13 from Furió and Calatayud, that the same molecular structure or closely analogous structures were present in adjacent questions. This is a potential problem because once a subject realizes this, he or she will become wary in order to try to stay consistent in his or her position regarding polarity, etc. between questions for fear of looking as if they have no idea what they are talking about.
Some subjects actually went back to change an answer in a previously covered item during the second interview because the current item reminded them of something important. They were allowed to do this, and the final answer they gave was the one that was counted for the data tabulation and analysis.

Sometimes a subject performed in an inconsistent manner. For example, subject 1A made a complete 180° reversal of her beliefs about symmetry and polarity between the second and third interview. This may be due to the fact that subjects are sometimes motivated to check their textbook, lecture notes, and materials immediately after an interview which contained questions they were unsure about. Subject 4A at (4A3:5), subject 3A at (3A4:42), and subject 8A at (8A1:49) all made direct reference to working on things they were unsure about from the interview on their own time with resources such as the textbook, notes, web sites, and tutors.

This “checking after the interview” dynamic is likely more prevalent than just these three subjects out of the sixteen because subjects were not asked directly if they were doing this between interviews. Subjects 3A, 4A, and 8A had spontaneously volunteered the information with no prompting. The reason the subjects were not asked directly about this as part of the interview protocol was the concern that asking would influence them to do this between interviews and introduce another bias into the data collection. This phenomenon of subjects checking into the subject between interviews is unavoidable – and indeed ought not to be discouraged since ideally participation in education research such as this project should be of intellectual (rather than strictly financial) benefit to the subjects.
The proper use of secondary probe questions during interviews are another concern with the reliability of the research reported in this work. Secondary probes are problematic because unless carefully and judiciously used they can be seen as manipulating the statements of the subject, in other words “leading the witness” as is sometimes objected to by a lawyer in a court of law. The rule followed by the investigator throughout the data collection when phrasing secondary probe questions was to never introduce chemistry terms that had not already been included in the diagnostic item or had not been already spoken or written by the subject. This was done in an effort to make secondary probe questions a tool for clarifying subject conceptions rather than introducing or influencing subject conceptions.

Researcher Bias

The author will not pretend that he does not have some prior experiences that may influence him both consciously and unconsciously, but this attempt to inform the reader empowers him or her to make his or her own decision as to the legitimacy of the project’s structure, data collection, and results. The author earned his Bachelor of Arts in chemistry in 1995, having succeeded in all of his coursework (albeit sometimes with a great deal of effort) the first time – except for second semester organic chemistry. In this course the author required multiple attempts to earn a satisfactory mark. This caused the author a great deal of frustration, because he had put in more effort (right from the start) toward this course than he had toward his other chemistry coursework. The author never
forgot this seemingly nonsensical experience, and it influenced his choice of topic for this work.

The author was a full time high school science teacher for three years, and then became a full time graduate student in the Mallinson Institute for Science Education at Western Michigan University, earning an M.A. in 2001 and continuing on toward a Ph.D. in science education. In this capacity he has taught inquiry learning and discovery learning laboratory-centered courses in physical science (both chemistry and physics oriented) to elementary education majors and he has also served as a teaching assistant in a number of first-year chemistry lab sections for the chemistry department. The consensus opinion of the author’s faculty is that traditional direct instruction “teaching by telling” coupled with verification-style laboratory work is not the most effective way of encouraging authentic, meaningful, and deep learning of scientific concepts. This consensus opinion argues that instruction and learning experiences ought to be designed in light of constructivist theories of learning, and that learning is best thought of as a socially mediated, collaborative process. The author of this work has been strongly influenced by his professional contact with his faculty, and his interpretation of the literature has convinced him that this consensus claim of his faculty is reasonable, has merit, and ought to influence thinking about science learning situations.

The author also has participated as a graduate student in inquiry classrooms that have been designed with the principles of constructivism in mind. He found this frustrating and odd at first, but later came to realize that he was learning science concepts in a more thorough and complete way that he had in the past.
It should also be pointed out that the Mallinson Institute for Science Education (MISE) has regular profession contact (and indeed shares some faculty in common) with the various science departments at Western Michigan University. This means that the consensus opinion of the MISE may also influencing the pedagogy that occurs in these science departments.
CHAPTER IV
DATA ANALYSIS

Introduction

The goal of this work is to answer the following question: how do general chemistry students understand the small number of precursor key concepts that will serve to boost their performance later on in organic chemistry? In order to accomplish this goal, the data analysis must quantify and characterize the subjects’ current beliefs and proficiencies regarding the key concepts.

Definitions

One of the major issues inherent to interpreting the responses of the subjects during the interviews is the way chemistry defines certain terms. Unfortunately for those attempting to learn chemistry, certain terms such as “polar” and “symmetrical” are used in other fields like biology, mathematics, geography, sociology, and political science in ways vastly different from how they are used in chemistry. For example, “polar” can mean relating to the regions of the planet Earth beyond approximately 66.5° North and 66.5° South latitudes, while in the social sciences “polar” can mean that a certain population is sharply divided into two opposing camps on a certain issue. The term “symmetrical” can refer to the bilateral symmetry of animals such as dogs and cats and
the radial symmetry of sea anemones and other marine invertebrates in biology, or the two-dimensional symmetry of shapes in a plane in Euclidian geometry which have a line or lines of symmetry. However, these words have precise meaning in chemistry. “Polar” refers to molecules which in three dimensions have an unbalanced amount of positive and negative charge, and “symmetrical” refers to molecules which are equivalent in all three dimensions about their centers (this is an even higher standard that the radial symmetry of biology.)

**Thematic Analysis**

The subjects provided a wide diversity of responses to the items and questions of the instruments. Some of these responses were in agreement with the way the chemistry community views the issues, in other words the responses were correct. However, often subjects provided incorrect responses, and for some of the items and questions the majority of the responses were incorrect. When the incorrect responses were studied, certain commonalities were found across several subjects. These incorrect responses needed to be grouped in some way to make the raw data more manageable for analysis because there were literally hundreds of responses to study.

The mistakes and misunderstandings of the subjects could be grouped under a small number of headings – nine to be exact. These nine headings have been expressed as assertions in this data analysis – and certain incorrect responses from the data set which help illustrate each particular heading have been provided alongside the analysis. Figures have also been included to help make clear certain responses by subjects – recall
that they often wrote on an erasable whiteboard while working out their answers to items and questions from the instrument.

The following headings were used to group the data:

- **Assertion 1.** Many subjects misunderstand the location and therefore the nature of intermolecular forces. They incorrectly identify where the intermolecular forces are – the typical mistake is to confuse them with the intramolecular forces between atoms in a molecule. Some subjects have only a weak grasp of the definitions of atom and molecule, which may be contributing to this confusion.

- **Assertion 2.** Subjects are clear about how the various elements numerically lie along the spectrum of electronegativity. However, they often misunderstand its influence by thinking that the concept is sufficient to determine the polarity of molecules. Many subjects also have problems trying to interpret $\delta^+$ and $\delta^-$ notation.

- **Assertion 3.** Most subjects understand that higher melting points and boiling points imply stronger intermolecular forces or attractions in a material. However, many subjects did not understand the difference between a covalent network solid (continuous covalent solid) and a covalent molecular solid.

- **Assertion 4.** Many subjects are confused about what makes a molecule polar or non-polar. They have serious difficulties determining whether or not a molecule is symmetrical in three dimensions. Often the confusion is related to what three-dimensional shape they think of as they interpret a flat diagram on a piece of paper. They can often be confused by formal charge differences or
large electronegativity differences between atoms in symmetrical molecules to falsely conclude that such molecules are polar.

- **Assertion 5.** Many subjects cannot reliably draw correct Lewis structures to represent molecules. A combination of carelessness and overuse of flawed algorithms accounts for their difficulties.

- **Assertion 6.** Some subjects are confused about the behavior of electrons as particles as this behavior influences bonding and molecular shape. They know that electrons tend to repel one another, therefore to many the concept of electrons bonding atoms together seems oxymoronic. Many do not have a good grasp of the concept of orbitals.

- **Assertion 7.** Many subjects misunderstand the function of the octet rule. Many cannot understand why it is sometimes not followed by chemical species, and some overemphasize its importance, thinking that it determines the shape of a molecule.

- **Assertion 8.** Most of the subjects are aware that polarity and electronegativity are not adequate to determine the shape of a molecule. Most of the subjects know that the Valence Shell Electron Repulsion Theory (VSEPR) theory is the best way to determine the shape, but a few apply it in incorrect ways and most do not have all the possible shapes well-learned, which leads to mistakes.

- **Assertion 9.** The subjects do not reason significantly differently, or with significantly different accuracy (correctness) when working with the various
representations of molecules such as ball-and-stick models, molecular formulas, or Lewis structures.

The assertions can be grouped to the key concepts mentioned by the organic chemistry instructors during the survey. Some of the assertions can be assigned to more than one key concept, thus assertion #2 and #7 appear twice in the following table.

Table 5. Grouping of assertions under key concepts

<table>
<thead>
<tr>
<th>Key Concepts</th>
<th>Assertions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Shape, Structure, &amp; Polarity</td>
<td>2,4,7,8</td>
</tr>
<tr>
<td>Bonding &amp; Intermolecular Forces</td>
<td>1,3,6,7</td>
</tr>
<tr>
<td>Lewis Structures &amp; Resonance</td>
<td>5,9</td>
</tr>
<tr>
<td>Electronegativity &amp; Periodic Trends</td>
<td>2</td>
</tr>
</tbody>
</table>

Assertion 1

Many subjects misunderstand the location and therefore the nature of intermolecular forces. They incorrectly identify where the intermolecular forces are – the typical mistake is to confuse them with the intramolecular forces between atoms in a molecule. Some subjects have only a weak grasp of the definitions of atom and molecule, which may be contributing to this confusion.
Table 6. Subject responses counts for assertion 1

<table>
<thead>
<tr>
<th>Item 4</th>
<th>Correct</th>
<th>Partly Correct</th>
<th>Incorrect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Answer</td>
<td>Reason</td>
<td>Answer</td>
<td>Reason</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Item 7</td>
<td>13</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Item 11</td>
<td>3</td>
<td>9</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Item 12</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The subjects were often unclear about the meanings of certain terms used in the diagnostic instrument questions – such as intermolecular force. In order to understand this term, the subjects must also understand the difference between a molecule and an atom. This difference was indistinct or completely absent for several subjects. Many subjects mixed their usage of the terms molecule and atom when talking about structures which they had written on the whiteboard or that were printed on the pages of the diagnostic instrument. This issue would not have been so disturbing if subjects realized they didn’t grasp what an intermolecular force was, but oddly enough some of those who made serious errors on this issue could give a “textbook correct” definition for the term. (i.e. that an intermolecular force is a force between molecules in a substance). Granted that this definition is a bit of a circular one, it is still fundamentally correct – but subjects can say this out loud and completely misuse it.

Many subjects (nine out of sixteen) seem to believe that the sticks drawn between element symbols in Lewis structures actually represent the intermolecular forces in the substances made up of those molecules. Even more curious, sometimes a subject can say
out loud the proper definition of intermolecular force and still make an error. For example, subject 1A can almost correctly say the proper location of the intermolecular force: “in the bonds between the molecules” (1A1:9) but when asked to indicate exactly where the intermolecular force is, something strange happens. On a whiteboard upon which was drawn correct Lewis Structures for water molecules, she clearly indicated the location of the intermolecular force as the location the bond between the atoms of hydrogen and oxygen. The arrow in figure 1 illustrates where her finger was pointing.

![Figure 1. Incorrect pointing out of intermolecular forces for water](image)

She did not notice the contradiction between what she had just said and where her finger was pointing. This was clearly not a case of merely mishearing intramolecular for intermolecular because subjects are given the printed diagnostic page to look at during the interview, and the word “intermolecular” is printed in both the wording of the question and in three of the four choices. But another reasonable explanation is that the subjects who had difficulties with this question don’t know the differences between the prefixes inter- and intra-. If they don’t know the different between these two prefixes, then their faulty answers do not provide definitive evidence that they don’t understand the location of intermolecular forces. Still another possibility is that the word “intermolecular” reminds subjects of the word “internal.” If this is the case, then it is not too surprising that the subject would try to find the intermolecular force inside the molecule rather than between molecules.
Subject 4B betrayed a conceptual misunderstanding concerning this theme during one of her interviews. She correctly gave the definition for intermolecular forces and correctly chose the answer that the H$_2$S as a gas and not a liquid like H$_2$O at room temperature and pressure. However, her reasoning was faulty. Subject 4B believed that sulfur holds its outer electrons more loosely than oxygen, which is true, but used this fact to say the reason for the difference in phase of the two substances was that the bond between the hydrogen and sulfur was “looser” than the bond between the oxygen and hydrogen (4B1:18). In other words, subject 4B indicated that the difference in strength of the intermolecular forces is due to the difference in the strength of the O-H and S-H covalent bonds within the individual molecules. Although it is true that an O-H bond is stronger than an S-H bond, that is not the reason for the phase difference between the two substances at room temperature and pressure. The phase difference has to do with the amount of attraction between adjacent molecules of each substance at a given ambient temperature and pressure. No intermolecular force exists between sulfur and hydrogen or oxygen and hydrogen when the two atoms are in the same molecule.

The definitions of the terms “atom” and “molecule” are unclear to many of the subjects – and not being clear about these definitions would make 1A’s and 4B’s statements more logically consistent and reasonable for themselves. There are, however, two other possibilities. First, the subjects may have not even noticed the contradiction while they were attempting to answer the question. Second, the subjects may have noticed the contradiction but deliberately chosen to ignore it for lack of a better idea at that time. Unfortunately insufficient secondary probing was used at this juncture so there is not enough data to choose one of these possibilities over the other.
Assertion 2

Subjects are clear about how the various elements numerically lie along the spectrum of electronegativity. However, they often misunderstand its influence by thinking that the concept is sufficient to determine the polarity of molecules. Many subjects also have problems trying to interpret $\delta^+$ and $\delta^-$ notation.

Table 7. Subject responses counts for assertion 2

<table>
<thead>
<tr>
<th></th>
<th>Correct</th>
<th>Partly Correct</th>
<th>Incorrect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Answer</td>
<td>Reason</td>
<td>Answer</td>
<td>Reason</td>
</tr>
<tr>
<td>Item 3a</td>
<td>14</td>
<td>9</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Item 6</td>
<td>11</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Item 9</td>
<td>11</td>
<td>7</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Item 14</td>
<td>15</td>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Quest. 11</td>
<td>8</td>
<td>*</td>
<td>1</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 12</td>
<td>10</td>
<td>*</td>
<td>1</td>
<td>*</td>
</tr>
</tbody>
</table>

Electronegativity was familiar to every subject, and five out of eighteen subjects spontaneously pointed out the general trends of electronegativity using the Periodic Table, namely that electronegativity increases as one goes up and to the right on the table, with the exceptions of the noble gases. However, the fact that they are clear about how the various elements numerically lie along the spectrum of electronegativity does not keep them from making errors in using the concept. The meaning of an element’s electronegativity value is not universally understood – subject 1A explicitly said that elements with a low electronegativity number resist losing an electron more than those
with a high electronegativity (1A1:26). This is the exact opposite of what really happens. Others such as 3A overemphasize electronegativity, thinking it is the only determinant of the strength of the intermolecular forces while ignoring factors such as the shape of the molecule, its polarity, the potential for hydrogen bonding, *et cetera*. Subject 3A stated that CF₄ possessed greater intermolecular forces than OF₂ because there is a bigger electronegativity difference between carbon and fluorine than there is between oxygen and fluorine (3A1:41). But in this case, the polarity of the OF₂ structure makes every molecule of oxygen difluoride attract its neighboring molecules to a significant extent. In contrast, CF₄ molecules only have weak London forces between them, making CF₄ behave almost like an ideal gas.

When considering the potential polarity of a molecule, four subjects seemed to ignore the three-dimensional spatial arrangement of the atoms in a molecule in favor of just considering the electronegativity of the atoms involved. Subject 1A held this position, explaining that SiF₄, BF₃, and OF₂ were all polar structures based on the electronegativity difference between the fluorines and the central atoms (1A2:10). Figure 2 shows contrasts the structures in the Peterson, Treagust, and Garnett diagnostic with structures that include dashed bonds and wedges. In other words, the subjects were working with limited visual information.
When asked to draw structures that were non-polar, the only examples subject 1 could come up with were diatomic elements such as hydrogen and fluorine (figure 3).

The interviewer asked a probing question to verify subject 1A’s position on this: “Can you draw me a molecule that has at least two different elements in it that is not polar?” Subject 1A considered the question and firmly replied “No” (1A2:41). Further probes were not used by the interviewer on subject 1A. Subject 2A was asked, “Is it possible to have a non-polar molecule made of atoms of different electronegativities?” He also replied, “No” (2A2:27) explaining that SiF₄, OF₂, and BF₃ were all polar structures based on the electronegativity difference between the fluorines and the central atoms. Subjects 1A and 2A had identical views on this matter. Subject 2B was considering this position as well, but said “Things that have a huge electronegativity difference are ionic, not covalent, so I’m not sure if electronegativity difference is really enough to make something polar.” (2B2:11). Subject 5B had no such qualms, and seemed very confident asserting that “I just saw this in the book, if [the differences in electronegativities] are 1-3 then its polar covalent, more than 3 it’s ionic, if it’s less that 0.5 it’s a non-polar bond” (5B2:4). Subject 5B made his position clear a few moments later while considering the potential polarity of boron trifluoride (BF₃), explaining that “boron is a 3+ ion and fluorine is a 1- and that is a large electronegativity difference so it’s polar” (5B2:8).
Unfortunately, subject 5B is mistaken, both in confusing the charges on the ionic species of the elements as their electronegativities, but also in ignoring the fact that BF₃ is a trigonal planar molecule which is symmetric in all three dimensions and is not polar.

The many correct answers subjects gave for item 1 can be attributed perhaps to the clear signal the research subjects got from the presence of the fluorine – every subject correctly sees this atom as a very electronegative or electron-hungry atom. However, thinking in this way can lead the subjects to making mistakes as well. Not every molecule that contains fluorine is polar. There is evidence from the interviews which asked questions about the boron trifluoride (BF₃) and the boron trichloride (BCl₃) molecule that this mistake does not always carry over to the other halogens – the misconception is much stronger with fluorine compounds. When students were given the boron trifluoride (BF₃) structure as a ball-and-stick drawing (one boron ball in the center bonded to three fluorine balls) in question 11, seven of sixteen falsely believed it to be polar, choosing SO₂ or CF₂Cl₂ instead as the non-polar molecule. However, question 12 (which was a polarity question asked immediately after question 11) gave as one of its possible answers the formula of boron trichloride (BCl₃), which was correctly identified by ten of the fourteen subjects who answered as the non-polar molecule. Since BF₃ and BCl₃ are close chemical analogs, how can subjects 9A, 10A, 6B, and 8B think the first is polar and the second non-polar? Perhaps this is a case of subjects seeing fluorine in a structure and immediately jumping to the conclusion that since fluorine is so electronegative, any molecular structure that contains it must certainly be polar. They know that chlorine is somewhat less dramatically electronegative, so perhaps they are willing to consider that a symmetrical molecule could be non-polar even though it has
chlorines in it. If this is why the subjects made their incorrect decisions, then they are seeing strong electronegativity as trumping symmetry considerations in determining a molecule’s polarity – but it does not.

This knowledge of fluorine’s higher electronegativity than hydrogen was bundled with some interesting albeit incorrect ideas. For example, subject 7B was confident that “fluorine is a smaller atom than hydrogen … it’s more electronegative, so it has a greater tendency to pull its negative electrons toward its positive nucleus” (7B3:8). This is untrue – hydrogen is the smallest atom on the entire Periodic Table. Subject 2B made an electrostatic argument for fluorine’s high electronegativity. He believed that “fluorine has more positive charge so it attracts electrons better than the hydrogen” (2B3:1). The problem with subject 2B’s argument is that every element on the Periodic Table which has a higher atomic number than fluorine has atoms with more protons (positive charge) at their nuclei than fluorine, yet fluorine has a greater ability to attract electrons. Later on, when considering the direction of polarity for a fluorine-oxygen bond in item 3, subject 8B told the interviewer that “fluorine is more electronegative than oxygen because it has more electrons in the outer shell” (8B3:11). Elements which have a higher atomic number than fluorine will usually have more electrons that it does, so subject 8B’s argument is also incorrect. Subject 4B said something quite different: “the seventh electron on the fluorine would go back toward the oxygen, which is a little bit smaller, so it might pull it into its outer orbital easier than fluorine could, making the oxygen [partially] negative” (4B3:2). Subject 4B was the only subject in the study who did not always consistently make reference to the electronegativity of fluorine (the highest of all the elements), she explained that “fluorine has nine protons in its nucleus, oxygen has
eight, so fluorine has more attraction for electrons, each little electron in the outer shell of fluorine has a net charge of 7+ on it, that’s why it’s pulled in closer” (4B3:9). Although this is not false reasoning for elements in the same period, thinking like this can lead students astray when thinking about elements from different periods. Instead of just thinking about the absolute numbers of positive and negative charges in the atom, the particular filling of the orbitals and the shielding effects of inner shells of electrons in the atoms needs to be considered when judging the relative electronegativity of the elements. The subjects are making the idea too facile.

Item 3 asked how the partial positive and partial negative charge symbols (δ + and δ -) should be drawn on a bond between oxygen and fluorine. Fourteen of sixteen subjects correctly chose the answer which gives oxygen the positive and fluorine the negative charge, and nine were able to choose the correct reason. It seems clear to most subjects that fluorine has a tendency to be negatively charged in every situation. This implies that most subjects have a solid grasp of the electronegativity trends on the Periodic Table.

Subjects gave very interesting responses when asked the secondary probe “What do the symbols δ + and δ – mean?” after answering item 3 which included this notation in the asking of the question. The answers were varied and often problematic. Subject 2B believed they meant a change in the charge of an atom (2B3:9), confusing δ (lower-case Greek letter delta) usage with Δ (capital Greek letter delta) which in the physical sciences often refers to the change of a variable, such as ΔT to signify change in temperature. Subject 4B believed they meant variable charges, for instance δ + meant the atom “could have a charge of 1+, 2+, or 3+” (4B2:8). She treated the symbol in the sense of an
algebraic variable that could have many values. Subject 8B thought the \( \delta^+ \) and \( \delta^- \) referred to d-bonds (8B2:4), in the sense that chemistry uses \( \sigma \)-bonds and \( \pi \)-bonds when discussing the structure of a molecule. This subject did not realize that although d-shell electrons are present in many of the heavier atoms, the bonds that they may participate in are still typically \( \sigma \)-bonds and \( \pi \)-bonds. Subject 3B explained that “I think it [\( \delta^+ \) and \( \delta^- \)] indicates a given atom’s ability to attract electrons or to prevent losing electrons. I think it represents which has positive and which has negative electronegativity” (3B3:10). This subject is improperly mixing the ideas of partial charge and electron density with electronegativity.

Item 14 gave the formula for sulfur dichloride (SCl\(_2\)), explained that the molecule had covalent bonds between the atoms, and asked which atom would be assigned the partial positive (\( \delta^+ \)) charge, and why. Fifteen of sixteen subjects correctly answered that the sulfur gets the partial positive, and twelve of sixteen were able to pick the correct reason, namely that chlorine has a high electronegativity and therefore the shared electron pair tends to be located closer to it. This is evidence to suggest that subjects may have a strong grasp of the trend in electronegativity on the Periodic Table.

Assertion 3

Most subjects understand that higher melting points and boiling points imply stronger intermolecular forces or attractions in a material. However, many subjects did not understand the difference between a covalent network solid (continuous covalent solid) and a covalent molecular solid.
Table 8. Subject responses counts for assertion 3

<table>
<thead>
<tr>
<th>Item</th>
<th>Correct Answer</th>
<th>Correct Reason</th>
<th>Partly Correct Answer</th>
<th>Partly Correct Reason</th>
<th>Incorrect Answer</th>
<th>Incorrect Reason</th>
<th>Total Answer</th>
<th>Total Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item 4</td>
<td>17</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>16</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>Item 7</td>
<td>13</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>11</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Item 11</td>
<td>3</td>
<td>9</td>
<td>0</td>
<td>1</td>
<td>15</td>
<td>8</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Item 12</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>13</td>
<td>19</td>
<td>15</td>
</tr>
</tbody>
</table>

Item 4 explained that silicon carbide has a high melting point and a high boiling point and asked if this suggested strong or weak bonds in the compound, and why. Seventeen out of nineteen subjects got item 4 correct, but only two solely and one partially chose the correct reason as well. Apparently it is clear to most students that a high melting point and boiling point implies strong bonds in a material, but they still think that covalent network solids are composed of discrete molecules – but they are not. Instead, they are like one giant macromolecule which has strong bonds between atoms in all three dimensions which must be overcome in order to melt the material. In other words, covalent network solids have the atoms arranged in huge three-dimensional lattices which go on for millions upon millions of atoms linked together by bonds. For example, silicon carbide can be represented as a nearly infinite network, a portion of which is shown in figure 4. Covalent molecular compounds, which are far more common, have atoms arranged in small bonded groups, nearly always less than a few dozen, and often less than five atoms.
The next question, item 7, stated that water (H₂O) and hydrogen sulfide (H₂S) have similar molecular structures and the same molecular shape (V-shaped or bent) but that at room temperature, water is a liquid whereas hydrogen sulfide is a gas. It then asked if this difference in state was due to strong intermolecular forces in water, or in hydrogen sulfide, and why. Thirteen of eighteen picked the correct choice, but only five could identify the correct reason, while the three false reasons were all chosen. Subjects 1A, 2A, 4A, 7A, 9A, 3B, 4B, and 8B knew that water has strong attractions between the molecules without realizing that this is due to water’s high polarity, which is great enough to facilitate “hydrogen bonding” between the hydrogen of one water molecule and the lone pair on the oxygen of another (figure 5). Hydrogen sulfide has a much lower polarity so its sulfur does not deshield its hydrogens enough for the hydrogens of one molecule to be appreciably attracted to the lone pairs of the sulfur in another molecule. In other words, hydrogen sulfide does not “hydrogen bond.”

In other words, hydrogen sulfide does not “hydrogen bond.”
Water’s properties are commonly referenced and discussed in textbooks and lessons in physical science. For example, the fact that water has a very high surface tension, and that water and oil will not mix when shaken together are often explained by water’s very high intermolecular forces. Therefore the subjects may have just previously memorized the fact that water has high intermolecular forces previously and never considered the more important question of “Why?”

Item 11 described the smooth, thick, cream-like texture of the substance Vaseline® and then asked if this compound was a covalent molecular or a covalent network material. Item 11 was answered correctly by only eight of eighteen subjects, and only nine of eighteen could clearly identify the correct reason. The reason for the radical difference in properties between covalent compounds such as paraffin wax or ethanol and covalent network compounds such as diamond or silicon carbide is apparently unknown to most of them. (The reason is that the substances in the former group are composed of tiny groups of bonded atoms, while substances in the latter group are composed of huge three-dimensional lattices of bonded atoms.) The difference between these two classes of substances is truly enormous, despite the names for the classes being similar.

Subjects were asked in Item 12 which had the greater intermolecular forces, CF₄ or OF₂, and why? The correct answer was chosen by only six out of the seventeen who tried, but oddly enough nine of these seventeen succeeded in picking the correct reason, namely that CF₄ was symmetrical and non-polar whereas OF₂ was neither. The others overemphasized the electronegativity difference between carbon and fluorine for their explanation, as was previously addressed under assertion 2.
Assertion 4

Many subjects are confused about what makes a molecule polar or non-polar. They have serious difficulties determining whether or not a molecule is symmetrical in three dimensions. Often the confusion is related to what three-dimensional shape they think of as they interpret a flat diagram on a piece of paper. They can often be confused by formal charge differences or large electronegativity differences between atoms in symmetrical molecules to falsely conclude that such molecules are polar.

Table 9. Subject responses counts for assertion 4

<table>
<thead>
<tr>
<th></th>
<th>Correct</th>
<th>Partly Correct</th>
<th>Incorrect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Answer</td>
<td>Reason</td>
<td>Answer</td>
<td>Reason</td>
</tr>
<tr>
<td>Item 6</td>
<td>11</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Item 7</td>
<td>13</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Item 11</td>
<td>3</td>
<td>9</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Item 12</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>Quest. 11</td>
<td>8</td>
<td>*</td>
<td>1</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>*</td>
</tr>
</tbody>
</table>

During the clinical interviews, polarity stood out as a concept around which students have built many misconceptions. Although some subjects like 8A and 9A clearly understand that a molecule must be asymmetrical in order to be polar, others such as 10A directly stated the opposite position that a molecule needed to be symmetrical to be polar. Subject 10A cannot truly understand the definition of the word “polar” that is used by chemists in their work if she holds such a misconception. Subject 10A either did not have a clear definition at the time of the interview or was using some other kind of
working definition from another field. Unfortunately the interviewer did not use secondary probes to find out if subject 10A was using a working definition of polar that may or may not have corresponded to what is used in political science, geography, _et cetera._

A related misconception espoused by subjects 1A and 2A is that molecules with different elements are always polar, regardless of shape. This disregards the fact that by definition a molecule which is symmetrical in all three dimensions cannot be polar because its symmetry precludes any spatially unbalanced forces between the different atoms in the molecule. It is true as subjects 3A and 8A pointed out that lone pairs on the central atom with the exception of the noble gases and some transition metals will make a molecule asymmetrical and thus polar. Subjects 1B, 2B, and 5B also commented on this fact. Subject 2B agreed with 3A and 8A in saying that “a lack of symmetry, often brought about by lone pairs, is the determiner of polarity” (2B2:9). However, subject 1B stated the logically inverse form of this, namely that if the central atom of a molecule does not have any lone pairs, then the molecule is non-polar (1B2:34). This is often but by no means always the case. Subject 5B made an error as well, directly claiming that “the non-bonding pairs do not determine the polarity.” (5B2:6). This is sometimes false, lone pairs occurring on a central atom typically do make the molecule polar, because they usually “break the symmetry” around the central atom. However there are exceptions, such as the case the square planar structure of XeF$_4$ which has two lone pairs on the central xenon atom in 180° opposition to one another.

Symmetry was problematic for many of the subjects. A common mistake here was to confuse bilateral symmetry with symmetry in all three dimensions, which is a
much higher standard for symmetry and the one which chemistry uses as part of the process to determine if a molecule is polar. For example, subject 3B believed that H₂S and H₂O were non-polar because of their bilateral symmetry (see figure 6). In other words one could draw a mirror plane down the center of the molecule through the central atom in both cases (3B1:26).

Subject 3B reiterated the same position in the second interview (3B2:9) so what he said in the first interview was not just an inadvertent slip. Subject 4B made the identical argument for OF₂ being non-polar by reason of its bilateral symmetry (4B1:33). Apparently subjects 3B and 4B are using a common biological definition of symmetry. They do not realize that bilateral symmetry is not what chemists consider sufficient to assure the non-polarity of a molecule – only symmetry in all three dimensions is sufficient to assure non-polarity. Subject 8B made the most curious form of this mistake, during the second interview he explained that H₂S was symmetrical but not “balanced” in the sense of charge density and polarity because of the lone pairs on the central sulfur atom (8B2:45). This is a case where the subject could correctly tell that the molecule was polar even though he has been told that symmetrical molecules are non-polar, and he falsely considered the bilateral symmetry of the molecule to be a sufficient proof of its spatial three-dimensional symmetry around its center.

Figure 6. Bilateral symmetry of H₂O and H₂S
Item 6 gave the correct Lewis Structures to SiF₄, OF₂, and BF₃ and asked which is polar and why? The distribution of choices among the subjects was curious – three of the subjects believed all three of the choices were correct. They did pick the correct choice, OF₂, but also were satisfied with two incorrect ones – SiF₄ and BF₃. Two subjects split their vote for the proper reason as well, choosing both the correct and one of the incorrect reasons. This resulted in twelve full and three partial votes out of sixteen for the correct answer, and six full and two partial votes out of sixteen for the correct reason. The subjects gave clues for their confusion on this item during the interviews. Subject 1A explained that “All molecules with polar bonds are polar” (1A2:28) and also claimed that all molecules with more than one element present are polar. This claim is false – molecules which have perfect symmetry in all three dimensions cannot have an overall molecular polarity, regardless of how many different kinds of atoms they possess. It is worth noting here that on a later date, during the third interview, subject 1A contradicted her position in the second interview, explaining that if a molecule had polar bonds and was asymmetrical, then it was polar. (The interviewer neglected to inquire further to find out if the subject had re-read the textbook, or asked someone like a peer or the instructor for help to account for this improved understanding.) Subject 2A concurred with the original idea stated by subject 1A when she was asked by the interviewer if it was possible to have a non-polar molecule made of atoms of different electronegativities and she replied “No” (2A2:27). However, perhaps this subject was not clear about the definition of polarity, because when explicitly asked what polarity was a few minutes later, she said “the ability of one molecule to attract electrons toward it” (2A2:29). This is evidence that subject 2A may be confusing polarity and electronegativity. If one word
substitution is performed on the previous quote – the word atom put in place of the word molecule – then she has given a clear definition of electronegativity. The third subject who tried to pick all three choices, subject 10A, knew that symmetry of the molecules did have to be taken into account when discussing polarity, but mistakenly expressed that it was the symmetrical structures which were the polar ones. However, this subject was not consistent, as she also picked OF$_2$ as polar, even though it is not symmetrical. There may be significant confusion in subject 10A’s mind about how to determine the polarity of a molecule.

Even when a subject like 9A correctly knows that symmetrical molecules are not polar, and that a molecule needs to be asymmetrical to be polar, the actual statements made may be betraying some incorrect or sloppy thinking. Subject 9A explained that if the molecule was symmetrical, then all of the electronegativities would cancel out (9A2:12). It seems that the student is thinking correctly that attraction for the electrons in the bonds can be equaled out in three dimensions like a tug-of-war with teams of equal strength, but she is incorrect if she thinks this somehow negates the electronegativity of each atom – which the atoms still possess regardless of how they are bonded. It is not that the electronegativities of the substituent atoms cease to exist, but rather since the atoms with equally high or low electronegativities lie in opposite directions relative to the central atom, they do not induce a net polarity. It is the net dipole moment that “cancels out” to become zero debyes -- the standard chemical unit of polarity.

Another issue that apparently influenced how students solve the problems in the interviews was the two-dimensional (printed on the pages of the diagnostic instrument) representations of three-dimensional molecules. For example, when considering the
tetrahedral structure of CF₂Cl₂, subject 4B was misled by the common practice of drawing three substituents below coming off at different angles like a tripod and one coming off directly above the central atom. She said the molecule was polar because three electronegative substituents were pulling on the carbon from below but only one was pulling from above (4B2:45). This is actually not the case – instead they are all pulling at 109.5° to one another in space. Subject 2B told the interviewer directly that “It’s hard to express three-dimensions in two-dimensions” (2B4:32). Subject 7B initially made the same kind of mistake as subject 4B: “… the SiF₄ has a pull down, it’s asymmetrical, three fluorines South and one fluorine North of silicon, while BF₃ has the fluorines pulling in a balanced way so it’s not polar” (7B2:14). However, subject 7B (see figure 7) soon reconsidered: “In three-dimensions it can be difficult to see how they are spaced out … the fluorines want to be as far apart as possible, a two-dimensional picture of SiF₄ can be misleading, so perhaps it’s nonpolar” (7B2:18).

Figure 7. Incorrect and correct spatial understanding of the polarity of SiF₄

Three of sixteen subjects demonstrated without any prompting a technique of calculating the formal charge of atoms in a molecule as one of the ways of gathering information to make a decision regarding a molecule’s polarity. Subject 8B was very
explicit about this: “I think polar means when you add up the formal charges and it’s not zero, that makes sense because you add up all the sides” (8B2:43). Subject 5B seemed to be thinking along the same lines – he correctly calculated the formal charges on the atoms in OF₂ and decided the molecule was non-polar because they all were zero (5B4:46). Subject 6B was not quite so sure about this method, but also was considering this idea (6B2:43). Unfortunately, this method is mistaken and is not a legitimate way to determine the polarity of a molecule.

When considering the potential polarity of a molecule, several subjects seemed to be ignoring the three-dimensional spatial arrangement of the atoms in a molecule in favor of just considering the electronegativity of the atoms involved. When subject 1A seemed to hold this position, the interviewer asked a probing question to clarify: “Can you draw me a molecule that has at least two different elements in it that is not polar?” Subject 1A considered the question and firmly replied “No.” (1A2:41). Subject 2A was asked, “Is it possible to have a non-polar molecule made of atoms of different electronegativities?” He also replied, “No.” (2A2:27). Subject 2B was considering this idea, but said “Things that have a huge electronegativity difference are ionic, not covalent, so I’m not sure if electronegativity difference [alone] is really enough to make something polar.” (2B2:11). Subject 5B had no such qualms, and seemed very confident asserting that “I just saw this in the book, if [the differences in electronegativities] are 1-3 then its polar covalent, more than 3 it’s ionic, if it’s less that 0.5 it’s a non-polar bond. (5B2:4). Subject 5B made his position clear a few moments later while considering the potential polarity of boron trifluoride (BF₃), explaining that “boron is a 3+ ion and fluorine is a 1- and that is a large electronegativity difference so it’s polar” (5B2:8). Unfortunately, subject 5B is mistaken.
He seems to be both confusing the charges on the ionic species of the elements as their electronegativities, and ignoring the fact that BF$_3$ is a trigonal planar molecule which is symmetrical in all three dimensions and is not polar. Even though it is flat, there is no net polarity into our out of the page, i.e. the three pulls of equal magnitude are acting at 120° to one another and are in perfect balance (figure 8).

![Figure 8. Correct understanding of non-polar nature of BF$_3$](image)

**Assertion 5**

*Many subjects cannot reliably draw correct Lewis structures to represent molecules. A combination of carelessness and overuse of flawed algorithms accounts for their difficulties.*

**Table 10. Subject responses counts for assertion 5**

<table>
<thead>
<tr>
<th></th>
<th>Correct</th>
<th>Partly Correct</th>
<th>Incorrect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer</td>
<td>9</td>
<td>6</td>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td>Reason</td>
<td>6</td>
<td>0</td>
<td>9</td>
<td>15</td>
</tr>
</tbody>
</table>

Some interview items focused on Lewis structures. One of the main problems here is that some subjects, for instance 2A and 3A, believe that the Lewis structure determines the molecular shape of the actual molecule. This is not entirely true, although
from a Lewis structure a proficient student may be able to infer much about the shape of the actual molecule.

When students are checking the legitimacy of their candidate Lewis structures, one possible pitfall is misreading element symbols, i.e. misidentifying one element as another while looking at the Periodic Table to check number of valence electrons to perform electron counting procedures. This happened with subject 3B who counted a Br which is bromine and has seven valence electrons as a B which is boron and has only three. This gave him serious difficulties while trying to draw boron trinitride (BN$_3$) even though he did have the correct idea that the boron was the central atom (3B4:2). Subject 8B made a similar mistake when trying to draw a Lewis structure for ethanol (C$_2$H$_5$OH), counting a C (carbon, four valence electrons) as a Cl which is chlorine and has seven valence electrons (8B3:27.) In this latter case, subject 8A was completely stumped for over five minutes and was furiously (and inappropriately) adding lone pairs to the central carbons in a vain attempt to get what he thought was the correct number of total valence electrons. (Subject 8A did have every atom for the ethanol structure in the correct spatial position during his confusion.) It is certain in both cases that these were cases of mistaken element identity, because upon probing by the interviewer each subjects caught his or her mistake and explained how it had happened.

Another pitfall when students are checking their candidate Lewis structures for accuracy is the proper counting of electrons. This is not as trivial as one might guess – for example subject 1B insisted on drawing out every single electron (see figure 9), with small “x’s” for the central atom’s valence electrons and dots for the substituent atoms’ valence electrons (1B1:34).
It should be noted that there is a potentially serious conceptual problem with this technique. An electron from a hydrogen is identical to one from an oxygen, but this technique tries to preserve the identity of the original “owner” of the electron. A correct Lewis structure requires that the total number of valence electrons is accurate, but where the electrons actually came from is not necessary information. Trying to keep track of where each electron came from may hinder the subject’s understanding later on in chemistry when learning about molecules that display resonance and share electrons freely between several atoms – even ones that aren’t adjacent to each other. Several cases of this are quite common, for example the phenoxide ion in which electrons can make a circuit around a ring and even down a substituent (figure 10).

Electrons are considered equivalent so it is not accurate to think of them as having specific atoms as their “owners.”

Subject 1B was very uncomfortable with trying to count each bond line as two electrons. And subject 4B may have shown why this is not a trivial issue – she counted
bond lines instead of drawing out every dot, but unfortunately she counted each bond line as one electron, not two. Her misconception on a stick in a Lewis structure counting for one electron and not two persisted the entire duration of the data collection and was clearly displayed at (4B2:29), (4B3:47), and (4B4:2).

Another problem with Lewis structures is that they can show misleading angles between atoms, such as the false idea that the hydrogens in methane (CH₄) are at 90° angles to each other, when in fact they are arranged tetrahedrally, at 109.5° angles to one another (figure 11).

![Figure 11. Two-dimensional and three-dimensional CH₄ structures](image)

Perhaps the biggest problem with Lewis structures, though, is the fact that the common algorithm for drawing them sometimes leads to structures that do not correspond to reality. Subject 8B seemed quite aware of this fact. When asked if a structure could have the right number of electrons and still be incorrect, he replied “I think so, I did it before in lab, [there are] ones that are less desirable, never happen, or flat-out don’t work …” (8B3:49). The same subject said in a later interview that “It [Lewis structure drawing] seems very abstract – you just move dots around until everything works – and there are rules for that” (8B4:6). A good example of the misleading algorithm was shown by subject 1A, who believed that Lewis structures are always drawn with the lone pairs adjacent on the central atom, and although this is typically the case, in the actual molecules the lone pairs are sometimes not adjacent. The
square planar molecules, like XeF₄, are examples of this – they have the two lone pairs 180° opposed on the central atom.

Some subjects like 1A, 3A, and 10A did realize that non-bonding electron pairs repel more than bonding pairs. Subject 3A gave the example of “the lone pair in NH₃ holding down the hydrogens” (3A3:17), and subject 10A said that “non-bonding electrons have a greater force” (10A3:8) and that “the non-bonding electrons repel more than the bonding” (10A3:31). Subject 2B concurred: “The non-bonded pairs are stronger than the bonded pair, so it seems like they should get on opposite sides, 180° … 180° is still the farthest you can get away … H₂O has an angle of 109.5°, hmmm…” (2B4:21). By and large, however, subjects do seem to understand, as subject 3B succinctly stated, that “the structure of a molecule has to do with the repulsion of electron pairs” (3B3:34).

Assertion 6

Some subjects are confused about the behavior of electrons as particles as this behavior influences bonding and molecular shape. They know that electrons tend to repel one another, therefore to many the concept of electrons bonding atoms together seems oxymoronic. Many do not have a good grasp of the concept of orbitals.

Table 11. Subject responses counts for assertion 6

<table>
<thead>
<tr>
<th></th>
<th>Correct</th>
<th>Partly Correct</th>
<th>Incorrect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item 1</td>
<td>Answer</td>
<td>Reason</td>
<td>Answer</td>
<td>Reason</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>12</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Some subjects expressed doubt as to whether bonding electron pairs could also repel each other or anything else. Subject 1A explained that “I’m not sure if the bonding ones do [repel] because they are busy [participating in bonding between two atoms]” (1A3:44) and Subject 8A was very disturbed by the idea of bonding pairs of electrons repelling anything. She explained that bonding electron repulsion was oxymoronic, because if the electrons are supposed to be bonding, then how can they repel? This comment suggests the possibility that subjects 1A and 8A have not separated in their minds the electron-to-electron orbital repulsions from the attractions facilitated by the electrons shared in the hybridized orbitals involved in covalent bonding. In addition, some subjects seem to confuse maximizing electron repulsion with maximizing electron spacing. Subject 3B illustrated this well: “I think it should be to maximize electron repulsion, not minimize it, the greatest distance that two given atoms on a molecule should be maximized” (3B4:38). Subject 5B said something very similar: “I’m not sure what they mean by minimize electron repulsion – you want to maximize it, keep the electrons as far apart as possible” (5B4:15). Subject 2B explained the oddity that “electrons that should repulse are forming bonds with each other.” (2B2:22). Subject 7B said in reference to this doubt that “I’m getting hung up on the word ‘repulsion’, they [the electrons] are bonding, so they must have been attracted” (7B3:23).

The commonly used analogy of the behavior of the poles adjacent magnets to electrostatic attraction may be contributing to this problem. Subject 1B explained that “the electrons want to be as far away from each other as they can” (1B3:31). When asked how he knew that, subject 1B replied “It’s like the two North poles of a magnet” (1B3:31). Subject 2B concurred: “I first learned about charge behavior in elementary
school – at that time I believed an analogy with magnets and likes repel, opposites attract” (8B3:2). Like many analogies, this is an useful but imperfect and sometimes misleading one – electrons in molecules are not static charges but rather constantly moving charges that occupy orbitals between atoms such that a lowest possible (most stable) energy level can be achieved.

Subject 4A stated that a bonding pair of electrons is stronger that a non-bonding pair, so it would have more pull for its size. (4A4:23). This statement of Subject 4A is incorrect. Electron pairs do not pull on one another but instead they push or repulse each other. Perhaps this subject has not separated the way two atoms are pulled toward each other while covalent bonding and eventually share an electron orbital from the way electron orbitals will repel each other. In other words, perhaps Subject 4A has not realized that the same particle can attract some things and repulse others simultaneously.

The subjects gave curious responses regarding the position of electrons in a bond. Item 1 gave two illustrations for the placement of the shared electron pair in the covalent molecule hydrogen fluoride (HF) and asked which was a better representation and why. Twelve of the sixteen subjects correctly chose the illustrations that showed the shared electron pair located closer to the fluorine (rather than equidistant between the atoms), and twelve full and one partial vote out of sixteen went toward the correct reason, namely that fluorine has a stronger attraction for the shared electron pair. This question bothered Subject 8B quite a bit, though, for a reason that struck the interviewer as very interesting. He stated that most likely the electron pair would lie in the middle between the hydrogen and fluorine: “the middle seems like a logical place” (8B3:3). However, he then went on to say that “fluorine has a greater attractive force [for the shared electron pair] but also a
greater repelling force because it has more electrons around it” (8B3:5). The second part of the preceding statement from Subject 8B is false. When asked if the shared electron pair lies in the middle for most covalent bonds, he replied “I’m not sure, it’s usually depicted as the electrons sitting in a loop moving around” (8B3:5). Subject 8B is certainly right that this is a common textbook representation – what he seems to not grasp is that the electron tends to spend much more time in some areas than others.

**Assertion 7**

*Many subjects misunderstand the function of the octet rule. Many cannot understand why it is sometimes not followed by chemical species, and some overemphasize its importance, thinking that it determines the shape of a molecule.*

Table 12. Subject responses counts for assertion 7

<table>
<thead>
<tr>
<th>Item</th>
<th>Correct</th>
<th>Partly Correct</th>
<th>Incorrect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>3b</td>
<td>11</td>
<td>7</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
<td>13</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>15</td>
<td>13</td>
<td>6</td>
<td>0</td>
<td>13</td>
</tr>
</tbody>
</table>

Judging from her answer to item 10, Subject 1A believed that the octet rule actually determined the shape of the molecule. This is mistaken – the octet rule is just a rule-of-thumb for trying to determine how many bonds an atom will make with other atoms. An appropriate model to determine the actual shape of the molecule is the Valence Shell Electron Pair Repulsion (VSEPR) theory. This latter model better respects
the three-dimensional nature of real molecules in space than does a Lewis structure
drawn on a flat surface with often necessary but misleading angles between atoms
included. Subjects 3A and 4A were well aware of this fact, explaining that the shape is
not determined by the octet rule, rather by the bonds, how many non-bonded electron
pairs are present, and how many atoms are involved in the structure. Subject 3B directly
contradicted this fact by saying that “I don’t think VSEPR has anything to do with the
shape of the molecule” (3B4:38).

Subjects were ambivalent about the octet rule and how closely it is followed by
chemical species. They often contradicted themselves only a few seconds or minutes
after an earlier statement. Subject 1B explained that “as far as the outermost [electrons]
you can never exceed eight to react, because that’s how many fit around the outside”
(1B3:12). This is incorrect, and subject 1B almost immediately backed away from this
rigid position by admitting that “for transition metals the d-shell can have more
[electrons]” (1B3:13). Subject 3B was confident that all elements and atoms followed the
octet rule (3B3:27) and subject 5B concurred, saying he believed all elements followed
the octet rule but then subject 5B disobeyed it while trying to draw the Lewis structure of
ammonium chloride by giving the nitrogen too many valence electrons. (5B3:38). Five
of sixteen subjects (1A, 2A, 9A, 10A, and 6B) explained that transition metals often
violate the octet rule. Four of out sixteen subjects (8A, 2B, 4B, and 6B) said that
hydrogen and helium were exceptions to the octet rule, while 7B only mentioned
hydrogen, ignoring helium. Three of sixteen (8A, 10A, and 2B) also mentioned that
noble gases could violate the octet rule.
Item 3 was asked in two different interviews as a longitudinal check to see if subjects would change their minds on a sample topic after a few weeks went by. Only three of sixteen did – subjects 4B and 6B drifted to the proper choice, and subject 3B drifted away from it. At least in the case of the polarity of an oxygen-fluorine bond, the subjects’ views held fairly constant throughout the data collection period.

Item 10 asked whether it was the shape of the molecule or the number of bonds an atom forms that could be determined by the octet rule. This item was both correctly answered (the number of bonds an atom forms) and reasoned (the octet rule states that an atom forms covalent bonds in order to have eight electrons in the outer shell) by fourteen out of sixteen subjects completely and partially by the two subjects who split their vote. Worth noting is that subject 1A again contradicted herself: although previously having stated in the interview that the octet rule determined molecular shape, on item 10 she chose the response that indicates the octet rule determines the number of bonds an atom will form, instead of the “octet rule determines the shape” choice. Apparently subject 1A’s beliefs are still in flux or not very robust, i.e. her knowledge at this point was still very tentative and fragile. The investigator did not confront subject 1A with this contradiction at the moment, hoping to find out indirectly what was causing it. Unfortunately, no clues became available as the interview went on, and the investigator did not return to the issue to use secondary probes to shed light on this.

Item 15 gave four potential Lewis structures for N₂Cl₄, asked which was the best representation and why. This item was correctly solved by thirteen out of sixteen, but only six of thirteen subjects were able to identify the correct reason, namely that the structure is due to repulsion between the four electron pairs, both bonding and non-
bonding, on the nitrogen atoms. Three subjects chose none of the reasons. It may be that the students have seen enough cases where nitrogen has three bonds and a lone pair that they gravitated to the correct choice even though they cannot fully justify it. Subject 3A explained that having seen nitrogen in that way several times influenced his correct answer, although he knew that wasn’t adequate justification. This is evidence that some of the subjects learning may have been simply by dint of repetition and habituation rather than by thinking and justification.

Assertion 8

Most of the subjects are aware that polarity and electronegativity are not adequate to determine the shape of a molecule. Most of the subjects know that the Valence Shell Electron Pair Repulsion theory (VSEPR) theory is the best way to determine the shape, but a few apply it in incorrect ways and most do not have all the possible shapes well-learned, which leads to mistakes.
Table 13. Subject responses counts for assertion 8

<table>
<thead>
<tr>
<th></th>
<th>Correct</th>
<th>Partly Correct</th>
<th>Incorrect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Answer</td>
<td>Reason</td>
<td>Answer</td>
<td>Reason</td>
</tr>
<tr>
<td>Item 13</td>
<td>15</td>
<td>8</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Quest. 1</td>
<td>16</td>
<td>*</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 2</td>
<td>14</td>
<td>*</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 3</td>
<td>10</td>
<td>*</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 4</td>
<td>15</td>
<td>*</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 6</td>
<td>14</td>
<td>*</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 9</td>
<td>10</td>
<td>*</td>
<td>0</td>
<td>*</td>
</tr>
</tbody>
</table>

Most of the subjects are aware that polarity and electronegativity are not adequate to determine the shape of a molecule. Indeed, Subject 3A went farther, explaining that “polarity and electronegativity have nothing to do with the shape of the molecule” (3A4:4) and subject 5A said that “polarity has nothing to do with the VSEPR theory and molecular shape” (5A4:20). They are both essentially correct. However subject 8A and possibly subject 10A suggested that these two key concepts were enough. Subject 8A explained that the shape is due to the electronegativity, and subject 10A while speaking about nitrogen tribromide (NBr₃) in solving item 2 said she knew that the lone pair pushed the bromines down, and wasn’t sure if that “is called polarity, electronegativity, or what” (10A4:3).

Another misconception that 8A and 10A seemed to hold is that a double bond or triple bond can distort the shape of a molecule into something different from what the
shape would have been had the bond been merely single. Subject 8A was very clear (but wrong) when talking about the shape of HCN while looking at its correct Lewis Structure: “if there’s a triple bond on one side, then it’s not linear” (8A4:24). Subject 10A was not willing to go that far, but did say that a double bond pushed “regular” [single] bonds more than another “regular” [single] bond would have. It is true that there is a bigger zone of electron repulsion around a double bond, but that fact does not change the molecular shape, i.e. the spatial arrangement of the atoms relative to each other.

Item 13 asked the subject what the VSEPR theory was used to determine. Fifteen of the sixteen subjects correctly chose that the theory was used to determine the shape of a molecule, rather than the polarity of a molecule. However, only eight of fifteen subjects were able to choose the correct reason for item 13, namely that the VSEPR theory states that “the shape of a molecule is due to the arrangement of the bonding and non-bonding electron pairs around the central atom to minimize electron repulsion.” Seven of the fifteen subjects who chose a reason picked the incorrect reason that “the theory states that the shape of the molecule is due to repulsion between the atoms in the molecule.” This is evidence which could suggest that many of the subjects falsely believe atoms to be more important than bonding and non-bonding electron pairs in determining shape -- which is certainly not the case. It also might reflect a confusion between the definitions of atom and molecule.

There is an interesting question along these lines that troubled subject 1A: Does a substituent (like an atom) or a lone pair of electrons on a central atom have more influence on the shape of the molecule? Subject 5A clearly stated that the lone pair has more repulsion than a substituent like a fluorine bonded to a central atom (5A4:34).
Subject 4A stated that a “non-bonding pair acts a little bit but it doesn’t play as big of a role as the hydrogens and chlorines on carbon [the central atom in question]” (4A4:23). She also stated the false idea that a bonding pair of electrons is stronger that a non-bonding pair, so it would have more pull for its size (4A4:23).

Item 2 asked what shape a molecule formed from a combination of nitrogen and bromine would possess, and why? The subjects were allowed to use the Periodic Table for this item, and all sixteen subjects checked the columns that the two elements are found in while working the problem. This item could only be answered correctly (trigonal pyramidal) by nine of the sixteen subjects, and only six of these individuals chose the correct reason that the tetrahedral arrangement of the bonding and non-bonding electron pairs around nitrogen results in the shape of the molecule. Item 5 asked if the molecule SCl₂ was linear or V-shaped, and why? The item was correctly solved by eleven of fifteen subjects (V-shaped), but again only eight individuals fully chose the correct reason (that repulsion between the bonding and non-bonding electron pairs results in the shape) and one partially chose it. Item 8 gave three candidate Lewis structures and asked which best indicated the shape of the COCl₂ molecule and why. The subjects did better on item 8 – thirteen of sixteen picking the right answer i.e. a trigonal planar arrangement and seven of sixteen choosing the right reason that the shape results from equal repulsion between the bonding regions formed by the atoms joined to the carbon.

Questions 1, 2, 3, 6, and 9 from Furió and Calatayud were on the general topic of molecular shapes – they gave several substances as choices and asked which one fit a particular shape, for instance: “Which one has tetrahedral geometry?” Questions 1, 3,
and 6 give Lewis structures for the possible answers, Item 2 gives molecular formulas, and item 9 gives ball-and-stick models.

The subjects performed rather well on questions 1, 2, and 6. All sixteen subjects got question 1 correct, fifteen of sixteen who answered got question 2 correct, and finally all fourteen of the subjects who were asked question 6 answered it correctly. Question 3 was more problematic – only ten out of fifteen subjects could answer it correctly. Three choices were given for this item (HCN, SnCl₂, and SCl₂) and the student was asked which had a linear geometry. The answer is the HCN, but all three choices were given as Lewis structures written in the traditional linear fashion. The subject needed to realize that the single lone pair shown on the tin central atom and the two lone pairs shown on the sulfur central atom distort those molecules away from linearity. Question 9 gave three ball-and-stick choices and asked which was pyramidal. This was troublesome to the subjects – again only nine of fourteen subjects could answer it correctly. Three of the students incorrectly identified the tetrahedral shape, which differs from the true pyramidal ball-and-stick model in that the tetrahedral model has an additional atom above the central atom, whereas the pyramidal model has a lone pair occupying this same position relative to the central atom. Some subjects have a great deal of difficulty differentiating the significant difference between a lone pair of electrons and a bonded substituent atom in determining the molecular geometry of a molecule. Others do understand this point well. Subject 1: “Parent shape is electron domain shape, includes the non-bonding pair, but the real shape you have to disregard the [electron domain] shape” (1B4:3). Subject 3 concurred: “It’s bent because each chlorine and this lone pair of non-bonding electrons are all trying to get as far away as possible, so bent – it could
look like a trigonal planar, but when you look at it you don’t see the lone pair – although they do have a role in determining the shape” (3B4:56). Another way of stating the misconception is that students do not understand the difference between electron-domain geometry (in which for example both a NH₃ molecule and a CH₄ molecule are tetrahedral) from the molecular geometry. The latter only considers the positions of the substituent atoms bonded to the central atom, acknowledging that their locations are influenced by any lone pairs present. In the previous example, NH₃ would be trigonal pyramidal (not trigonal planar because the lone pair present on the nitrogen is pushing the hydrogens out of a planar arrangement) and the CH₄ would still be tetrahedral.

Question 4 gives a formula and a Lewis structure for a compound (COCl₂) and gives ball-and-stick models as the possible choices for the shape of the molecule. This seemed to pose no great challenge to the subjects because fifteen of the sixteen asked this question successfully answered it.

**Assertion 9**

*The subjects do not reason significantly differently, or with significantly different accuracy (correctness) when working with the various representations of molecules such as ball-and-stick models, molecular formulas, or Lewis structures.*
Table 14. Subject responses counts for assertion 9

<table>
<thead>
<tr>
<th></th>
<th>Correct</th>
<th>Partly Correct</th>
<th>Incorrect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Answer</td>
<td>Reason</td>
<td>Answer</td>
<td>Reason</td>
</tr>
<tr>
<td>Quest. 11</td>
<td>8</td>
<td>*</td>
<td>1</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 12</td>
<td>10</td>
<td>*</td>
<td>1</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 13</td>
<td>6</td>
<td>*</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 15</td>
<td>7</td>
<td>*</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td>Quest. 16</td>
<td>7</td>
<td>*</td>
<td>0</td>
<td>*</td>
</tr>
</tbody>
</table>

Questions 11, 12, 13, 15, and 16 all dealt with the same issue – figuring out what compounds from a given list are polar and which are non-polar. The questions do differ as to how the choices are given: questions 11 and 15 have possible answers drawn as ball-and-stick models, questions 12 and 13 have just molecular formulas listed, and question 16 gives the Lewis structures of the four possible answers.

There was no clear “winner” among these three formats for the possible answers to these questions that tended to enhance subjects’ performance. It appeared more important exactly which chemical substances were chosen as the possibilities rather than how that substance’s structure was expressed, be it as a ball-and-stick model, a molecular formula, or a Lewis structure. However, there was one interesting exception in the case of the boron trifluoride (BF₃) molecule. When students were given the structure as a ball-and-stick in question 11, seven of sixteen falsely believed it to be polar, choosing SO₂ or CF₂Cl₂ instead as the non-polar molecule. However, question 12 was asked immediately after question 11 and gave a very similar compound boron trichloride (BCl₃) but gave it
as a molecular formula rather than a ball-and-stick diagram. In this case, it was correctly identified by ten of the fourteen subjects who answered as the non-polar molecule, and one additional subject split his vote, partially for this choice. This is probably not a case of the format of the question, because as it was explained under Assertion 2 the presence of fluorine in a structure elicits a strong prejudice of polarity for many subjects regardless of symmetry considerations.

Field Observation

During the two semesters of data collection, field note-taking and some videotaping (of the instructors and their materials only) were conducted. These data were examined to see if there were cases where the subjects’ alternative conceptions were derived from the instruction they received in lecture. Very little was found – on October 12, 2004 the instructor of the first semester misleadingly referred to the octet rule as the reason that SF$_2$ has two lone pairs on the central atom, while the true reason is that two lone pairs are needed for the structure to have the correct number of valence electrons. His referral to the octet rule as a justification was incorrect and was contradicted by the very next example which he correctly explained, namely SF$_4$. Sulfur tetroxide is a compound in which the sulfur has an expanded octet of 10 electrons (with one lone pair on the central atom) to again accommodate the real reason of having the right number of valence electrons in the final structure. It is possible that the “A” subjects could have been influenced to overemphasize the importance of the octet rule based on their instructor’s comment at this point – but the misleading comment was an isolated case and
proper terminology was used in all the other examples which spanned over several days. In other words, the first instructor merely misspoke during lecture rather than actually espoused the misconception throughout the semester. The investigator noted one other mistake of the first instructor: on November 17, 2004 he used the term “molecules” for the smallest units of table salt (NaCl) present in the crystals before dissolving in water. Strictly speaking, that usage is incorrect. Rather, as a crystal the sodium chloride exists as a lattice of ions, and each smallest possible portion of the salt would be known as a formula unit, to reflect the fact that it is not covalently bonded and will immediately dissociate upon dissolving. These two deviations from standard “best currently accepted” chemistry were the only ones noted in an entire semester of close observation. Only the first deviation had any significant chance of supporting incorrect thinking on the part of the research subjects 1A through 10A.

In the second semester, the second instructor was carefully observed in the same manner as the first. Again, a few deviations from standard “best currently accepted” chemistry practice were noted. On January 19, 2005 the instructor said that “cations and anions come together to make molecules.” This is incorrect – they come together to form ionic lattices, the smallest repeating unit of which is called a formula unit, not a molecule. On February 11, 2005 the second instructor was speaking about enthalpy calculations and said you can “break certain bonds to get energy out.” Strictly speaking, this is incorrect – the breaking of any molecular bond requires an input of energy. What releases energy during a chemical reaction is the forming of the bonds of the products, and if the energy released when the new bonds are formed is greater than the energy that was required to break the bonds of the reactants, then a net amount of energy is released into the
environment. Neither of these two errors is directly pertinent to any of the questions posed on the diagnostics, and no other problem areas were noted.

This is solid evidence that the misconceptions are very rarely being directly reinforced by the instructor in lecture. Indeed, the very few small errors noted, except for the octet rule comment by the first semester instructor, do not even directly relate to any of the items and questions from the diagnostics. Although the possibility exists that misconceptions may be introduced or reinforced more often in office hours, this chance seems remote judging from the quality of the lectures. The author is very confident that the misunderstandings and chemical misconceptions displayed during the data collection had not been directly or intentionally transferred from instructor to student in lecture.

As far as general classroom characteristics and climate, the first semester course was a semi-traditional large lecture hall course structure modified by innovative techniques. These included attempts to make the environment more interactive by throwing a ball into the crowd and having the student who catches it answer a question, and then throw the ball to another part of the audience, and having students publicly vote for their current subject matter beliefs by standing up or raising one hand or two hands when multiple choice questions were posed. The first instructor also had designed a custom website for the course and encouraged his students to visit it often for sample problems, additional illustrations, and so forth. The second semester was a very traditional large lecture hall course structure, and while the second instructor did not have a customized website, he did make the use of a certain nationally published workbook with many sample problems a requirement of the course. Both semesters did offer the flexibility of allowing students from the audience to pose questions directly to the
lecturer on a regular basis, often at the beginning of the session. Neither instructor seemed negligent as far as trying to provide a reasonable classroom learning opportunity. In other words, both instructors were making a sustained genuine effort to foster student learning. No obvious deficiencies were noted in either case.

Textbook Proofing

The textbook (Brown, LeMay, Bursten, & Burdage, 2003) was also checked in the appropriate chapters for trouble spots that may be introducing or reinforcing misconceptions. No errors were found, despite a careful page-by-page, diagram-by-diagram search. Since this textbook is in its fourth edition, this is perhaps to be expected. This certainly does not eliminate the chance that students are building misconceptions through their incorrect interpretations of the text and its diagrams. However, since the textbook makes no discernable concrete errors in the chapters which deal with the key concepts, mistaken ideas that the students may pick up from these materials are not intended by the authors.

Another issue is the problem of the textbook using as its example of a situation or definition the same compound that is present in an item on the diagnostic. For example, the authors of the text use the example of silicon carbide (SiC) on page 437 when talking about a covalent network solid, and this is the same compound used in item 4 of Peterson and Treagust. This may have boosted the performance of the students on this question, but the question was actually about the relationship of high melting points and boiling points of a substance to the strength of its bonds, rather than identifying silicon carbide
from a list of possibilities as the covalent network solid. This kept the investigator from just throwing out the item during the first interview. However, the investigator admits that already knowing silicon carbide is a covalent network solid may have given subjects who had recently read (and remembered!) their textbook an advantage in choosing the correct reason in item 4.

Generalized Commentary

There were a few spontaneous general comments that kept occurring and cut across all the assertions previously discussed. The most common one, that subjects 4A, 5A, 8A, and 9A mentioned, makes reference to the problem of exceptions in chemistry. It seems to them that every time a rule is given, it will soon be broken, making them question the value of the rule in the first place. Sometimes a subject seemed markedly irritated by this. For example, subject 4A noted that “Every time you get a rule, there’s always exceptions, and the, like, the exception doesn’t follow the trend so you have to memorize these thousands of exceptions. Like the Periodic Table, boron doesn’t follow its bonding thing [the octet rule] … even the Periodic Table isn’t solid” (4A1:10). During a later interview the same subject was more forgiving about this: “Chemistry is like that, there’s an exception to everything. I’m sure there’s good reasons for the exceptions.” (4A3:20). Subject 5A contrasted chemistry with mathematics, explaining that “I like something solid, math is always solid, you use the same rules and it always goes the same way (5A1:10). Subject 8A actually indulged in a bit of anthropomorphizing of the natural chemical word while complaining about this issue: “I
don’t know why you’d break the octet rule, but nature likes to screw with us” (8A2:13). During the same interview subject 8A (a fifth-year senior) also expressed frustration that this course was going to be the first C grade earned in her career: “I want it to click like everything else … but it doesn’t. They give us a rule and they come up with 20 exceptions and here’s why …” (8A2:30). When asked regarding a possible Lewis structure if the electron counts gotten from the sum of the valence electrons of the elements and the total of all dots/bonds in the drawing had to agree, subject 9A exclaimed, “I would hope so, but chemistry often doesn’t abide by the rules that it makes for itself … there are a lot of exceptions” (9A3:30).

Subject 2B expressed his frustration with this issue while he was solving problems from the instrument. First he said “There’s no consistent rules in chemistry” (2B2:30), later that “there’s no rules in chemistry” (2B2:35), and finally near the end of his second interview “But chemistry has no rules so it’s all OK.” (2B2:47). In the last interview the same subject expressed his frustrations again while referring to an exercise involving Lewis structures during the lab period which included XeF₄ as an example of a square planar molecule. He wondered “…why we’re talking about XeF₄ in lab? Noble gases technically don’t bond with anything but nah, we’re just going to make crap up” (2B4:19). The reader should note that since 1962 certain compounds containing noble gas atoms have been successfully synthesized, but even at the present time they are still uncommon and relatively exotic. This is why this group of elements is now called the noble gases rather than the inert gases.

Perhaps this frustration stems from the fact that in their efforts to bolster student understanding, both the textbook authors and lecture instructors sometimes resort to pithy
rules that students can easily “grab onto” when just starting to learn about a concept. The problem is that the students often don’t realize that the rule is often only the reasonable first approximation to the complex reality of the chemical situation at hand. Chemistry is certainly not alone in doing this, for example the discipline of physics is notorious for working motion problems in the absence of friction and air resistance -- making the solving of most problems partially fantastical. In addition, physicists teach Newtonian mechanics when they well know that Einsteinian relativity has supplanted Newton and gives more accurate results for problems concerning the wide range of motions we can study in our universe. But chemists and physicists are using these first approximations pedagogically because going straight to the most complete modern understanding of chemical or physical phenomena is conceptually very difficult for novices and time is limited in a semester course. The real issue here is this: Is the perceived efficiency in using first approximations worth the later confusion and frustration this gives students in chemistry? This issue will be addressed in chapter 5.

Another observation made by some subjects referred to the abstract quality of the discipline. Subject 4A explained how she felt the subject was difficult because “I can’t see molecules” (4A1:57), and the subject 8A spoke of the “weirdness of chemistry … it’s out there… like science fiction (8A1:23). Subject 7B said that “Chemistry, it seems weird, it’s very confusing until you get it and then it’s so easy.” (7B4:51). Subject 6B, a biology major, contrasted his major field with chemistry in explaining that biology is more hands-on and doesn’t involve things that are too small to directly observe (6B1:12). Since subject 6B is a second-year undergraduate, he probably doesn’t yet realize that as one continues to study biology, the level of study goes even smaller than the cells that
can be observed directly with an optical microscope to enzymes, parts of genes, and DNA strands that cannot be directly observed. But subject 6B is certainly right in thinking that biology is a far more concrete science in lecture and lab (at least at the introductory level) than chemistry is.
CHAPTER V

CONCLUSIONS AND IMPLICATIONS

Subjects’ Patterns of Thinking

The subjects often displayed a comfort level with certain answers and reasons which may have been based on past exposure to similar situations rather than rational thought. Recall the case of Item 15, which gave four potential Lewis structures for \( \text{N}_2\text{Cl}_4 \), asked which was the best representation, and why? This item was correctly solved by thirteen out of sixteen, but only six of thirteen subjects were able to identify the correct reason, namely that the structure is due to repulsion between the four electron pairs, both bonding and non-bonding, on the nitrogen atoms. This is very surprising – less than half of the subjects who knew the correct molecular structure knew why it was the correct one. The author suspects that the students have seen enough cases where nitrogen has three bonds and a lone pair that they gravitated to the correct choice even though they cannot fully justify it. Subject 3A explained that having seen nitrogen that way several times influenced his correct answer, although he knew that wasn’t adequate justification.

Another good example of this phenomenon was Item 7, in which thirteen of eighteen knew that water rather than hydrogen sulfide is a liquid at room temperature because of strong intermolecular forces in water. But only five of these subjects, fewer
than a third, knew that this was the case because water is a more polar molecule than hydrogen sulfide. It may be the case that the some of the subjects have seen references to water’s special properties from prior textbooks or heard references to them from prior teachers during their educations. Such sources of information may have used the strong intermolecular attractions present in water to explain water’s high surface tension, its ability to be liquid under a wide range of conditions even though nearly every other compound with such a tiny molecular weight is a gas, and so forth. This is evidence that some of his (and other subjects’) learning was simply by dint of repetition and habituation rather than by thinking and justification.

It is important to point out here that the term “rote learning” ought not always to be equated with “bad learning” or “shallow learning.” Some things, like the letters of the alphabet, the human anatomical structures in medicine, and the symbols of the chemical elements are appropriately learned by dint of repetition. The problem comes in when students see textbooks as repositories of facts to be memorized, and that the goal of the chemistry course is reached when perhaps 80% or more of the facts in the text have been successfully memorized. The author suspects some of the research subjects are wholly unaware that a much better goal for the chemistry course is a conceptual understanding that can account for the facts and examples presented in their textbook. It is far preferable for students to be able to use the octet rule, determine the number of valence electrons on nitrogen based on its position on the Periodic Table, and draw Lewis structures to convince themselves that the structure in which nitrogen has three bonds of other atoms and a lone pair of electrons is correct, rather than just remembering that “nitrogen forms three bonds!” The former understanding will allow the student to
successfully work with dozens of kinds of atoms, the latter fact will only work for nitrogen in many cases. Unfortunately for the students who like to memorize facts, nitrogen can in fact form four bonds with other atoms in cases where it ionizes to take on a positive charge, such as in the case of the ammonium ion (NH₄⁺) which is common even in general chemistry. When one goes on to organic chemistry, there are more instances, for example in the cases of the commonly found quarternary ammonium salts of amines and somewhat less commonly seen arenediazonium salts (figure 12).

![Figure 12. A typical salt of an amine and an arenediazonium salt](image)

There are even relatively common cases where amide salts in which the nitrogen takes on a negative charge, like lithium diisopropylamide in which the nitrogen has only two bonds and a lone pair (figure 13).

![Figure 13. Lithium diisopropylamide](image)

The previous examples show that this memorization strategy, even if it works except for the exception of the ammonium salt in general chemistry, is going to collapse under the weight of counterexamples once the student studies organic chemistry. If the
student had made the effort and managed to grasp the octet rule, the way nitrogen’s position of the Periodic Table determines its number of valence electrons, and how to draw proper Lewis structures, then these new cases are easily explained and do not create a crisis. This level of understanding ought to be the goal of the general chemistry course, rather than just the accumulation of facts with limited applicability.

Many subjects are unclear about the proper definitions of chemistry terms used over and over in the course. This is true even though definitions are always given in their textbooks and sometimes in lectures to terms like “atom”, “molecule”, “intermolecular force”, “polarity”, and “electronegativity.” It’s easy for instructors to assume that if a student has read the chapter in the textbook then that student at least knows proper definitions for these foundational terms, but the data clearly indicate such confidence is misplaced. The instructors did not consistently give definitions for every chemistry term they used; this is apparently a pedagogical mistake.

The importance of a proper definition cannot be overemphasized. An adaptation of Phillip M. Sadler’s comment about proper conceptual understanding in the film “Minds of our Own” says it best: if the meaning of the term is not fully understood, then everything involving that term that the subject encounters tends to have problems. And students can be quite good at fooling their instructors by sounding more knowledgeable than they really are – under assertion 1 of the data analysis chapter of this work there is clear evidence that subjects 1A and 4B both fit into this category. Those who teach must be wary of students who can recite correctly – they may often be just parroting back what they have heard or read.
Instructors might also think that students would catch their own misunderstandings of terms used over and over, but again the subjects involved in the research sample of this work showed that this is often not the case. Some of these words, like “atom” and “molecule” have almost certainly been heard before by the subjects in first-year college chemistry even if they have no prior chemistry background. Perhaps they are bringing misconceptions from high school or even earlier to their college experience, and the further instruction is not forcing them to challenge their current alternative conceptions. This resiliency of faulty definitions for basic terms is a very large impediment to further student success in chemistry. For example, first-year graduate students often display severe misunderstandings that are at least partially rooted in sincerely-held faulty definitions (Bodner, 1991).

How Students Go Astray in Learning Chemistry

The subjects’ performance during the interviews seems like a symptom of a larger problem. Chemistry is a complicated subject where many factors influence the characteristics of molecules, such as their shape, polarity, and bonding behavior. To deal with this complexity, both instructors and students use algorithms, which can be defined as “a predetermined set of instructions for solving a specific problem in a limited number of steps” (Neufeldt, 1988, p. 34). Unfortunately, easy-to-learn and easy-to-follow algorithms fail to capture the subject in all its complexity – and when rules like the octet rule are given it is only a matter of time before exceptions begin popping up, often by the next day’s lecture. There are good reasons for these exceptions – in other words, they are
not completely arbitrary, capricious, or random. However, from some subjects’ point of view, this is exactly what they are. This is because subjects do not yet appreciate the complex richness of chemical behavior. Many of the subjects who made mistakes by slavishly following algorithms suspected that they were going astray, but admitted that they did not know what else to do since a potentially incorrect answer is better than no answer at all. It is unclear to the author whether this over-reliance of chemistry students upon algorithms is best considered more as a symptom or more as a contributing cause to student difficulties. Perhaps this over-reliance is both symptom and contributing cause simultaneously in the sense that it is a pedagogical and cognitive “vicious circle.” Frank, Baker, and Herron have explained how an algorithm can severely limit student intellectual creativity toward chemistry problems and how “we need to help students apply algorithms as part of a problem-solving process, not as the entire means of solution” (Frank, Baker, and Herron, 1987, p. 514). This is not to say that algorithms are always bad – they can thought of as strategies or techniques that reduce the load on the chemistry problem solvers’ working memories, freeing up precious mental capacity (Bodner, 1987). In other words, the algorithms can serve to make chemistry problems simpler and organize what the student already knows so that he or she can spend less mental effort keeping this knowledge handy during problem-solving (Johnstone & El-Banna, 1986).

The subjects also misuse what they do know and are sure of when faced with unclear situations. For example, every subject knew that fluorine was a very electronegative atom and knew therefore by reasoning that every bond that fluorine would form with another element would be polar. Unfortunately, many students
“overapplied” this understanding to incorrectly conclude that symmetrical molecules like BF$_3$ that contain fluorine must then also be polar. These subjects completely ignored the symmetry of the molecule – their attention was completely focused on the fact that the compound had the ultimately electronegative kind of atom within it. The subjects who made mistakes here were not able to get past the presence of fluorine while thinking about the molecule’s properties. It was not, however, simply a case of being unable to hold onto more than one variable or consideration at the same time. Some of the subjects who could not see that BF$_3$ was non-polar were nevertheless able to see that BCl$_3$ was non-polar. The presence of chlorines does not distract them or overwhelm their thinking as much as the presence of fluorines even though the subjects knew that chlorine was also strongly electronegative.

Another example of subjects’ overemphasizing what they have grasped is shown by how many of them understand the octet rule. Some subjects falsely believe that all elements must follow it, and even the majority of subjects who know that not all elements follow it were unable to give the identities of the common exceptions. Even more disturbing, there was one subject who went so far as to say that the octet rule determines the shape of the molecule, and two others who leaned toward this idea. This is not a tendency unique to this data sample – Taber identified this misconception (along with many others) in a study of A-level chemistry students in the United Kingdom (Taber, 1998). Robinson has explained that Taber’s results show that students often have an entire alternative framework for chemical bonding based on the octet rule, believing that “bonds form in order to satisfy the octet rule … rather than use[ing] the octet rule as a guide to identify stable species” (Robinson, 1998, p. 1075). This faulty idea is crippling
to a real understanding of how the valence shell electron pair repulsion theory explains the shapes that molecules will take. And it may also mislead the student into thinking that the octet rule is driving reactions, rather than kinetic or thermodynamic considerations. Complete electronic shells of eight electrons do often result from chemical reactions and bonding, but the converse is not an accurate description of chemical behavior. Subjects may be confusing the octet rule with hybridization of orbitals.

The octet rule was developed merely as a rule-of-thumb to help predict bonding and draw Lewis structures; it was never intended as a foundational axiomatic truth for deductive reasoning in the sense that Issac Newton considered his Three Laws of Motion in classical mechanics. Although this issue was not a focus of this investigation, it is likely that the poor understanding of the epistemology or nature of science is showing itself here.

Subjects are also confused about the priority of potentially conflicting ideas, in other words how to settle a question when two different variables seem to be pointing to two different conclusions about a chemical behavior. A clear example from the data set is molecules that have greatly differing electronegativities between the bonded atoms and are symmetrical. The first characteristic is proof positive that there are strongly polar bonds within the molecule, the second is proof positive that the molecule is nevertheless non-polar overall. Several subjects are not clear that symmetry concerns “overrule” or “trump” the fact that there are greatly differing electronegativities in the molecule. Another example is the way many subjects are confused about how electrons can be both electrostatically repelling each other (due to their like negative charges) and bond
together atoms. The words “bonding” and “repelling” seem mutually exclusive.

Electrons indeed do repel each other, but the quantum mechanics of the 20th century revealed that while they repel each other they also orbit atoms in certain predictable mathematically defined paths of probabilistic positions called orbitals.

Subjects also seem to display a high degree of “selective hearing” or “selective attention” when attending lectures. Subject 5B claimed to have never seen $\delta^+$ and $\delta^-$ notation, so that he could not say what it meant (5B2:6). This was an extremely curious statement, since the professor had used the notation on the chalkboard during the lecture which the subject had attended and that had concluded just 10 minutes before the interview started. Even stranger, subject 5B was able to make reference to a structure for HF during the interview that occurred only a few minutes before the mentioning of $\delta^+$ and $\delta^-$ notation. Subject 6B also said something unexpected: “I’m not sure the charge on the ions [using an improper term to refer to the atoms of oxygen and fluorine] has anything to do with the $\delta^+$ and $\delta^-$ …” (6B2:23). This subject seems to be doubtful that these symbols had anything to do with charge. He did say he had seen the symbols in lecture but did not know what they meant exactly because “the professor didn’t go over it” (6B2:3). This is also untrue – the professor had told the class the meaning of $\delta^+$ and $\delta^-$ after labeling a structure on the chalkboard just the day before in lecture. However, the meaning was given only in passing (lasting less than 60 seconds) and apparently subject 6B did not catch it.

The kind of notation which is drilled into a subject during the drawing of Lewis structures may also lead to problems with a subject’s future performance in chemistry. For example, subject 1B was very uncomfortable drawing two electrons as a bond line –
instead she insisted on drawing out every single electron (as illustrated in figure 9) with small “x’s” for the central atom’s valence electrons and dots for the substituent atoms valence electrons (1B1:34).

Subject 1B was skilled at Lewis structures and did not make any errors with them during the data collection. However, it should be noted that there is a potentially serious conceptual problem with this technique. An electron from a hydrogen is identical to one from an oxygen, but this technique tries to preserve the identity of the original “owner” of the electron. A correct Lewis structure requires that the total number of valence electrons is accurate, but where the electrons actually came from is not necessary information. Trying to keep track of where each electron came from may hinder the subject’s understanding later on in chemistry when learning about molecules that display resonance and share electrons freely between several atoms – even ones that aren’t adjacent to each other. The items and questions from the diagnostics do not include a situation such as this, so direct evidence was not collected on this point, but an example of a chemical species where this issue matters is the phenoxide ion, shown in figure 10.

Still, perhaps the risk of overemphasizing the “ownership” of certain electrons by atoms is worth it, if the kind of counting mistakes that subject 4B was making are common to the general population. Subject 4B used bond lines, but counted each line as a single electron, rather than as two electrons. She held onto this misconception throughout the last three interviews, and it made her drawing of accurate Lewis structures impossible. Instructors may think that notation is too obvious to spend a great deal of time on in class, but apparently subjects don’t always catch their mistakes, even when given an entire semester to do so.
Another potential problem was brought up by Subject 7B. She explained that “I wish all of these [shape names] started with something other than T” (7B4:1). Perhaps the fact that certain shapes are named tetrahedral, trigonal planar, T-shaped, and trigonal bipyramidal makes it harder to memorize them and keep them distinct in one’s mind.

Comments on the Current State of Chemical Education

It was quite disturbing to the researcher to see individuals knowing an answer but being unable to understand why it is correct. Have we trained our undergraduates to be good guessers rather than good reasoners? If so, we have not only done our undergraduates a great disservice, but we have also harmed our discipline of chemistry as a whole. The difference between someone who has “taken some chemistry” and a proficient “practicing chemist” is not primarily a matter of how much chemical content matter each knows relative to the other. This is often assumed by the uninitiated to be the case, and it is true that practicing chemists need a thorough background in the basic facts in the field. However, what is most important is not their personal mental storehouse of information, but rather their conceptual framework of chemical behavior. If we don’t emphasize students knowing the reasons why the molecules behave as they do, our students will miss out on the main point of their chemistry coursework.

Have we as instructors been content too long with writing exam questions that can be successfully completed by those who have only a very shallow grasp of the material? In other words, are we reinforcing student “shallowness” and never forcing the students to stretch themselves mentally as an absolutely necessary effort for their earning of the
course credits? The author suspects that in too many cases, the answer here is “Yes!” As suggested in the previous paragraph, our chief goal as instructors ought not to build little encyclopedia of chemical behavior out of our students, but rather to help our students build skill in explaining and predicting chemical behavior. When they are in their careers, be it medicine, engineering, chemistry, etc. they will be able to look up specific information as needed. They will not be able to quickly reference the key concepts they may need to successfully handle the challenges that their profession will send their way.

One of the biggest issues that came out of the data collection is the problem of student self-correction, or rather the lack of it, as time goes on. Although it is all but inevitable that students will often misunderstand things they are exposed to in the general chemistry offering and have cognitive conflicts with previously-learned conceptions, it does not follow that these students are doomed to hold onto their alternative conceptions forever. Students need to use (or develop in the first place) the ability to catch their own mistakes and misunderstandings through interactions with problem sets, lectures, the textbook, websites, and other academic resources. This habit of mind or ability is a higher-order skill than just trying to absorb (and regurgitate at the appropriate time) lots of technical information about atoms, molecules, and chemical reactions. Some subjects provided evidence from interview to interview (or even during an hour interview) of self-correction. This usually came about from the subject having a suspicion or an intuitive sense that their understanding of the question being asked was incomplete or even entirely faulty. Other subjects blithely made the same mistake over and over again, even in the face of repeated “grilling” by the interviewer about what they were doing and why they were doing it. The author wonders if there might be some way to boost, support, or
engender in the first place a self-critical thought habit in chemistry students. Perhaps we as instructors hold too closely the idea that we are trying to impart a body of knowledge – that is one of our legitimate goals in the classroom, but it ought not to be the only one. We need to make sure we are concerned with our students developing a healthy skepticism of what they think and believe, in other words, a “scientific attitude.”

Implications for Lecturers and Textbook Authors

The most important thing that lectures can do when planning and executing their duties is to stay mindful of the proper end of instruction – conceptual growth in students. Instructors need to re-think the traditional organizational scheme that may have pieces like “a unit on bonding”, “a unit on atoms”, “a unit on Lewis structures” and so forth. Rather than trying to teach skills in isolation, instructors ought to take stock of the key concepts that will most likely boost future learning, and find ways to spiral back to this small number of key concepts again and again through different situations.

Instructors have to break themselves of the habit of packing the lessons with factual information. As Mies van der Rohe once said in talking about modern architecture, “Less is more.” In other words, instructors should be more judicious about what facts they include in lecture, making sure they help flesh out and illustrate the key idea, rather than distract student attention from it. The fact-laden presentation common in the chemistry lecture hall sends students the message that chemistry is really a discipline of fact collecting, in the sense of the hobbyists who enjoy stamp collecting. Chemistry is actually a discipline of explaining and predicting chemical behavior rather
than just a technician’s exercise of compiling data. The instructors may certainly use concrete examples to pique student interest, but in a way that is always mindful of a core concept that can be illustrated with the example, rather than as a “Gee Whiz!” sort of moment.

Instructors need to be mindful of the common misconceptions their students are likely to display on a given topic if they are to have a reasonable chance of designing instruction that can take seriously what the student already have in their minds rather that just assuming that one is starting with a clean slate (Haslam & Treagust, 1987). Certain proven pedagogical techniques should be instituted to encourage a self-correcting critical thinking habit. For example, dedicating some time in lecture to public audience voting of multiple-choice questions encourages students to think about what they know and talk with their neighbors about it right in the lecture hall. Another good idea is demonstrating concept mapping, and allowing the students a few minutes a week to practice this skill with their peers in the middle of lecture. This will help even the most rote of learners to think along more conceptual lines in their hours of study (Cardellini, 2004).

Our choices for assessing student performance are the strongest way we communicate to our students what we value. We must guard against using innovative methods in the lecture and ignoring improvements to how and what we grade. If we only require a rote understanding of the chemistry during evaluation activities like exams, then we will have taken away much of the incentive of students to learn in an authentic and deep way. As much as possible, we should “require students to describe why and how choices were made” (Henderleiter, Smart, Anderson, & Elian 2001, p 1129). We must not accept reasons like “I followed the algorithm.” We must force students to get past the
memorization of the rote methods and to question what they know, and how they know it. We cannot just give lip service to conceptual development – instead we must make it an absolute necessity to earn a high mark in a chemistry course. For example, the data showed that some students were picking a Lewis structure from a list of candidates for \( \text{N}_2\text{Cl}_4 \) in which nitrogen had three bonds just because that functionality seemed common. It is a common behavior of nitrogen, but not because nitrogen has some capricious desire to always have three bonds – rather the valence number of nitrogen based on its position on the Periodic Table coupled with orbital theory (expressed in this case by the octet rule) is why a certain structure is correct. And the reasons the false Lewis structures are incorrect is not just because nitrogen has two, four, or five bonds, but rather because they have incorrect numbers of valence electrons or unfavored bonding patterns based on available orbitals.

Chemistry textbook authors need to guard against the tendency to make the books thicker and heavier with every passing edition. Indeed, many current textbooks already have too many facts, and certainly enough (if not too many) color photos of chemical demonstrations and lab equipment. What needs to be encouraged is authors deliberately choosing to “cover less content” so that what can be discussed in proper detail is the small number of key core concepts, including more of the evidence and reasoning that led chemists to these core concepts. General chemistry generally only takes up two semesters which means many of the topics in these compendia which pass for textbooks will never be addressed even at a fast and shallow rate of teaching on the part of the instructor.

There are actually two distinct problems that arise from the way most general chemistry textbooks are currently written. Ronald Gillespie explains the more obvious of
the two succinctly: “Many students are overwhelmed by the amount of material and
detail in most texts” (Gillespie, 1997). The students see all of this information too often
as disconnected bits, and their perception encourages a rote memorization strategy of
learning to the detriment of their chemistry conceptual framework growth.

The other problem is perhaps more subtle but no less important: when textbooks
become exhaustive collections of facts, data and evidence to support scientific principles
tend to be de-emphasized or wholly absent. This has been a concern in the field of
science education for many decades. Joseph Schwab explained that he felt that science
was being taught as “a nearly unmitigated rhetoric of conclusions … making no mention
of reasons or evidence for what it asserts” (Schwab, 1962, p. 24). George DeBoer
attributes some of the responsibility for Schwab’s complaint on the rise of professional
educators as textbook authors rather than professional scientists from the 1920s through
the 1940s (DeBoer, 1991). However it is the opinion of the author that modern
professional educators are more sensitive to the need to support student conceptual
development and when working in conjunction with chemists and cognitive psychologists
can write textbooks that would ameliorate Schwab’s concerns.

Strengths and Limitations

This project obtained data from subjects who had studied under two different
instructors who used somewhat different lecture styles and classroom methods. Both
instructors used the same textbook, but one supplemented it liberally with problems from
a required student workbook but had no custom-designed problems posted on an
instructor website, while the other made no reference to any workbook but often talked about custom-designed problems present on his instructor website. These differences made no significant qualitative difference in how the subjects as two distinct groups (1A through 10A and 1B through 9B) thought about the key ideas. In other words, it is not possible just by closely studying a subject’s responses to tell of which group he or she was a member. This provides face validity to the claim that this data transcends any one specific classroom – rather it represents the sort of thinking that is common in college undergraduates trying to learn general chemistry. The literature also supports the contention that these data are more than experimental artifact present at only one university – work in the United Kingdom (Taber, 1998), in Australia (Peterson, Treagust, & Garnett 1989) and in the United States (Birk & Kurtz, 1999) are good examples.

Proper technique in interviewing which enables reliable data collection is essential to qualitative educational research studies. Although there were some problems noted in the methodology chapter in this work under the heading “Reliability of Interviews” they were sporadic rather than foundational in nature. To use the language of analytical chemistry, the irregularities previously noted constitute random error rather than systematic error, which can never be completely eliminated. This ought not to invalidate this education research; it is simply something we must live with as designers, executors, and consumers of education research. There are other well-documented factors such as the Hawthorne Effect which also cannot be eliminated from education research designs, so the investigator’s position here has clear precedent.

A weakness of this dissertation is the implicit assumption that good problem solving ability of items and questions from the diagnostics can be equated with good
conceptual understanding of the key concepts. Some subjects may be good at solving problems using skills other than their understanding of the chemical key concepts involved as explained in Chapter III under the heading “Instrumentation.” However it seems highly unlikely that there is not a strong correlation between performance and conceptual knowledge in the subjects. This is because the items and questions from the diagnostics are given in isolation, apart from context that could offer clues.

Further Research

This project attempted to obtain a thorough sample of pre-organic chemistry students to see how they thought about the key concepts. However, it is acknowledged that the claims in this manuscript would have better support had a class been solicited for subjects at a different type of tertiary institution which was using a different textbook entirely. This worthwhile addition to the existing data set was not collected out of time and monetary considerations.

Perhaps the greatest limitation of the research reported here is that it was not specifically designed to find out what sorts of instructional environments are most likely to build authentic and thorough learning of the key concepts. This worthy goal could influence the design of future work building on this project.

A worthwhile investigation would be to expand and change the recruiting of subjects to focus on current organic chemistry students. The conceptual understanding of these students could be statistically compared with their organic chemistry exam scores to check the assumption that high performance on the items of the diagnostics really does
correlate to high performance in the organic chemistry examination room. Not only would this idea serve as a check to the preceding assumption, but it would supply a wealth of data which could be compared to the data of this study to answer a further question. Assuming there is a significant difference between the performance of these two samples, is the difference between the conceptions of pre-organic and current organic chemistry students merely a matter of degree (i.e. refinements of ideas) or does it reflect dramatic “paradigm-shifts” (Kuhn, 1970) in the subjects’ thinking? These two possibilities represent dramatically different processes going on in students’ minds.

Another intriguing investigation would be another expansion of the research sample, this time to include organic chemistry instructors and organic chemists who do not teach at all, but instead perform research in industry or in government laboratories. How would their performance and conceptions of these key ideas compare with that of students? The possibility exists that the key ideas revealed in the survey are not necessarily essential for high organic chemistry performance – and this investigation would check that assumption in this project’s research design. It would also determine whether there are significant differences in the conceptual understanding of strictly research organic chemists and teaching organic chemists (who may or may not be currently conducting research.)
Appendix A

Protocol Clearance From the Human Subjects Institutional Review Board
Date: May 28, 2004

To: Bill Cobern, Principal Investigator
    Patrick Meyer, Student Investigator

From: Mary Lagerwey, Ph.D., Chair

Re: HSIRB Project Number: 04-05-20

This letter will serve as confirmation that your research project entitled "A Study of Five Precursor Key Concepts for Organic Chemistry" has been approved under the exempt category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition, if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: May 28, 2005
Date: October 13, 2004

To: William Cobern, Principal Investigator
    Patrick Meyer, Student Investigator for dissertation

From: Amy Naugle, Ph.D., Interim Chair

Re: HSIRB Project Number: 04-10-13

This letter will serve as confirmation that your research project entitled “A Study of How Key Concepts for Organic Chemistry Success are Introduced to and Understood by General Chemistry Students” has been approved under the exempt category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: October 13, 2005
WESTERN MICHIGAN UNIVERSITY - Mallinson Institute for Science Education

Principal Investigator: Dr. Bill Cobern

Student Investigator: Pat Meyer

My name is Pat Meyer and I am a doctoral candidate in Science Education from Western Michigan University. As a part of my dissertation work I am studying what key concepts from first-year general chemistry are most important for an undergraduate to learn in order to have a strong foundation to do well in organic chemistry. My immediate goal is to identify the five or so key concepts that organic chemistry instructors feel are most important for student success, and the reasons those five concepts were chosen.

You have been invited to fill out a survey about your professional opinions regarding the prior chemistry background students need in order to do well in organic chemistry.

This research involves no known physical, intellectual, or psychological risks beyond which is inherent to attending to your professional duties on the campus which provides your employment.

Your participation may give you an opportunity to consider and possibly improve your current syllabus in your chemistry courses. Your participation may assist in the writing of the student investigator's dissertation, and as such may enrich the chemical education literature on the subjects of general and organic chemistry curriculum design.

Any data you provide is confidential. Data will be stored, analyzed, and reported using code numbers instead of names. That means the portion of the survey above the dashed line will be removed immediately upon receipt at which point a code number will be added to the survey. The student investigator will keep a master list of names and code numbers. Once the data are collected and analyzed, the master list will be destroyed. All documentation will be retained for at least three years in a locked file in the principal investigator's office.

You may revoke permission to use your survey at any time. If you have any questions or concerns about this study, you may contact either Dr. Bill Cobern at 269-387-2971 or Pat Meyer at 269-692-2769. You may also contact the chair of Human Subjects Institutional Review Board at 269-387-8293 or the vice president for research at 269-387-8298 with any concerns that you have.

This consent form has been approved for use for one year by the Human Subjects Institutional Review Board as indicated by the stamped date and signature of the board chair in the upper right corner. Do not participate in this study if the stamped date is more than one year old.

Your signature below indicated that you have read the purpose and structure of this study and that you agree to participate.

Signature ___________________________ Date ____________

Printed Name _____________________________

Consent obtained by: ___________________________ Date ____________
You have been invited to participate in a research project entitled "A Study of How Key Concepts for Organic Chemistry Success Are Introduced to and Understood by General Chemistry Students." The research is intended to investigate how students are thinking about certain key chemistry concepts that will tend to boost their performance later on in their undergraduate work.

You will be asked to attend four one-hour individual sessions which are designed to investigate your current understanding of certain fundamental principles which you have encountered in general chemistry. At each session, you will be given certain chemistry problems to work on which you will attempt to solve using dry-erase markers on a whiteboard. You will be asked questions by the student investigator during this session about how you are thinking about the problems. These individual sessions will be videotaped. During the first session you will also be asked to fill out a survey which asks for your demographic information (gender, class year, etc.) and your past academic experience.

This research involves no known physical risks beyond that of attending classes on main campus. There is the possible intellectual risk that the tutoring sessions could lead you to a misunderstanding, and the risk that the individual interview could make you anxious by reminding you of academic difficulties. However, it is the opinion of the investigators that this risk is more than offset by the chance to learn the material in a deeper way. In addition, your participation may assist Western Michigan University and other schools in providing more effective instruction in future semesters.

All the information (survey, videotapes, and transcripts written from the videotapes) collected from you is confidential. This means that your name or other identifying information will not appear on any papers on which information is recorded. Instead each of you will be given code numbers to label the information you provide. The student investigator will keep a separate master list of names and code numbers. Once the data are collected and analyzed, the master list will be destroyed. All documentation will be retained for at least three years in a locked file in the principal investigator's office.

This project is not being directed or supervised by your chemistry professor, and your professor will not have access to the data collected from you. This assures that your participation or lack of participation cannot influence your course grade in any way. You will be financially compensated for your time by a payment of $15 at the end of each interview, and if you attend all four interviews, you will receive a bonus of an additional $15. In other words, you will receive a payment of $30 at the end of the fourth interview if you have also participated in the first, second, and third interviews.

You may refuse to participate or quit at any time during the study without affecting your course grades or class experience in any way. If you have any questions or concerns about this study, you may contact either Dr. Bill Cobern at 387-5407 or Pat Meyer at 692-2769. You may also contact the chair of Human Subjects Institutional Review Board at 387-8293 or the vice president for research at 387-8298 with any concerns that you have.

This consent form has been approved for use for one year by the Human Subjects Institutional Review Board as indicated by the stamped date and signature of the board chair in the upper right corner. Do not participate in this study if the stamped date is more than one year old.

Your signature below indicated that you have read the purpose and requirements of the study and that you agree to participate.

Signature ___________________________ Date __________ e-mail address ___________________________
Consent obtained by: ___________________________ Initials of researcher Initials of researcher Date __________
WESTERN MICHIGAN UNIVERSITY – Mallinson Institute for Science Education (instructor form)

Principal Investigator: Dr. Bill Cobern

Student Investigator: Pat Meyer

You have been invited to participate in a research project entitled “A Study of How Key Concepts for Organic Chemistry Success Are Introduced to and Understood by General Chemistry Students.” The research is intended to investigate how students are thinking about certain key chemistry concepts that will tend to boost their performance later on in their undergraduate work. The instruction that students receive in their lecture session is part of their learning environment, so the investigators are interested in recording some of it for future study.

You will be asked to allow the student investigator to videotape certain lessons you provide to your section of CHEM 110. The camera will be set up in the lecture hall McCraken 3292 and pointed so as to only capture your actions at the front of the room, not the audience’s.

This research involves no known physical risks beyond that of teaching classes on main campus. There is the possible intellectual/professional risk that you may make a subject matter mistake, or perform an action that you feel reflects negatively upon your professionalism while being taped. There is also the risk that being recorded could make you self-conscious and distract you from the lesson. However, the investigators would like you to know that at your request, they are willing to edit or destroy any session’s tape which you would prefer not be kept, no questions asked. Your participation may assist Western Michigan University and other schools in providing more effective instruction in future semesters.

All the information (videotapes, and transcripts written from the videotapes) collected from you is confidential. This means that your name or other identifying information will not appear on any papers on which information is recorded. All documentation will be retained for at least three years in a locked file in the principal investigator’s office.

You may refuse to participate or quit at any time during the study without affecting your course grades or class experience in any way. If you have any questions or concerns about this study, you may contact either Dr. Bill Cobern at 387-5407 or Pat Meyer at 692-2769. You may also contact the chair of Human Subjects Institutional Review Board at 387-8293 or the vice president for research at 387-8298 with any concerns that you have.

This consent form has been approved for use for one year by the Human Subjects Institutional Review Board as indicated by the stamped date and signature of the board chair in the upper right corner. Do not participate in this study if the stamped date is more than one year old.

Your signature below indicates that you have read the purpose and requirements of the study and that you agree to participate.

______________________________  ____________________________
Signature                      Date

Consent obtained by: __________________________
Initials of researcher

__________________________  ____________________________
Date                      Date
Dear Chemistry Educator:

My name is Pat Meyer and I am a doctoral candidate in Science Education from Western Michigan University. As a part of my dissertation work I am studying what key concepts from first-year general chemistry are most important for an undergraduate to learn in order to have a strong foundation to do well in organic chemistry. My immediate goal is to identify the five or so key concepts that organic chemistry instructors feel are most important for student success.

To this end, I would like to solicit your input. In the next few days you will receive via US Postal Service an envelope from the Mallinson Institute for Science Education at Western Michigan University. It contains a cover letter, consent document, and survey. A stamped return envelope is also provided. I would like to ask you the favor of looking over these documents upon receipt and hope you will consider participating.

Sincerely,

Pat Meyer
Mallinson Institute for Science Education
Western Michigan University
Chemistry Instructor Survey

Name: __________________________ Institution: __________________________

(On questions four and five please feel free to write on the back or attach a page if needed.)

1. Have you taught college organic chemistry? For how many years? List most recent calendar year taught.

2. Have you taught first-year college chemistry? For how many years? List most recent calendar year taught.

3. In your professional life do you see yourself primarily as a: (circle choice)
   A. college-level science instructor
   B. research chemist
   C. education researcher
   D. college administrator
   E. some equal proportion of two or more of these (circle all that apply in that case)

4a. Which five or so foundational or “key” concepts do you think most important for your students to have learned in first-year general chemistry so that they might be effective learners in organic chemistry?

4b. Why have you chosen these particular concepts?

5. Please briefly describe the three to five most important chemistry content knowledge deficits you have noticed with your organic chemistry students that hinder their performance.
RECRUITMENT SCRIPTS AND INFORMATION PERTAINING THERETO

The recruitment will be conducted in the ordinary lecture hall of CHEM 110, namely McCracken 3292. Only after the instructor is asked to leave the room, and the door shut behind him or her, will this script be followed.

1. chemistry student subject recruitment:

   (Hand out the consent document to students.)

   Good morning (afternoon) ladies and gentlemen. My name is Pat Meyer and I am a graduate student in Science Education here at Western Michigan University. I am here today to tell you about an education research project which will take place this term, and an opportunity for you to take part in it. I will be conducting individual interviews that explore how students understand certain fundamental principles in chemistry. The students who attend the first one-hour individual session will be asked to fill out a survey with their demographic information and a few questions about their academic career. They will then be videotaped while working on a few sample chemistry problems and asked questions about how they are trying to solve these problems. After the first interview, many of the participants will be invited back for further interviews, with a maximum of four interviews possible. All participants will be financially compensated for their time after each session. This collected data will not be available to your professor during the semester so it will not influence your grades in any way. Your name will not be associated with the collected data, rather code numbers will be used to keep track of any information you provide. If you have any questions after having the consent document, please raise your hand (wait for and answer questions.) At this time, if you are interested in taking part in this education research project, please sign the form, date it, and pass it to the end of the row.

2. instructor subject recruitment:

   Good morning (afternoon). My name is Pat Meyer and I am a graduate student in Science Education here at Western Michigan University. I am here today to tell you about an education research project which will take place this term, and an opportunity for you to take part in it. I would like to ask you for two things: The first is permission to use five minutes of your class time to solicit potential research subjects for individual interviews that explore how students understand certain fundamental principles in chemistry. The second is permission to videotape certain lessons you provide for your CHEM 110 section. (Provide consent document.) If you have any questions, please feel free to ask at this time. (wait) If you are interested in taking part in this education research project, please sign the form and date it.
Appendix B

Interview Diagnostics
COVALENT BONDING AND STRUCTURE

INSTRUCTIONS TO STUDENTS

This test consists of 15 questions which examine your knowledge of covalent bonding and structure in chemistry.

Each question has two parts: A Multiple Choice Response followed by a Multiple Choice Reason. You are asked to make one choice from both the Multiple Choice Response section and one choice from the Multiple Choice Reason section for each question. There are 15 questions in this test.

Answer all questions on the separate sheet

1. Read each question carefully
2. Take time to calculate and consider your answer
3. Record your answer in the correct box on the Answer Sheet
   e.g. 12.  2  REASON □
4. Read the set of possible reasons for your answer
5. Carefully select a reason which best matches your thinking when you work out the answer
6. Record your answer in the correct reason box on the Answer Sheet
   e.g. 12.  2  REASON  C
7. If you change your mind about an answer, cross out the old answer and add the new choice
   e.g. 12.  2  REASON  X  A

Don't forget to record your name and other details on your Answer Sheet

Used with permission from Ray Peterson, copyright ©1989

Science and Mathematics Education Centre,
Western Australian Institute of Technology,
Kent Street, Bentley, WA., 6102.

Ray Peterson ©
TEST ON COVALENT BONDING
AND STRUCTURE

ANSWER SHEET

Name________________ Chemisty Class_________

Male ___ Female ___

Age ___ years

1. □ Reason □
2. □ Reason □
3. □ Reason □
4. □ Reason □
5. □ Reason □
6. □ Reason □
7. □ Reason □
8. □ Reason □
9. □ Reason □
10. □ Reason □
11. □ Reason □
12. □ Reason □
13. □ Reason □
14. □ Reason □
15. □ Reason □
1. Which of the following best represents the position of the shared electron pair in the HF molecule

(1) \( \text{H} : \text{F} : \)  
(2) \( \text{H} : \text{F} : \)

Reason

(A) Non-bonding electrons influence the position of the bonding or shared electron pair.

(B) As hydrogen and fluorine form a covalent bond the electron pair must be centrally located.

(C) Fluorine has a stronger attraction for the shared electron pair.

(D) Fluorine is the larger of the two atoms and hence exerts greater control over the shared electron pair.

2. Nitrogen (a group 5 element) combines with bromine (a group 7 element) to form a molecule. This molecule is likely to have a shape which is best described as

(1) trigonal planar
(2) trigonal pyramidal
(3) tetrahedral

Reason

(A) Nitrogen forms three bonds which equally repel each other to form a trigonal planar shape.

(B) The tetrahedral arrangement of the bonding and non-bonding electron pairs around nitrogen results in the shape of the molecule.

(C) The polarity of the nitrogen-bromine bonds determines the shape of the molecule.

(D) The difference in electronegativity values for bromine and nitrogen determine the shape of the molecule.
3. The polarity of the oxygen–fluorine bond would be best shown as

\[ \begin{align*}
\text{(1)} & \quad \text{O}^+ \text{F}^- \\
\text{(2)} & \quad \text{O}^- \text{F}^+
\end{align*} \]

Reason

(A) The non-bonding electron pairs present on each atom determine the polarity of the bond.

(B) A polar covalent bond forms as oxygen has six outer shell electrons and fluorine seven outer shell electrons.

(C) The shared electron pair is closer to fluorine.

(D) The polarity of the bond is due to the oxygen atom forming an \( \text{O}^2- \) ion, whereas fluorine forms an \( \text{F}^- \) ion.

4. Silicon Carbide has a high melting point and a high boiling point. This information suggests that the bonds in silicon carbide are

\[ \begin{align*}
\text{(1)} & \quad \text{weak} \\
\text{(2)} & \quad \text{strong}
\end{align*} \]

Reason

(A) Silicon carbide is a covalent network solid (continuous covalent lattice) composed of covalently bonded molecules.

(B) A large amount of energy is required to break the intermolecular forces in the silicon carbide lattice.

(C) Silicon carbide is a covalent molecular solid.

(D) Silicon carbide is a covalent network solid (continuous covalent lattice) composed of covalently bonded atoms.
5. The molecule $\text{SCl}_2$ is likely to be

(1) V-shaped  (2) Linear

Reason

(A) Repulsion between the bonding and non-bonding electron pairs results in the shape. 

(B) Repulsion between the non-bonding electron pairs results in the shape.

(C) The two sulphur-chlorine bonds are equally repelled to linear positions as $\text{SCl}_2$ has an electron dot structure shown as

\[
\begin{array}{c}
\text{F} \\
\text{Si} \\
\text{F} \\
\text{F} \\
\text{F} \\
\text{F} \\
\text{Cl} \\
\text{S} \\
\text{Cl} \\
\end{array}
\]

(D) The high electronegativity of chlorine compared to sulphur is the major factor influencing the shape of the molecule.

6. Which of the following molecules is polar

\[
\begin{array}{c}
\text{F} \\
\text{Si} \\
\text{F} \\
\text{F} \\
\text{F} \\
\text{F} \\
\text{Cl} \\
\end{array} \quad \begin{array}{c}
\cdot \text{O}^- \\
\text{F} \\
\text{F} \\
\text{F} \\
\text{B} \\
\text{F} \\
\end{array} \quad \begin{array}{c}
\text{F} \\
\text{B} \\
\text{F} \\
\text{F} \\
\end{array}
\]

(1) (2) (3)

Reason

(A) The polarity of the molecule is due to the high electronegativity of fluorine.

(B) Non-symmetrical molecules containing different atoms are polar.

(C) Non-bonding electrons on an atom in the molecule produce a dipole and hence a polar molecule.

(D) A large difference in the electronegativities of the atoms involved in bonding results in a polar molecule.
7. Water (H$_2$O) and Hydrogen Sulphide (H$_2$S) have similar chemical formalae and have V-shaped structures. At room temperature, water is a liquid and Hydrogen Sulphide a gas. The difference in state between water and Hydrogen Sulphide is due to the presence of strong intermolecular forces between

(1) H$_2$O molecules
(2) H$_2$S molecules

Reason

(A) The difference in strength of the intermolecular forces is due to the difference in the strength of the O-H and S-H covalent bonds.

(B) The bonds in H$_2$S are easily broken, whereas in H$_2$O they are not.

(C) The difference in strength of the intermolecular forces is due to the difference in polarity of the molecules.

(D) The difference in strength of the intermolecular forces is due to the fact that H$_2$O is a polar molecule, whereas H$_2$S is a non-polar molecule.

8. Which of the following best indicates the shape of the COCl$_2$ molecule

(1) \[ \begin{array}{c}
  \text{C} \\
  \text{O} \quad \text{Cl} \quad \text{Cl}
\end{array} \]
(2) \[ \begin{array}{c}
  \text{Cl} \\
  \text{C} = \text{O} \\
  \text{Cl}
\end{array} \]
(3) \[ \begin{array}{c}
  \text{Cl} \quad \text{C} \quad \text{Cl}
\end{array} \]

Reason

(A) The shape of COCl$_2$ is dependent on the electronegativity of each atom.

(B) The shape of COCl$_2$ is due to approximately equal repulsion between the bonding and the non-bonding electron pairs on the carbon.

(C) The shape of COCl$_2$ is due to the stronger polarity of the C=O double bond in the molecule.

(D) The shape of COCl$_2$ is due to equal repulsion between the bonding regions formed by the atoms joining to the carbon.
9. The substance chlorine trifluoride (ClF₃) is often described as a planar, T-shaped molecule, whose structure can be represented as:

\[ \text{F} - \text{Cl} - \text{F} \]

Based on this information ClF₃ is most likely to be a

(1) polar molecule   (2) non-polar molecule

**Reason**

(A) The molecule is polar as it has polar bonds.

(B) As fluorine has a very high electronegativity the molecule is polar.

(C) The T-shaped arrangement of the polar bonds results in a polar molecule.

(D) The molecule is non-polar because there is very little difference between the electronegativity values of Cl and F.

10. The octet rule is used to determine the

(1) shape of a molecule

(2) number of bonds an atom forms

**Reason**

(A) The octet rule states that an atom forms covalent bonds through the sharing of electrons in order to have 8 electrons in the valence shell.

(B) The octet rule states that the number of bonds formed equals the number of electrons in the outer shell.

(C) The octet rule states that the shape of a molecule is dependent on the number of shared electron pairs.

(D) The octet rule states that the shape of a molecule is due to 4 electron pairs being located in tetrahedral positions.
11. The commercially available substance 'Vaseline' has a smooth, thick, cream like texture. Based on this, Vaseline would be classified as being a

(1) covalent molecular substance
(2) covalent network (continuous covalent) substance continuous covalent network.

(C) The molecules in the substance experience weak intermolecular forces and easily move to accommodate changes in the shape of the solid.

(D) The bonds within the molecules of the substance break easily to accommodate the changes in shape of the solid.

12. When comparing the molecules OF$_2$ and CF$_4$, it is most likely that the strength of the intermolecular forces will be

(1) greater between OF$_2$ molecules
(2) greater between CF$_4$ molecules
(3) the same for each type of molecule

Reason

(A) There are four polar bonds in CF$_4$ and only two in OF$_2$.

(B) The similar electronegativities of oxygen and fluorine result in OF$_2$ being non-polar.

(C) The large electronegativity difference between carbon and fluorine atoms results in CF$_4$ being polar.

(D) CF$_4$ is symmetrical and non-polar, whereas OF$_2$ is non-symmetrical and polar.
13. The 'electron pair repulsion theory' is used to determine the

(1) polarity of a molecule  (2) shape of a molecule

Reason

(A) Non-bonding electrons determine the polarity of the molecule. For example, non-bonding electrons on the atom B in the molecule

\[ A \quad B \quad C \]

cause B to become partially negative (\( \delta^- \)).

(B) The theory states that the shape of a molecule is due to the arrangement of the bonding and non-bonding electron pairs around the central atom to minimize electron repulsion.

(C) The theory states that the polarity of a molecule is dependent on the number of polar bonds present.

(D) The theory states that the shape of a molecule is due to repulsion between the atoms in the molecule.

14. The molecule \( \text{SCl}_2 \) has polar covalent bonds between the sulphur and the chlorine atoms. The atom assigned the partial positive charge (\( \delta^+ \)) in these bonds would be

(1) Sulphur
(2) Chlorine

Reason

(A) Sulphur donates one electron to the chlorine atom resulting in the formation of \( S^- \) and \( Cl^- \) ions.

(B) Sulphur is partially negative (\( \delta^- \)) as it can form an \( S^- \) ion, whereas chlorine can only form a \( Cl^- \) ion.

(C) The number of valence electrons on sulphur and chlorine determine the polarity of the bonds.

(D) Chlorine has a high electronegativity and the shared electron pair tends to be located slightly closer to it than the sulphur atom.
15. Which of the following best represents the structure of \( \text{N}_2\text{Cl}_4 \)?

(1) \[
\begin{array}{c}
\text{Cl} \\
\text{N} \quad \text{N} \\
\text{Cl} \\
\end{array}
\]

(2) \[
\begin{array}{c}
\text{Cl} \\
\text{N} \quad \text{N} \\
\text{Cl} \\
\end{array}
\]

(3) \[
\begin{array}{c}
\text{Cl} \\
\text{N} \quad \text{N} \\
\text{Cl} \\
\end{array}
\]

(4) \[
\begin{array}{c}
\text{Cl} \\
\text{N} \quad \text{N} \\
\text{Cl} \\
\end{array}
\]

Reason

(A) The high electronegativity of nitrogen requires that a double or triple bond is always present.

(B) The structure is due to repulsion between the 5 electron pairs (including bonding and non-bonding pairs) on the nitrogen atom.

(C) The structure is due to repulsion between the 4 electron pairs (including bonding and non-bonding pairs) on the nitrogen atom.

(D) The structure is due to the repulsion between bonds in the molecule.
Appendix 1. Questionnaire

Item 1. Which of the following molecules has tetrahedral geometry?
   a. $\text{H}_2\text{P} \text{H}$  b. $\text{H}_2\text{S} \text{H}$  c. $\text{CH}_2\text{C} \text{Cl}$

Item 2. Which of the following molecules has tetrahedral geometry?
   (a) $\text{CF}_4$  (b) $\text{SCl}_4$  (c) $\text{SeCl}_4$

Item 3. Which of the following molecules has linear geometry?
   a. $\text{H} - \text{Cl} = \text{N}$  b. $\text{Cl} - \text{Sn} - \text{Cl}$  c. $\text{Cl} - \text{S} - \text{Cl}$

Item 4. Which is the molecular shape of $\text{COCl}_2$?
   a.  
   b.  
   c.  

Item 5. Describe the molecular geometry for each of the following molecules (X is the central atom, and it has no lone pairs):
   (a) $\text{XY}_2$  (b) $\text{XY}_3$  (c) $\text{XY}_4$  (d) $\text{XY}_5$

Item 6. Which of the following molecules has tetrahedral geometry?
   a.  
   b.  
   c.  

Item 7. What is the molecular shape of $\text{SnCl}_2$?
   $\text{SnCl}_2$

Item 8. Name the following molecular shapes:
   a.  
   b.  
   c.  
   d.  

Item 9. Which of the following representations has a pyramidal shape?
   a.  
   b.  
   c.  

Item 10. Predict the molecular shape of each of the following molecules:
   a.  
   b.  
   c.  

Item 11. Which of the following is not polar?
   a.  
   b.  
   c.  
   d.  

Item 12. Which of the following molecules is not polar?
   a. $\text{CHCl}_3$  b. $\text{CH}_2\text{Cl}_2$  c. $\text{CH}_2\text{Cl}_2$  d. $\text{BCl}_3$

Item 13. Which of the following molecules is polar?
   a. $\text{BeCl}_2$  b. $\text{NH}_3$  c. $\text{CCl}_4$  d. $\text{P}_2\text{O}_5$

Item 14. Given formula of compound $\text{AB}_4$, explain the steps to follow to determine if the molecule of this compound is polar or nonpolar.

Item 15. Which of the following molecules is not polar?
   a.  
   b.  
   c.  

Item 16. Given Lewis structure for following molecules. Which of them is not polar?
   a. $\text{N} = \text{O} - \text{O}$  b. $\text{H} - \text{O} - \text{H}$  c. $\text{O} = \text{C} = \text{O}$  d. $\text{H} - \text{Se} - \text{H}$
Appendix C

Interview Multiple-Choice Responses Tables
<table>
<thead>
<tr>
<th>Item</th>
<th>Answer 1</th>
<th>Answer 2</th>
<th>Answer 3</th>
<th>Answer 4</th>
<th>Reason A</th>
<th>Reason B</th>
<th>Reason C</th>
<th>Reason D</th>
</tr>
</thead>
<tbody>
<tr>
<td>#4</td>
<td>3</td>
<td>1,2,4,5,6,7,8,9,10</td>
<td></td>
<td></td>
<td>3,5/2</td>
<td>1,2,4,6,7,8,9,10</td>
<td></td>
<td>5/2</td>
</tr>
<tr>
<td>#7</td>
<td>1,2,3,4,7,8,9</td>
<td>5,6,10</td>
<td></td>
<td></td>
<td>1,2,4</td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,5,6,8,10</td>
<td>9</td>
</tr>
<tr>
<td>#11</td>
<td>3,6,10</td>
<td>2,4,5,7,8,9</td>
<td></td>
<td></td>
<td>4</td>
<td>2,5,7,9</td>
<td></td>
<td>3,8,10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>#12</td>
<td>4,8,9</td>
<td>6,7,10</td>
<td>2,3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,6,7/2,10</td>
</tr>
<tr>
<td>#3</td>
<td></td>
<td>1,2,3,4,5,8,9,10</td>
<td></td>
<td></td>
<td>2,8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td>1/2,2/3,10/3</td>
<td>1/3,2/3,3,4,5,8,9,10,10/3</td>
<td>1/2,2/3,10/3</td>
<td></td>
<td>5/3</td>
<td></td>
<td></td>
<td>4,5/3,8/2,9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,8/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,2,5/3,10</td>
</tr>
<tr>
<td>#9</td>
<td>1,2,2,3,4,5,9</td>
<td>2/2,8,10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2/2,5/3</td>
<td>1,3,5/3,9/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8,10</td>
</tr>
<tr>
<td>#14</td>
<td>1,2,3,4,5,8,9,10</td>
<td></td>
<td></td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#1</td>
<td>1,2,3,4,5,9</td>
<td>8,10</td>
<td></td>
<td></td>
<td>10/2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,2,3,4,5,9,10/2</td>
</tr>
<tr>
<td>#3</td>
<td></td>
<td>4,8,9,10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9,10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>#10</td>
<td>2/2,9/2</td>
<td>1,2/2,3,4,5,8,9,2,10</td>
<td></td>
<td></td>
<td></td>
<td>1,2/2,3,4,5,8,9,2,10</td>
<td></td>
<td>2/2,9/2</td>
</tr>
<tr>
<td>#15</td>
<td></td>
<td>2,9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,3,4,5,8,10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4,8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,9,10</td>
</tr>
<tr>
<td>#2</td>
<td>2,3,4,8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,3,4,8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,10</td>
</tr>
<tr>
<td>#5</td>
<td>1,3,4,5,10</td>
<td>2,8</td>
<td></td>
<td></td>
<td></td>
<td>3,5/2,10</td>
<td></td>
<td>1,5/2,8,2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,4,8/2</td>
</tr>
<tr>
<td>#8</td>
<td></td>
<td>2,3,4,5,9,10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4,10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,3,5,9</td>
</tr>
<tr>
<td>#13</td>
<td></td>
<td>9/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,2,3,4,5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/2,2,8,9,10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Item</td>
<td>Answer 1</td>
<td>Answer 2</td>
<td>Answer 3</td>
<td>Answer 4</td>
<td>Reason A</td>
<td>Reason B</td>
<td>Reason C</td>
<td>Reason D</td>
</tr>
<tr>
<td>------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>#4</td>
<td>3</td>
<td>1,2,4,5,6,7,8,9</td>
<td></td>
<td>3,7,9</td>
<td>2,4,5</td>
<td></td>
<td>1,6</td>
<td></td>
</tr>
<tr>
<td>#7</td>
<td>1,3,4,7,8,9</td>
<td>5,6</td>
<td></td>
<td>2/2,4,5,8</td>
<td>2/2,3</td>
<td>1,7,9</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>#11</td>
<td>3,4,5,7,8</td>
<td>1,2,6,9</td>
<td></td>
<td></td>
<td>6</td>
<td>1,2/2,3,4,5,7,8</td>
<td>2/2,9</td>
<td></td>
</tr>
<tr>
<td>#12</td>
<td>1,5,6</td>
<td>2,3,4,7,8,9</td>
<td>2,3</td>
<td>3,4</td>
<td>6</td>
<td></td>
<td>1,2,5,7,8,9</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>4,6</td>
<td>1,2,3,5,7,8</td>
<td></td>
<td>2/2,3,4,8</td>
<td>1,2/2,6,7</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td>1,2,3,4,6,7,8</td>
<td>5</td>
<td></td>
<td>1,3,4,8</td>
<td>2,6,7</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#9</td>
<td>1,2,3,4,7,8</td>
<td>5,6</td>
<td></td>
<td></td>
<td>1,2,3,4,7,8</td>
<td>5,6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#14</td>
<td>1,2,4,5,6,7,8</td>
<td>3</td>
<td></td>
<td></td>
<td>8</td>
<td>4</td>
<td>1,2,3,5,6,7</td>
<td></td>
</tr>
<tr>
<td>#1</td>
<td>1,2,4,5,6,7</td>
<td>3,8</td>
<td></td>
<td>8</td>
<td>3</td>
<td>1,2,4,5,6,7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>3</td>
<td>1,2,4,5,6,7,8</td>
<td>2,8</td>
<td>3</td>
<td>1,4,5,6,7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#10</td>
<td>1,2,3,4,5,6,7,8</td>
<td>1,2,3,4,5,6,7</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#15</td>
<td></td>
<td>1,2,3,5,6,7,8</td>
<td>4</td>
<td>3,4</td>
<td>1,2,6,8</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>4</td>
<td>1,2,3,5,8</td>
<td>6,7</td>
<td>4</td>
<td>1,2,5,6,7,3,8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>1,2,3,5,6,7</td>
<td>4,8</td>
<td></td>
<td>1,2,3,5,6,7</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#8</td>
<td>1,2,4,5,6,7,8</td>
<td>3</td>
<td></td>
<td>4/2</td>
<td>2</td>
<td>1,4/2,6,8,3,5,7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#13</td>
<td>4/2</td>
<td>1,2,3,4,2,5,6,7,8</td>
<td></td>
<td></td>
<td>1,2,6,7,8</td>
<td>3,5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Responses for “A” subjects on Furió and Calatayud questions

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer A</th>
<th>Answer B</th>
<th>Answer C</th>
<th>Answer D</th>
</tr>
</thead>
<tbody>
<tr>
<td>#11</td>
<td>1,8,9/3,10</td>
<td>9/3</td>
<td>2,3,4,5</td>
<td>9/3</td>
</tr>
<tr>
<td>#12</td>
<td></td>
<td></td>
<td>4/2,8</td>
<td>3,4/2,5,9,10</td>
</tr>
<tr>
<td>#13</td>
<td>8,10</td>
<td>4,5</td>
<td>3,9</td>
<td></td>
</tr>
<tr>
<td>#15</td>
<td></td>
<td></td>
<td>3,5,8,10</td>
<td></td>
</tr>
<tr>
<td>#16</td>
<td>10</td>
<td>8/2</td>
<td>3,5,9</td>
<td>8/2</td>
</tr>
<tr>
<td>#1</td>
<td></td>
<td></td>
<td>1,2,3,4,5,8,9,10</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>2,3,4,5,8,10</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>3,5,9,10</td>
<td>4</td>
<td>2,8</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>1,2,3,5,8,9,10</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td></td>
<td></td>
<td>2,3,4,5,8,10</td>
<td></td>
</tr>
<tr>
<td>#9</td>
<td>3,5,9,10</td>
<td></td>
<td>2,4,8</td>
<td></td>
</tr>
</tbody>
</table>
Responses for “B” subjects on Furió and Calatayud questions

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer A</th>
<th>Answer B</th>
<th>Answer C</th>
<th>Answer D</th>
</tr>
</thead>
<tbody>
<tr>
<td>#11</td>
<td>5,6</td>
<td></td>
<td>1,2,3,4,7</td>
<td>2,2,8</td>
</tr>
<tr>
<td>#12</td>
<td></td>
<td>4</td>
<td>5</td>
<td>1,2,3,6,7,8</td>
</tr>
<tr>
<td>#13</td>
<td></td>
<td>1,2,6,8</td>
<td>3,5,7</td>
<td></td>
</tr>
<tr>
<td>#15</td>
<td>5</td>
<td>3</td>
<td>2,6,8</td>
<td></td>
</tr>
<tr>
<td>#16</td>
<td>3</td>
<td>5</td>
<td>1,2,6,8</td>
<td></td>
</tr>
<tr>
<td>#1</td>
<td></td>
<td></td>
<td>1,2,3,4,5,6,7,8</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>1,2,3,4,5,6,7,8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>1,2,3,5,6,8</td>
<td></td>
<td>4,7</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>1,2,3,4,5,6,7,8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td></td>
<td></td>
<td>1,2,3,4,5,6,7,8</td>
<td></td>
</tr>
<tr>
<td>#9</td>
<td>1,2,3,5,7,8</td>
<td></td>
<td>4,6</td>
<td></td>
</tr>
</tbody>
</table>
BIBLIOGRAPHY


