Bridging the gap between structures and properties: An investigation and evaluation of students' representational competence

Sonia Underwood
Clemson University, sunderw@clemson.edu

Follow this and additional works at: https://tigerprints.clemson.edu/all_dissertations
Part of the Chemistry Commons

Recommended Citation
Underwood, Sonia, "Bridging the gap between structures and properties: An investigation and evaluation of students' representational competence" (2011). All Dissertations. 757.
https://tigerprints.clemson.edu/all_dissertations/757

This Dissertation is brought to you for free and open access by the Dissertations at TigerPrints. It has been accepted for inclusion in All Dissertations by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.
BRIDGING THE GAP BETWEEN STRUCTURES AND PROPERTIES: AN INVESTIGATION AND EVALUATION OF STUDENTS’ REPRESENTATIONAL COMPETENCE

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Chemistry

by
Sonia Miller Underwood
August 2011

Accepted by:
Dr. Melanie M. Cooper, Committee Chair
Dr. Gautam Bhattacharyya
Dr. Brian Dominy
Dr. Zahra Hazari
ABSTRACT

The heart of learning chemistry is the ability to connect a compound’s structure to its function; Lewis structures provide an essential link in this process. In many cases, their construction is taught using an algorithmic approach, containing a set of step-by-step rules. We believe that this approach is in direct conflict with the precepts of meaningful learning. From a sequential, mixed methods study, we found that students have much difficulty constructing these structures and that the step-by-step rules do not make use of students’ relevant prior knowledge. This causes students to develop “home grown” rules when unsure of how to progress with the construction process. It also became clear that most students are uncertain of the importance of Lewis structures since they perceive them as being useful only for obtaining structural information but not property information. Using responses from student interviews and open ended questions, the Information from Lewis Structures Survey (ILSS) was developed, validated, and found reliable to assess students’ representational competence by determining their understanding of the purpose of Lewis structures. Since students had many problems with the relationship of structures and properties, an alternative curriculum was evaluated to determine if it could help students develop a more meaningful understanding of this process. This instruction was part of a larger NSF-funded general chemistry curriculum redesign called Chemistry, Life, the Universe and Everything (CLUE). Using a control and treatment group, the effectiveness of this new curriculum was evaluated for two main aspects: 1. the students’ ability to construct Lewis structures using OrganicPad and 2. the students’ representational competence
using the ILSS. Through four main studies (a pilot study, instructor effect study, main study, and retention study), we found that the CLUE curriculum helps students develop more expert-like strategies for constructing Lewis structures and a better understanding of why these structures are important by encouraging more meaningfully learning.
DEDICATION

This dissertation is dedicated to my loving husband, Christopher, who has supported me for the last seven years, throughout undergraduate and graduate school, even with uncertainties in my life’s ambitions. He has truly been able to understand the importance of graduate school and the hard work it requires; therefore, I am honored to go through this process with him. I would also like to dedicate this to my family, especially my parents (Glenn and Linda Miller) and brother’s family (Michael, Michelle, and Ethan Miller) for all of their emotional support and continuous encouragement along with my late grandfather (Robert Kirkpatrick) that always encouraged the sciences.
ACKNOWLEDGMENTS

I would first like to acknowledge my advisor, Dr. Melanie Cooper, for all of her guidance, inspiration, and support. I am blessed to have had the opportunity to work with her for the last four and a half years. She truly made an impact in the person that I have become and for that, I am forever grateful. I would also like to acknowledge Dr. Zahra Hazari and Dr. Geoff Potvin for all of the knowledge they have provided me throughout graduate school and for going above and beyond to help me grow professionally and personally. I would also like to thank my other committee members, Dr. Gautam Bhattacharyya and Dr. Brian Dominy, for their help throughout graduate school. I would also like to give a special thank you to all of my current and previous group members, to Dr. Nathaniel Grove and Dr. Santiago Sandí-Ureña for their mentorship, to Caleb Hilley for all of his help analyzing data, to Sam Bryfczynski for all of his help and patience while we continually updated OrganicPad, to Barbara Bull for proof-reading this dissertation, and to all of the participants for making this research possible – the students, TAs, Mrs. Barbara Lewis, and Dr. Sean O’Connor. Also thank you to my wonderful cheerleaders, Kelly and Kaitlyn Dixon, especially near the end of this process.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE PAGE</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iv</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>I.  INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Research questions and goals</td>
<td>3</td>
</tr>
<tr>
<td>II. THEORETICAL FRAMEWORKS</td>
<td>6</td>
</tr>
<tr>
<td>The learning process</td>
<td>6</td>
</tr>
<tr>
<td>Ways people learn</td>
<td>8</td>
</tr>
<tr>
<td>Meaningful learning</td>
<td>9</td>
</tr>
<tr>
<td>Three domains of thought</td>
<td>10</td>
</tr>
<tr>
<td>Representational competence</td>
<td>11</td>
</tr>
<tr>
<td>Concluding remarks</td>
<td>13</td>
</tr>
<tr>
<td>III. A JACK OF ALL TRADES: USING ORGANICPAD</td>
<td>15</td>
</tr>
<tr>
<td>FOR TEACHING AND RESEARCH</td>
<td></td>
</tr>
<tr>
<td>OrganidPad’s tools</td>
<td>16</td>
</tr>
<tr>
<td>OrganidPad’s features</td>
<td>17</td>
</tr>
<tr>
<td>Validating collection results from <em>OrganicPad</em></td>
<td>30</td>
</tr>
<tr>
<td>Conclusions</td>
<td>30</td>
</tr>
<tr>
<td>IV. STUDENTS’ DIFFICULTIES WITH THE CONSTRUCTION PROCESS OF LEWIS</td>
<td>32</td>
</tr>
<tr>
<td>STRUCTURES</td>
<td></td>
</tr>
</tbody>
</table>
Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantitative study</td>
<td>34</td>
</tr>
<tr>
<td>Qualitative study</td>
<td>38</td>
</tr>
<tr>
<td>Conclusions</td>
<td>42</td>
</tr>
</tbody>
</table>

V. STUDENTS’ DISCONNECT BETWEEN STRUCTURES AND THEIR PROPERTIES ............................................ 44

Student think-aloud interviews ......................................... 45
Development of the Information from Lewis Structures Survey (ILSS) ........................................ 46
Validity and reliability of the ILSS ................................... 54
Conclusions ........................................................................... 58

VI. ALTERNATIVE APPROACHES FOR THE GENERAL CHEMISTRY CURRICULUM ........................................ 61

Education reform ................................................................. 61
Description of CLUE and Atoms First curricula ..................... 63
Organization of material for the different approaches ............... 66
Comparing instructional plans for Lewis structures and predicting properties ........................................... 68

VII. EVALUATION OF STUDENTS’ REPRESENTATIONAL COMPETENCE TO DETERMINE THE EFFECTIVENESS OF THE CLUE CURRICULUM ............................................. 73

Methodology for pilot and main study .................................. 73
Pilot study of the instructional plan ...................................... 76
Are the students’ improvements due to an instructor effect ......... 84
Main study of the instructional plan ..................................... 87
Do the students retain the knowledge? ................................. 106
Conclusions ......................................................................... 116
Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIII. CONCLUSIONS AND FUTURE WORK</td>
<td>119</td>
</tr>
<tr>
<td>Conclusions</td>
<td>119</td>
</tr>
<tr>
<td>Implications for teaching</td>
<td>124</td>
</tr>
<tr>
<td>Future directions</td>
<td>126</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>128</td>
</tr>
<tr>
<td>A: OrganicPad’s user manual</td>
<td>129</td>
</tr>
<tr>
<td>B: Multi-tiered feedback system</td>
<td>157</td>
</tr>
<tr>
<td>C: Versions and changes for the ILSS</td>
<td>159</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>161</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Comparison of general chemistry students’ exam and <em>OrganicPad</em> structures for validation measures</td>
</tr>
<tr>
<td>5.1</td>
<td>Summary of structural information obtained using Lewis structures</td>
</tr>
<tr>
<td>5.2</td>
<td>Summary of property information obtained using Lewis structures</td>
</tr>
<tr>
<td>5.3</td>
<td>Students’ understanding of the utilization of Lewis structures</td>
</tr>
<tr>
<td>6.1</td>
<td><em>Chemistry, Life, the Universe and Everything</em> chapter order of material instructed</td>
</tr>
<tr>
<td>6.2</td>
<td><em>Chemistry A Molecular Approach</em> chapter order of material instructed</td>
</tr>
<tr>
<td>6.3</td>
<td><em>General Chemistry: Atoms First</em> chapter order of material instructed</td>
</tr>
<tr>
<td>7.1</td>
<td>Comparison of pre-test assessments for pilot study</td>
</tr>
<tr>
<td>7.2</td>
<td>Statistical values for pilot study’s post-test <em>OrganicPad</em> structures</td>
</tr>
<tr>
<td>7.3</td>
<td>Statistical values for pilot study’s post-test ILSS</td>
</tr>
<tr>
<td>7.4</td>
<td>Comparison of pre-test assessments for instructor effect study</td>
</tr>
<tr>
<td>7.5</td>
<td>Comparison of pre-test assessments for main study</td>
</tr>
<tr>
<td>7.6</td>
<td>Statistical values for main study’s post-test <em>OrganicPad</em> structures</td>
</tr>
<tr>
<td>7.7</td>
<td>Statistical values for types of errors on the main study’s post-test <em>OrganicPad</em> structures</td>
</tr>
</tbody>
</table>
List of Tables (Continued)

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.8</td>
<td>Statistical values for types of errors on the main study’s post-test OrganicPad structure of CH₄O</td>
</tr>
<tr>
<td>7.9</td>
<td>Statistical values for the main study’s post-test OrganicPad structures including structures only missing lone pairs as correct</td>
</tr>
<tr>
<td>7.10</td>
<td>Statistical values for the individual types of information on the main study’s post-test ILSS</td>
</tr>
<tr>
<td>7.11</td>
<td>Statistical values for the categories of information on the main study’s post-test ILSS</td>
</tr>
<tr>
<td>7.12</td>
<td>Comparison of pre-test assessments for retention study</td>
</tr>
<tr>
<td>7.13</td>
<td>Statistical values for retention study’s beginning of the semester OrganicPad structures</td>
</tr>
<tr>
<td>7.14</td>
<td>Statistical values for retention study’s end of the semester OrganicPad structures</td>
</tr>
<tr>
<td>7.15</td>
<td>Percentage correct and statistical values for retention study’s end of the semester OrganicPad structures including structures only missing lone pairs as correct</td>
</tr>
<tr>
<td>7.16</td>
<td>Statistical values for retention study’s end of the semester ILSS</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Examples of different representations</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Example of textbook showing all three levels</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>Information processing model</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>The continuum from rote to meaningful learning</td>
<td>9</td>
</tr>
<tr>
<td>2.3</td>
<td>The interplay of instructor, student, and subject matter for meaningful learning</td>
<td>10</td>
</tr>
<tr>
<td>2.4</td>
<td>Johnstone’s three levels of chemistry</td>
<td>11</td>
</tr>
<tr>
<td>3.1</td>
<td><em>OrganicPad</em>’s versatility</td>
<td>17</td>
</tr>
<tr>
<td>3.2</td>
<td><em>Teacher-student interaction</em> feature with the teacher’s window and student’s window</td>
<td>19</td>
</tr>
<tr>
<td>3.3</td>
<td>Example of <em>contextual feedback</em> feature’s first tier, less specific</td>
<td>22</td>
</tr>
<tr>
<td>3.4</td>
<td>Example of <em>contextual feedback</em> feature’s second tier, more specific</td>
<td>23</td>
</tr>
<tr>
<td>3.5</td>
<td>An example of “molecule atom frequency mismatch” feedback</td>
<td>24</td>
</tr>
<tr>
<td>3.6</td>
<td>Example of the <em>grading</em> feature using <em>H₂O</em></td>
<td>25</td>
</tr>
<tr>
<td>3.7</td>
<td>Example of how a student’s replay is converted into a Markov model</td>
<td>27</td>
</tr>
<tr>
<td>3.8</td>
<td>Two students’ individual Markov models combined to form a larger Markov model</td>
<td>27</td>
</tr>
<tr>
<td>3.9</td>
<td>Example of the <em>Markov modeling</em> feature for <em>H₂O</em></td>
<td>28</td>
</tr>
<tr>
<td>3.10</td>
<td>Tags available for the <em>tagging</em> feature of <em>OrganicPad</em></td>
<td>29</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Number of students with each type of construction error</td>
</tr>
<tr>
<td>4.2</td>
<td>Average success rate versus number of atoms</td>
</tr>
<tr>
<td>4.3</td>
<td>Jack’s interview structure of C₃H₇NO</td>
</tr>
<tr>
<td>4.4</td>
<td>Ben’s altered structure of CH₄S</td>
</tr>
<tr>
<td>4.5</td>
<td>Kate’s interview structure of NH₂⁻</td>
</tr>
<tr>
<td>5.1</td>
<td>Structures of dimethyl ether and ethanol</td>
</tr>
<tr>
<td>5.2</td>
<td>An example of the coding feature for Ed’s Tools</td>
</tr>
<tr>
<td>5.3</td>
<td>The administered pilot version of the ILSS</td>
</tr>
<tr>
<td>5.4</td>
<td>The administered final version of the ILSS</td>
</tr>
<tr>
<td>5.5</td>
<td>The process for connecting structures and properties</td>
</tr>
<tr>
<td>5.6</td>
<td>Comparing second-semester organic and general chemistry students’ responses to the ILSS</td>
</tr>
<tr>
<td>5.7</td>
<td>ILSS reliability results for two similar groups of students</td>
</tr>
<tr>
<td>6.1</td>
<td>New instructional plan for Lewis structures</td>
</tr>
<tr>
<td>6.2</td>
<td>Diamond versus graphite</td>
</tr>
<tr>
<td>6.3</td>
<td>Three-dimensional representation of methane</td>
</tr>
<tr>
<td>7.1</td>
<td>Experimental design for the pilot and main studies</td>
</tr>
<tr>
<td>7.2</td>
<td>Comparison of percent correct for the pilot study’s post-test OrganicPad structures</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3</td>
<td>Examples of other valid Lewis structures for CH₃CO₂H and CH₃COOH</td>
</tr>
<tr>
<td>7.4</td>
<td>Percentage of students that selected each type of information for the pilot study’s post-test ILSS</td>
</tr>
<tr>
<td>7.5</td>
<td>Percentage of students that selected each category of information for pilot study’s post-test ILSS</td>
</tr>
<tr>
<td>7.6</td>
<td>Comparison of percent correct for the instructor effect study’s post-test OrganicPad structures</td>
</tr>
<tr>
<td>7.7</td>
<td>Distribution of the control and treatment groups’ majors for the main study</td>
</tr>
<tr>
<td>7.8</td>
<td>Percentage of students that selected each type of information for main study’s pre-test ILSS</td>
</tr>
<tr>
<td>7.9</td>
<td>Percentage of students that selected each category of information for main study’s pre-test ILSS</td>
</tr>
<tr>
<td>7.10</td>
<td>Comparison of percent correct for the main study’s post-test OrganicPad structures</td>
</tr>
<tr>
<td>7.11</td>
<td>Types of errors for the main study’s post-test seven harder OrganicPad structures</td>
</tr>
<tr>
<td>7.12</td>
<td>Types of errors for the main study’s post-test OrganicPad structure of CH₄O</td>
</tr>
<tr>
<td>7.13</td>
<td>Control group’s Markov model for the main study’s post-test OrganicPad structure of CH₄O</td>
</tr>
<tr>
<td>7.14</td>
<td>Treatment group’s Markov model for the main study’s post-test OrganicPad structure of CH₄O</td>
</tr>
<tr>
<td>7.15</td>
<td>Comparison of percent correct for the main study’s post-test OrganicPad structures including structures only missing lone pairs as correct</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.16</td>
<td>Percentage of students that selected each type of information for the main study’s post-test ILSS</td>
<td>102</td>
</tr>
<tr>
<td>7.17</td>
<td>Percentage of students that selected each category of information for the main study’s post-test ILSS</td>
<td>104</td>
</tr>
<tr>
<td>7.18</td>
<td>Comparison of the control and treatment groups on the structure-property final exam question</td>
<td>105</td>
</tr>
<tr>
<td>7.19</td>
<td>Comparison of the percent correct for the retention study’s beginning of the semester <em>OrganicPad</em> structures</td>
<td>109</td>
</tr>
<tr>
<td>7.20</td>
<td>Comparison of the percent correct for the retention study’s end of the semester <em>OrganicPad</em> structures</td>
<td>111</td>
</tr>
<tr>
<td>7.21</td>
<td>Percentage of students that selected each type of information for the retention study’s end of the semester ILSS</td>
<td>113</td>
</tr>
<tr>
<td>7.22</td>
<td>Percentage of students that selected each category of information for the retention study’s end of the semester ILSS</td>
<td>115</td>
</tr>
<tr>
<td>8.1</td>
<td><em>BeSocratic</em>’s versatility</td>
<td>127</td>
</tr>
</tbody>
</table>
CHAPTER ONE

INTRODUCTION

Chemistry is inherently abstract in nature and has an abundance of representations, which can make it seem like one is learning a new language (Orna, 1994; Markow, 1988). For example, there are many representations for the depiction of molecules: Lewis structure, ball and stick, space filling, dash-wedge, fisher projections, etc. (Figure 1.1). All of these representations have distinct intentions for their use; however, students do not always understand their purpose. Some of the difficulties that students experience with understanding these representations stems from their focus on the macroscopic level – things they can feel, touch, and smell – and their inability to relate to the microscopic (particulate) level – contains structures, molecules, and atoms (Johnstone, 2000; Johnstone, 1991). Since Johnstone first described these difficulties, textbooks have incorporated these different levels to help students relate between them (Figure 1.2). However, the manner that this has been incorporated does not aid in students comprehension of the relationship between structures and their properties.

Figure 1.1: Examples of Different Representations
Student difficulty with understanding representations could potentially cause misunderstandings and even further, misconceptions. Misconceptions can be defined as deeply-rooted incorrect facets of knowledge that are resilient to instructional confrontation and could serve as barriers to more profound understanding (Chi & Roscoe, 2002; Chi, 2008; Duit & Treagust, 2003). Students’ misconceptions have been found in almost every topic of chemistry (Kind, 2004), including chemical bonding (Taber & Coll, 2002) and particulate nature of matter (Harrison & Treagust, 2002). One example found at all levels, including graduate students, is with phase changes where many students believe that when water boils, the bubbles consist of hydrogen and oxygen gas instead of water vapor (Bodner, 1991; Kruse & Roehrig, 2005; Mulford & Robinson, 2002). It has also been found that students have difficulty understanding intermolecular forces.
Both of these misconceptions reemphasize the difficulties that students have with the particulate level due to its abstract nature.

**Research Questions and Goals**

Since research has shown that students have difficulties with the individual aspects involved in connecting structures and their properties, we wanted to develop a better understanding of how/if the students are making this connection process. Little research has been conducted on this interest (Schmidt, 1996; Shane & Bodner, 2006). Two main questions guided this research project: 1. How do students construct and utilize Lewis structures? and 2. Can an alternative instructional approach to teaching Lewis structure (Chemistry, Life, the Universe and Everything – CLUE) improve students’ construction ability and representational competence (the ability to pull together and transfer among multiple representations to explain a phenomenon) of Lewis structures (Kozma & Russell, 1997)?

In order to help answer these fundamental questions, four goals were created.

- Investigate students’ construction process of Lewis structures. Develop an understanding of how students construct Lewis structures using a sequential mixed method approach. Using OrganicPad (Chapter 3) will answer the question of “what” students are doing, while think-aloud interviews can explain the question of “why” students are constructing their structures in a particular fashion.
Investigate what students believe is the purpose of Lewis structures. Open-ended questions on *Ed’s Tools* (Chapter 4) and think-aloud interviews can be used to develop an understanding of what types of information students can obtain using a Lewis structure.

Develop a reliable and valid survey question to assess students’ representational competence. Using student responses from the second goal will allow for the evaluation of students’ understanding of structure and property relationships. For determining how large groups of students understand this connection, a survey was necessary. Through multiple administrations and alterations the survey can be proven to be reliable and valid.

Evaluate the CLUE curriculum, in particular the instructional plan for Lewis structures, to determine any increases in students’ representational competence. Through a pilot study and main study, students’ immediate improvement in structure construction and understanding of the purpose of these structures can be explored using a control and treatment group with pre- and post-test assessments. The students’ long-term effects can be evaluated through a retention study and, most importantly, an instructor effect study can verify that student changes are truly caused from instruction and not the instructor.

Chapter 2 includes the theoretical frameworks used for this research, while Chapter 3 describes the computer program *OrganicPad* and its many features used throughout this research project. Chapters 4 and 5 address the first three research goals and the first research question: how students’ construct and utilize Lewis structures. Chapter 6
describes an alternative approach for the general chemistry curriculum, CLUE, while comparing it to the other available curricula, Atoms First and traditional. Chapter 7 evaluates the CLUE curriculum for the connection of structures and properties through four different studies (pilot, instructor effect, main, and retention) while Chapter 8 draws conclusions based on the research from this project and includes details about its implications for instruction and future directions.
CHAPTER TWO
THEORETICAL FRAMEWORKS

The development of learning theories and interest in understanding how people learn can be found as far back as the days of Aristotle. More recently, this area of research has been influenced by pioneers such as Jean Piaget, B. F. Skinner, and David Ausubel. Ausubel was the most influential, in the development of the theory of meaningful learning. The subsumption theory, later known as assimilation learning theory, defines meaningful learning as a process of relating new knowledge to already relevant existing knowledge (Novak, 1977) or prior knowledge. This stems from the ideas of constructivism in that students are not “blank slates” to whom instructors can passively transfer knowledge (Locke, 2001), but instead “knowledge is constructed in the mind of the learner” (Ausubel, 1968; Bodner, 1986) and that learning is an active process.

The Learning Process

It is important to first examine how knowledge is constructed. Concepts are incorporated into our cognitive structure which is best defined as “the knowledge one possesses and the manner in which it is arranged” (White, 1979). Several researchers have assembled their own theories as to how information is processed (Atkinson & Shiffrin, 1968; Atkinson & Shiffrin, 1971); however, in chemistry education, Johnstone's theory is most often referenced. Using Johnstone’s version of the information processing model, Figure 2.1, prior knowledge, or information from the long-term memory (LTM), assumes an important role in determining the information that is allowed to enter the
working memory (WM) through the perception filter (Broadbent, 1958; Johnstone, 1997). This perception filter is controlled by one’s current knowledge and beliefs and is used to filter out extraneous stimuli (Johnstone, 2000). Therefore, subsequent learning that occurs is influenced through the interaction of prior knowledge with the new knowledge in the WM space (Johnstone, 1997), where all conscious cognitive processing occurs (Paas, Renkl, & Sweller, 2003). This space is limited and according to Miller, only about seven (plus or minus two) items can be held at a time when problem-solving or thinking and reasoning. The items held in the WM can be more resourceful when stored as chunks of information, which allows for an efficient use of this limited working space (Miller, 1956). This space is responsible for balancing the storage of information that must be held in the conscious memory, along with the actual processing abilities required to interpret, rearrange, compare, and prepare it for LTM storage (Johnstone, 1997). Therefore, if too many chunks of information are being held in the WM, little space remains to connect the new information with prior information (Johnstone, 2010). Once the information has moved from the WM space to the LTM, two occurrences can happen: 1. the information can interact with other information already in the LTM to serve as a linkage between smaller networks to produce larger networks or 2. if there is no information in the LTM, then the new information could remain in isolation or be forgotten (Gabel, 1999).
Ways People Learn

Two of the most discussed ways of learning are rote and meaningful. Rote learning occurs when new knowledge is acquired through memorization and arbitrarily incorporated into the learner’s cognitive structure (Novak & Gowin, 1985), while meaningful learning arises from the learner choosing to relate new material to their prior knowledge. There are three requirements for meaningful learning: 1. the learner must possess relevant prior knowledge – that is, the learner must have some existing knowledge that relates to the new information in some non-arbitrary manner, 2. the material must be perceived as meaningful – the new knowledge must be relevant to other knowledge, and 3. the learner must choose to learn meaningfully – “the learner must consciously and deliberately choose to relate new knowledge to knowledge the learner already knows in some nontrivial way” (Novak, 1998).

When considering meaningful learning versus rote learning, these concepts should be viewed as a continuum and not a dichotomy (Novak, 1977). This continuum, Figure 2.2, implies that most learning occurs in the fashion of rote learning (Novak, 1998).

Figure 2.1: Information Processing Model (Johnstone, 1997)
Therefore, if an instructor is to attain the goal of meaningful learning for their students, they should try to create instruction that provides for more creative production from students (Novak, 1998) through allowing them to think critically and learn how to problem solve (Hermann, 1969).

Figure 2.2: The Continuum from Rote to Meaningful Learning (Novak, 1998)

Meaningful Learning

To further indicate the instructor’s role in students choosing to learn meaningfully, Figure 2.3 shows the interplay of three main elements: the learner, the teacher, and the subject matter. This concept map highlights that the instructor should select meaningful material that is hierarchically organized (new information is an extension from previously learned knowledge) and assess the students’ prior knowledge
so that the instructor can help bridge how the students’ prior knowledge fits together with the new material being learned. The instructor should also encourage the students to learn meaningfully and discourage rote learning (Novak, 1998). If one or more of these requirements are not fulfilled, a student might resort to merely utilizing rote memorization.

Figure 2.3: The Interplay of Instructor, Student, and Subject Matter for Meaningful Learning (Novak, 1998; Bretz, 2001)

Three Domains of Thought

One reason for students’ difficulty in understanding meaningful connections within chemistry is due to its abstract and heavily representative nature. Johnstone defines three main levels of thought, shown in Figure 2.4: macroscopic, sub-microscopic (particulate), and symbolic (Johnstone, 1991). He defines the macroscopic level to include anything that can be seen, touched, and smelled, while the particulate level includes atoms, molecules, ions and structures, and the symbolic level includes symbols,
formulae, equations, etc. (Johnstone, 2000). Novices encounter a great deal of difficulty in transferring between the three levels, while experts tend to move easily among them simultaneously. This difference is believed to be because novices mostly think in the concrete macroscopic level as opposed to the other two more abstract levels of thought (Johnstone, 1991) and their uncertainty of what the submicroscopic and symbolic mean. Most instruction occurs in the most abstract form, the symbolic domain, which can become troublesome, especially since it is often assumed that students are making these connections by themselves (Gabel, 1999).

![Figure 2.4: Johnstone’s Three Levels of Chemistry](image)

**Figure 2.4: Johnstone’s Three Levels of Chemistry** (Johnstone, 1991; Gabel, 1999)

**Representational Competence**

Johnstone’s ideas about how novices and experts differ in their abilities to incorporate these three domains parallel Kozma and Russell’s findings in their study of how both groups handle a variety of chemistry representations (Kozma & Russell, 1997). They state experts have knowledge that “consists of a large number of interconnected elements that are stored and recalled as extended, coherent chunks of information,” while novices have “unconnected fragments that correspond to common experiences with the everyday world” (Kozma & Russell, 1997). These fragments of knowledge are also referred to as phenomenological primitives or “p-prims” (diSessa & Sherin, 1998).
The differences between experts and novices in their representational competence have been studied (Wu, Krajcik, & Soloway, 2001; Kozma & Russell, 1997; Chi, Feltovich, & Glaser, 1981; Kohl & Finkelstein, 2007), along with the progression of novices to experts (Stains & Talanquer, 2008; Stains & Talanquer, 2007) and how novices can attain representational competence (Schank & Kozma, 2002; Wu, Krajcik, & Soloway, 2001). The term representational competence can best be defined as “a set of skills and practices that allow a person to reflectively use a variety of representations or visualizations, singly and together, to think about, communicate, and act on chemical phenomena in terms of underlying, aperceptual physical entities and processes” (pg. 131) (Kozma & Russell, 2005). Therefore, an individual has the ability to portray a concept in various ways without losing their overall understanding. Beginning with the least sophisticated level of comprehension, where a person’s focus is on physical features of the representation to derive meaning, and increasing to the highest level of understanding, where a person can pull together and transfer among multiple representations to draw conclusions or make predictions about a phenomenon (Kozma & Russell, 1997), the five levels of comprehension are: 1. representation as depiction, 2. early symbolic skills, 3. syntactic use of formal representations, 4. semantic use of formal representations, and 5. reflective, rhetorical use of representations (Kozma & Russell, 2005). It is important to note that even if a person has a high level of representational competence with one concept, does not mean they have a similar competency with a different concept.

A focus on structural features can inhibit a novice’s ability to develop a robust conceptual understanding. This becomes problematic since “the use and understanding
of a range of representations is not only a significant part of what chemists do—in a profound sense it is chemistry” (pg. 17) (Kozma, 2000). Therefore, the use of visual representations can further promote the connection of new knowledge with previous knowledge (Cook, 2006; Roth, Bowen, & McGinn, 1999) for the organization of difficult concepts.

**Concluding Remarks**

Novak encapsulates all of the previously discussed theories best with this quote about the important of prior knowledge and how it influences meaningful learning (Novak, 1998).

*The more we learn and organize knowledge in a given domain, the easier it is to acquire and use new knowledge in that domain. The curse is that when we try to learn new knowledge in a domain where we know little, and/or what we know is poorly organized, meaningful learning is difficult, usually time consuming, and tiring. Too often, we escape the challenge by resorting to rote learning, even though we know that what we learn will soon be forgotten and it will not be of value in future learning. Such fraudulent learning may allow us to pass school exams, but contribute little or nothing to future learning or acting (p. 24)*

Meaningful learning and representational competence is not something that comes easy but is something that must be embraced by the learner and encouraged by the instructor. Therefore, representational competence can be encouraged through the construction of
meaningful connections among one's own knowledge so that one can seamlessly transition between different types of information.
Instructors currently have many options for using technology in their classroom: videos to show reactions that might be too dangerous to demonstrate, personal response systems (i.e. clickers (Caldwell, 2007)) to evaluate students’ understanding, and animations to represent molecular level changes. No matter how one decides to use technology in the classroom, it is unlikely that it is non-existent. For chemistry, visualization tools have become commonly used to help students understand how molecules interact on the molecular level (Tasker & Dalton, 2006) since the abstract nature of these interactions cause students much difficulty. Because chemists function in a representationally intense field and typically use two-dimensional structures as their communication language, it can be very beneficial when technology transitions between these two domains.

Currently, there are a number of computer applications available that allow users to construct structural representations (CambridgeSoft, 2010; Pearson Prentice Hall, 2009a; Pearson Prentice Hall, 2009b); although for the purpose of educational research, these may not be very useful. The applications designed for the practicing chemists typically present users with a wide range of drop-down menus and/or construction options that could be overwhelming for a student. On the other hand, structure drawing programs specifically designed for the learner often impose restrictions on the user’s construction process. For example, some provide students with a grid to place their
atoms in order to limit the number of bonds for each atom, and typically present a rather rigid interface (Cooper, et. al., 2009). Although these programs are useful, they do not provide an environment where novices can construct what they envision the structure to be. In order to provide an alternative, a new computer application, OrganicPad, was developed to allow research into how students actually construct structures and to provide a free-form construction environment (Cooper, et. al., 2009; Cooper, Underwood, et al., 2010). That is: to provide students with the freedom to construct their structures without any restrictions. For example, the program will allow students to construct their Lewis structure containing a carbon with six bonds – and provide the appropriate feedback. By removing these restrictions, OrganicPad permits the researcher or instructor to develop a better understanding of how the students’ behave “in the wild.”

OrganicPad is designed so that it can interpret the construction of line structures and Lewis structures, and even mechanisms (Figure 3.1) using graph isomorphism algorithms (Toran, 2004). While OrganicPad was developed for the tablet-PC, it can instead be used with a WACOM slate, mouse, or trackpad. It is currently available for free download at www.clemson.edu/organicpad.

OrganicPad’s Tools

Upon first opening OrganicPad, the user is faced with an open canvas upon which to draw, and a pallet of tools as shown in Figure 3.1. The tools available are Draw, Push, Erase, Pen, Select, 3D, Undo, Check, Reset, and the Periodic Table (Cooper, et al., 2009; Cooper, Underwood, et al., 2010). Step-by-step instructions for these tools are
located in the User Manual, Appendix A. When creating the interface of this program and the available tools, we wanted to maintain a relatively small learning curve so that the user is not focused on how to maneuver within the program.

**OrganicPad’s Versatility**

**OrganicPad’s Features**

*OrganicPad* has many features for the instructor and/or researcher that will be referenced in future chapters. Their detailed step-by-step instructions can also be found in Appendix A.

**Replay Capability Feature**

One of *OrganicPad’s* most important features is its ability to record and replay every stroke that the student writes on the screen (Cooper, et al., 2009; Cooper, Grove, et al., 2010). The *replay* feature provides a non-intrusive way to observe the students during their structure or mechanism construction process. This is important since it
allows the researcher to understand how students behave “in the wild,” rather than in a less naturalistic environment such as an interview situation where the very fact of being observed may affect how the student performs. Using this feature, researchers can identify the order in which students construct their structures, for example, if the bonds were drawn before the atoms or vice versa, and difficulties that arise during the construction process. A glimpse into the students’ thought process while they are drawing structures (for example, if they realize something is wrong and erase it to start again) can indicate to the teacher/researcher a topic/concept that requires attention (Bryfczynski et al., 2010).

**Teacher-Student Interaction Feature**

In the classroom, OrganicPad has the ability to connect the instructor’s computer to all of the student’s computers. The *student-teacher interaction* feature, shown in Figure 3.2, provides live feedback in the classroom for both students and instructors (Cooper, et al., 2009; Cooper, Underwood, et al., 2010). This feature can be useful to determine if concepts are understood by students once some initial instruction has been given. For this interaction, students can either participate individually or in a small group (usually not more than three so that each student can see the screen) depending on available resources. This feature allows for the instructor to grade the students’ structures automatically and receive data in the form of a pie chart to depict the proportions of correct and incorrect structures (Cooper, et al., 2009).
By looking through the students’ structure submissions, instructors can identify and correct common errors the students are making during the classroom lecture. For example, we have observed (from watching replays of students submissions) that students often have difficulty constructing the Lewis structure for the condensed chemical formula of methanol, CH₄O (Cooper, Grove, et al., 2010). A common problem that students have with this structure is the placement of oxygen as a terminal atom instead of the hydrogen. Use of this feature in the classroom setting could allow for an early detection of errors and indicate to the instructor perhaps a more in-depth discussion might be needed. There is also an anonymous button during these interactions that can be selected to allow the instructor to display a particular student’s structure. Another beneficial aspect of this feature is that as students construct their structures, the instructor can move the cursor over a student’s name to view what the student is currently drawing (Cooper, et al., 2009); this can be useful both to verify that students stay on task and to monitor their progress. It should be noted that if students do not connect the atoms in their structure, it
would be counted as incorrect unless the instructor selects each of those structures as a solution.

**Quiz Feature**

The *quiz* feature is one of the most frequently used features of *OrganicPad* since it allows researchers/instructors to create questions beforehand so that students can work through them individually at their own pace either in or out of class time. With this feature, students do not receive any feedback as they construct and submit their responses in the form of structures or mechanisms. The researcher can view students’ replays to develop a better understanding of how the students construct their structures or mechanisms without any intervention or influence from the program.

**Tutorial Feature**

When initially using *OrganicPad*, students are asked to complete a short tutorial in order to become familiar with how the program recognizes hand-drawn characters. This is because *OrganicPad* requires the user to pause after each group of strokes to allow for recognition of an atom; for example, when drawing the H for hydrogen. In a tutorial students are not shown how to construct a certain structure, rather they are asked to draw, for example, fluorine with eight electrons and a negative charge. The purpose of this exercise is to introduce the user to the capabilities of the program. The *tutorial* feature can be used separately or in conjunction with the *quiz* feature.
One of the most important features of OrganicPad is the ability to provide tiered contextual feedback to students as they construct their structures (Cooper, Underwood, et al., 2010). Rather than merely telling students whether the structure is right or wrong, students are provided with prompts that are designed to make them think about what they are doing, be more metacognitive. The goal is that the student will eventually be able to correct their errors themselves, rather than following instructions. Metacognition is most commonly defined as the knowledge and regulation of one’s own cognitive system (Brown, 1987) although it can be more easily understood as the “awareness of how one learns; awareness of when one does and does not understand; knowledge of how to use available information to achieve a goal; ability to judge the cognitive demands of a particular task; knowledge of what strategies to use for what purposes; and assessment of one’s progress both during and after performance” (Gourgey, 2001).

The prompts provided to the students are multi-tiered in that they begin with vague, although useful, feedback and transition to more specific feedback as the student continues to struggle (Cooper, Underwood, et al., 2010). Since this feature is designed to guide students towards a more metacognitive state, OrganicPad will never give students the answer. An example of a first and second tier feedback to encourage the student to think about valence electrons is shown in Figures 3.3 and 3.4. (Note that the feedback shown in these figures have been magnified for easier viewing). This system is currently only accessible for modifications through the programming interface; however, it was
designed to have universal responses that address most errors that could be encountered.

The logic of the multi-tiered feedback design is described in Appendix B.

Figure 3.3: Example of Contextual Feedback Feature’s First Tier, Less Specific
Figure 3.4: Example of Contextual Feedback Feature’s Second Tier, More Specific

The contextual feedback feature can be used within the quiz feature by selecting the “require correct” button and “allow students to use check button.” Currently, we use the contextual feedback feature for the construction of structures and it can recognize both line structures and Lewis structures. An example of feedback that would be given to a student that did not use the correct number and types of elements is shown in Figure 3.5.

To calculate the total number of valence electrons, remember H has 1 valence electrons and O has 6 valence electrons.

Draw the Lewis structure for $\text{H}_2\text{O}$. When finished drawing your structure, click the check button.
Once the students submit their structures, there are multiple methods to analyze the results; one such feature is grading (Bryfczynski et al., 2010). When using this feature, the program automatically groups together structures that are constructed in the same manner and presents the instructor/researcher with an assortment of different structures to select which ones are correct. For example, Figure 3.6 shows the two unique structures that second-semester general chemistry students ($N = 17$) constructed when asked to draw the Lewis structure for $\text{H}_2\text{O}$. If the structure contains any
unconnected bonds, the program would recognize this as a different structure from one
where all of the bonds are connected. OrganicPad does not differentiate structures based
on positions and orientation of atoms; instead, the equivalence is determined by the
connections among the atoms. The numbers inside the boxes in Figure 3.6 represent the
quantity of students that drew that particular structure. After the instructor/researcher
selects the structures that are deemed “correct” for each question and clicks Done, the
program will automatically grade the students’ structures. The program then marks all of
the students that drew the “correct” structures as correct, indicated with a value of 1, and
the other students would be incorrect, indicated with a value of 0. These results are then
provided in table format to the user, which can be exported into Excel.

![Figure 3.6: Example of the Grading Feature Using H₂O](image)

*Markov Modeling Feature*

While the *replay* feature (described above) is beneficial to determine how each
student constructs their structure or mechanism, it is a very time-consuming process to
replay the construction processes of a large group of students. The *Markov modeling*
feature can help alleviate this problem by providing the user a way to visualize how a group of students construct a specific structure (Bryfczynski et al., 2010; Cooper, Underwood, et al., 2010).

Our Markov models are graphic representations of all the possible paths that students may take in their solution process. The Markov models are products of the Markov property, which simply states “future states of a system are only dependent on the current state.” For our application, this translates to “all of the future partial structures a student will draw only depends on their currently drawn structure.” While this may not necessarily be true (as student may be thinking several structural steps ahead), creating models with this property begins to show insight into student thinking.

Our Markov models are constructed by combining student replays together into a larger map structure. Each replay sequence can be represented by a series of partial solutions (structure). An example of such a series is shown below in Figure 3.7. We then use the Markov property to create directed paths from our series. Figure 3.7 shows the series transformed into a directed path. Each path now has states (partial solutions) encapsulated within boxes. In addition, directed arrows connect these states and are labeled with the frequency of students who made that transition and the probability of that state transition. Since our example only contains one student and there were no repeated structures, all of the arrows are labeled with 1 to indicate there is a 100% chance of transitioning between states. Once multiple series have been converted to this representation, the multiple paths are combined together into a larger map and the state transitions are updated accordingly. Figure 3.8 shows an example of two students’
Markov models combined to form a larger Markov model. Note the points of divergence and convergence in the model, which signify places where student solved the problem in different ways.

Figure 3.7: Example of How a Student's Replay is Converted into a Markov Model: States Being Represented by Partial Solutions and Transitions According to How the Student Moved from One Partial Solution to Another

Figure 3.8: Two Students’ Individual Markov Models Combined to Form a Larger Markov Model

Another example of the Markov modeling feature for H₂O, Figure 3.9, shows the construction process for a larger group of second-semester general chemistry students (N = 17). This feature helps determine how a group of students construct a given structure as well as guide the development of the tiers for the contextual feedback feature described above.
Figure 3.9: Example of the Markov Modeling Feature for H₂O

When using a Markov model to determine how a given group of students construct a particular structure, the researcher can look for a couple of different aspects depending on their research goals. For example, if a researcher needs to know if a particular step is problematic, they can search for commonalities by looking for converging areas (as described above), or states, where most students arrive. The state “H-O-H” in Figure 3.9, would be considered a converging area, however, it is not a problematic state. By identifying these common problematic states, a researcher could further investigate any causes and could use this error as a guiding point for prompting in the contextual feedback feature. It might also be important to determine the probability of students arriving at a correct structure if they have difficulty with their construction process. In order to simplify the Markov model some of the less common pathways can be removed with the slider control. This allows for a clearer visualization of the most important pathways used by students for a particular structure.
Tagging Feature

The last way to analyze the data using OrganicPad is the tagging feature, which can be used for coding common errors. Using this feature the researcher can select the appropriate tags provided to them for each of the unique structures. Figure 3.10 displays the eleven codes that are currently available. For example, the most widespread problem that students’ exhibit is writing the correct atom connections in the structure due to their uncertainty about where to begin, this would be tagged as “atom connection arrangement.” Most of the tags are self-explanatory except for saturation problem, which indicates that the student’s structure contains eight electrons around every atom regardless of the number of possible valence electrons. It should be noted that it is possible for a structure to contain more than one type of error. The tagging feature allows for a more accurate and time-efficient coding process.

![Figure 3.10: Tags Available for the Tagging Feature of OrganicPad](image)

- 29 -
Validating Collection Results from OrganicPad

While OrganicPad is an excellent tool for recording and analyzing student structural data, it is important to know if the majority of students take the assignments seriously. A group of 44 first-semester general chemistry students’ submitted structures on OrganicPad were compared to their answers from an exam given that same week. In both of these situations, the students were asked to construct a Lewis structure from specific chemical formulas: CO$_2$ and CH$_3$OH. Table 3.1 shows the percentage of students that constructed the structures correctly for each occasion. A Wilcoxon Signed Rank test for each structure revealed that the students' construction ability on OrganicPad and on their exam was equivalent. Therefore, we concluded that the students are taking OrganicPad seriously and submitted structures are actually a true representation of typical student performances.

Table 3.1: Comparison of General Chemistry Students’ Exam and OrganicPad Structures for Validation Measures

<table>
<thead>
<tr>
<th>Chemical Formula</th>
<th>Mean Percent Correct for Exam</th>
<th>Mean Percent Correct for OrganicPad</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>68.2</td>
<td>70.5</td>
<td>0.74</td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>77.3</td>
<td>79.5</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Conclusions

Whether for research and/or teaching purposes, OrganicPad accommodates a variety of needs. Its various features make it a versatile tool for the researcher and/or the instructor to understand students’ structure construction process. Most all of the features
described in this chapter have been utilized in some manner and will be referenced to in subsequent chapters.
CHAPTER FOUR

STUDENTS’ DIFFICULTIES WITH THE CONSTRUCTION PROCESS OF LEWIS STRUCTURES

Different types of chemical representations can convey various amounts of information about compounds. Typically, Lewis structures are the first structural representation that students encounter with some type of property information. We define Lewis structures as structures that show the number of bonds, lone pairs, and connectivity in a structure. Currently, students learn how to construct Lewis structures using a set of rules: 1. create the skeletal structure for the molecule, 2. calculate the total number of valence electrons for the Lewis structure, 3. distribute the available electrons among the different atoms to give as many octets as possible, remember that hydrogen has a duet, and 4. place double or triple bonds for any atoms that lack octets to form octets as necessary (Tro, 2008). There is a vast amount of literature currently available for methods to help students construct Lewis structures (Ahmad & Omar, 1992; DeKock, 1987; McGoran, 1991; Carroll, 1986; Ahmad & Zakaria, 2000; Clark, 1984; Eberlin & Monroe, 1982; Imkampe, 1975; Lever, 1972; Malerich, 1987; Miburo, 1998; Pardo, 1989; Zandler & Talaty, 1984). However, most of these approaches usually comprise empirical step-by-step rules (i.e. octet rule, valence electron tally, and formal charge) which only differ slightly from each other, and are not methods validated through research.

Despite the numerous rule-based methods available and an insistence by one author that “if students follow a set of rules faithfully, the difficulties...[with student
understanding] should not arise” (Packer & Woodgate, 1991), the construction of valid Lewis structures remains difficult for many students. One suggestion for the causes of this struggle is the inconsistencies in the way Lewis structures, formal charges, and the octet rule are introduced in textbooks (Purser, 1999). To compound this issue, students are also faced with many exceptions to these step-by-step rules described above. For example, the octet rule only works for most of the second row of the periodic table since elements in periods 3-7 are allowed to have “expanded octets.” These elements require a separate set of rules (Maleric, 1987; Suidan et al., 1995), along with different sets needed for radical species, polyatomic ions, and incomplete octets (Tro, 2008).

We believe that students’ difficulties with the construction of Lewis structures arise from the rules themselves not being meaningful to the students. The first rule of meaningful learning requires that the students must possess prior knowledge that relates to the new information in a non-trivial manner (Novak, 1998). For example, take the worked problem of constructing carbon dioxide and ammonia in Tro’s *General Chemistry* (Tro, 2008). The textbook states that carbon is the central atom for CO₂ because it is the least electronegative atom, while for NH₃, nitrogen is the central atom since hydrogen is always terminal. Although this reasoning for the individual structures might be true, there is an apparent contradiction since nitrogen is more electronegative than hydrogen. It should be noted that the book does not explain why the least electronegative atom is placed in the center or why the hydrogen is always terminal, which can become problematic since students have not learned the relevant prior knowledge of why atoms are arranged in this specific formation. Unfortunately, this can
encourage students to choose rote memorization for learning how to construct the skeletal structure of molecules. Some textbooks ignore the placement of atoms in the structure altogether (Zumdahl & Zumdahl, 2000).

**Methodology**

To improve our understanding of the construction process for Lewis structures we implemented a “sequential mixed-method” (Tashakkori & Teddlie, 1998) also known as “two-phase” (Creswell, 2009) design. The quantitative portion of this study utilized *OrganicPad* to determine how students’ constructed Lewis structures and to identify any complications that occurred during the construction process. Once we understood the types of difficulties students have with the construction process, think-aloud interviews were conducted for the qualitative portion of this study to further understand why students were having such difficulties.

**Quantitative Study**

In Fall 2008, first-semester organic chemistry students (*N* = 70) were asked to construct a Lewis structure for nine different chemical formulas using the *quiz* feature of *OrganicPad* (Chapter 3). The nine chemical formulas given (CH₄O, CH₃COOH, CH₂O, HCN, CH₃OH, CH₆N⁺, C₂H₅O⁻, CH₃O⁺, and C₂H₅O₂⁻) were chosen because of their range of structural characteristics such as functional groups, the inclusion of heteroatoms, charges, and different number of carbon atoms (Cooper, Grove, et al., 2010). All of the structures should be reasonable since the participants were organic chemistry students.
and they had previously covered the topics of Lewis structures and functional groups. Each structure was analyzed to determine its correctness using our working definition of a Lewis structure. It should be noted, however, that if the student drew the Lewis Electron Dot structure, (i.e. they drew all the bonds as shared electrons) their structure was also accepted as correct. Note that in some cases, students did not submit a final answer for the Lewis structure tasks, thus, explaining the apparent discrepancy between the number of submitted structures (527) and the total possible (630). For the structures submitted, 338 (64.1%) were considered correct while the other 189 (35.6%) were incorrect (Figure 4.1), which was troubling given that these participants used structures routinely in their study of organic chemistry and had previously learned this material in general chemistry.

![Figure 4.1: Number of Students with Each Type of Construction Error](image-url)
When analyzing the students’ incorrect structures for possible errors, several trends emerged as shown in Figure 4.1. One of the most common errors involved difficulties with the first step in the construction process, determining a correct skeletal structure. This process places students in a “catch 22” situation because one cannot really know how to arrange the atoms in a structure until they have been correctly ordered. This has been equated by Taber to a form of intellectual “bootstrapping” (Taber, 2001).

In other words, although we may think of chemistry as being a logical subject, many chemical concepts can not be learnt in an entirely logical manner, at least not in terms of clearly following deductively from previously accepted ideas and/or interpretation of empirical evidence (p.125).

The other common error occurred when students forgot to place non-bonded electrons (lone pairs) on their structures. One possible explanation for why these organic students leave off their lone pairs could be because they have already been introduced to Kekulé structures, Lewis structures without lone pairs. Another explanation might be that students were overwhelmed during the construction process and forgot this last step. However, we determined that students were more cautious with the proper electron arrangement on carbon, while heteroatoms like nitrogen and oxygen seemed to cause more uncertainty. As shown in Figure 4.1, the number of occurrences for difficulties with heteroatoms is twice that of carbon.
Another interesting effect is shown in Figure 4.2. A significant decrease in the students’ ability to construct a valid Lewis structure was evident when the chemical formula increased from six to seven atoms. This drop in success rate coincides with a change from a one carbon compound to a two carbon compound (Cooper, Grove, et al., 2010) – again a rather troubling finding since most organic (not to mention all biological) compounds contain more than one carbon atom.

![Figure 4.2: Average Success Rate Versus Number of Atoms](image)

Watching the OrganicPad replays of the students’ structures showed that many students seemed to place their atoms randomly. There was little evidence to support the premise that students acknowledge and use functional group information when constructing their structures unless the structure included specific structural cues (for example, CH$_3$OH). From the replays, it was also apparent that there was some confusion about how to handle charges since many students were removing or adding an electron after the completion of their structure, resulting in radical species (Cooper, Grove, et al.,
With an understanding of how students were going through the construction process for Lewis structures, it was imperative to determine why the students were making these types of errors and having difficulties in arriving at the correct structure.

**Qualitative Portion**

To determine why the students were making the errors described above, think-aloud interviews were conducted during the Fall 2008 and Spring 2009 semesters. Think-aloud interviews (Bowen, 1994; Patton, 2002) were conducted with three general chemistry students, seven organic chemistry students, two junior and three senior students enrolled in higher level chemistry courses, six graduate chemistry students, and six chemistry faculty members. For these interviews, the participants were asked to explain their thought process as they constructed a series of Lewis structures: \( \text{NH}_2^-, \text{NO}, \text{CH}_4\text{S}, \text{C}_2\text{H}_6\text{O}, \text{and C}_3\text{H}_7\text{NO} \) (Cooper, Grove, et al., 2010). If at any point the interviewee paused or described something unclearly, the interviewer would ask follow-up questions for clarity. The interviews lasted anywhere from 20 to 60 minutes per person, depending on the amount of elaboration and whether the participant encountered difficulties during the construction process. All of the names in this chapter are pseudonyms and all of the structures were re-created by the interviewers to comply with the IRB regulations and ensure student anonymity.

To analyze the interview results, we used a grounded theory approach, which can best be described where “one does not begin with a theory, then prove it. Rather, one begins with an area of study and what is relevant to that area is allowed to emerge”
(Fraenkel & Wallen, 2003). Using this method, two broad categories emerged for how students constructed their Lewis structures. The first being instructional-based strategies, consisting of rules that at some point were taught to the students, such as the octet rule, resonance, determining the central atom, and valence electron tally. The second category was home grown strategies, meaning that the students were utilizing procedures that had not been explicitly taught to them. Four types of home grown rules were identified: trial and error, symmetry, connectivity, and previous knowledge. Students may have created these rules as a result of not knowing what to do during the construction process.

One example of connectivity came from Libby, a general chemistry student, who was constructing a Lewis structure for C₂H₆O. She stated that “well, it has two carbons that are going to be attached to each other; it’s gonna be a carbon chain.” Although this did not cause problems for her when creating the structural isomer ethanol, this “rule” would not allow her to create the other structural isomer, dimethyl ether. Another example comes from Jack, an organic chemistry student, who was trying to construct a Lewis structure for C₃H₇NO. He stated that “I always feel like the most common way would just be in one chain with all the main atoms in one row…just write it all out” (Cooper, Grove, et al., 2010). The Lewis structure he created is shown in Figure 4.3. Again, this uncertainty for how to arrange atoms becomes quite clear as students start to generate their own rules to determine the skeletal structure.
Symmetry was another rule commonly invoked during these interviews. An example of this comes from Jack when he discussed his structure for $\text{C}_2\text{H}_6\text{O}$ (Cooper, Grove, et al., 2010), “symmetry always seems to lead to the right answer with chemistry…it seems like it would be stable if it were more symmetrical.” In Jack’s case, the use of symmetry was helpful since he constructed a correct Lewis structure; however, for Ben, a general chemistry student, it was not as successful. Ben originally constructed a valid Lewis structure for $\text{CH}_4\text{S}$, which contained three hydrogens on the carbon and one hydrogen on the sulfur; however, this structure was troublesome to him because it lacked symmetry (Cooper, Grove, et al., 2010). His altered structure, shown in Figure 4.4, contained the symmetry he desired but was incorrect.

By observing students construct their Lewis structures during the think-aloud interviews, we also noticed errors caused by the rules themselves. For example the “octet rule” caused a number of recurring problems, particularly with nitrogen and oxygen, since a number of students constructed structures containing expanded octets. One
explanation for students’ difficulty with this comes from Kate, an organic chemistry student. Her structure, shown in Figure 4.5, was depicted with ten electrons, but to her it only contained eight. She believed that only one electron in the covalent bond is counted towards that atom’s valency:

![Figure 4.5: Kate’s Interview Structure of NH₂⁻](image)

**Figure 4.5: Kate’s Interview Structure of NH₂⁻**

**Interviewer:** So, how many electrons are in those bonds that you’re drawing?

**Kate:** One. Like, there’s one here and one there [Kate proceeds to draw two electrons in the bond – one next to the hydrogen; the other next to the nitrogen].

**Interviewer:** So, if you’re counting from the perspective of the nitrogen, how do those electrons count?

**Kate:** Well, the lone pairs are two electrons and the bonds are one electron each.

**Interviewer:** Okay. So, the nitrogen has one of the electrons from the bond and then the hydrogen has the other?

**Kate:** Yeah.

One possible explanation for this confusion could emanate from the way formal charges are calculated. The formal charge for a particular atom is calculated from the following equation:

\[
FC = (\text{valence } e') - (\text{non-bonded } e') - \frac{1}{2} (\text{bonded } e')
\]
The misunderstanding can arise from how some count the bonded electrons. Some approaches count only one electron from each bond instead of counting the bond as two electrons and then dividing; however, this hypothesis would have to be further studied.

Conclusions

Currently, there exists a vast literature describing “new and improved” methods for constructing Lewis structures. All of these methods are similar in that they contain a list of rules for students to follow. To compound matters, these rules often have a list of exceptions such as how to handle expanded octets or polyatomic ions. The results from OrganicPad and the think-aloud interviews showed that students have great difficulty with the construction process. One of the most common problems that became evident from this study was students’ difficulty in determining the skeletal arrangement of the structure, which is the first step in the construction process. This difficulty may well result from success only coming to the individual who already knows how to arrange the atoms.

During the construction process for the think-aloud interviews, it was startling that some students created their own rules for constructing Lewis structures. Students’ “home-grown” strategies consisted of rules that were never explicitly taught to them; instead these rules were possibly deduced from observing many different examples of previous structures. For example, if students are commonly requested to construct Lewis structures that contain structural cues, then it would be reasonable to think that students believe the atom arrangement can be determined from the order of the elements in the
chemical formula (i.e. CH$_3$OH). Perhaps students’ creation of their own rules during the construction process stems from forgetting rules and/or their uncertainty about how to progress during the construction process. These construction rules often contain many exceptions and do not rely on any of the students’ previous knowledge. Therefore, this encourages students to rely on rote (memorized) learning instead of deeper, more meaningful learning for the construction process.

We believe that the Lewis structure construction process must become meaningful to students so they can develop a more robust understanding of how and why this is an important task to learn. Therefore, we determined that an investigation into students’ understanding of structure and property relationships must be considered.
CHAPTER FIVE

STUDENTS’ DISCONNECT BETWEEN STRUCTURES AND THEIR PROPERTIES

G. Lewis first created Lewis structures as a way to quickly differentiate between polar and non-polar molecules (Lewis, 1916). He described polar molecules as reactive and exhibiting high intermolecular attraction, while non-polar molecules showed the opposite properties. Thus Lewis created these structures as an essential link between the structure of chemical compounds and their function. Even today, chemists utilize these structures for their original purpose and 10 out of 23 organic chemistry educators interviewed and surveyed cited “correlation between structure and properties” as an important fundamental concept that students need for organic chemistry (Duis, 2011). However, research suggests that students have difficulty trying to make this connection (Shane & Bodner, 2006) and even transferring a structural representation into a molecular level representation (Nicoll, 2003).

The chemical formula of C₂H₆O is a great example why the molecular structure (as opposed to the molecular formula) is crucial to predict chemical/physical properties. There are two structural isomers that exist for this chemical formula, ethanol and dimethyl ether (Figure 5.1). Even though both of these structures are polar and have some common intermolecular forces (London dispersion forces and dipole-dipole interactions), they have one major difference – the possibility of ethanol to hydrogen bond to itself, while dimethyl ether cannot. This structural difference causes ethanol to be a liquid at room temperature (boiling point 78.4°C) and dimethyl ether to be a gas at room temperature (boiling point -23°C). Since chemists rely on the predictive power of
structures to give properties, we wanted to determine if students understood why they were learning these structures.

![Lewis structures of Dimethyl Ether and Ethanol](image)

**Figure 5.1: Structures of Dimethyl Ether (Left) and Ethanol (Right)**

**Student Think-Aloud Interviews**

At the end of the think-aloud interviews ($N = 21$) from the qualitative portion of the sequential mixed-method study in Chapter 4, the students were asked some additional questions about the connection between Lewis structures and their properties. The question of most importance was “What information can be obtained from a Lewis structure?” Responses from the interviewees ranged from Lewis structures being unimportant to students fully understanding the importance of them. An example of two extreme viewpoints for this continuum come from Rose and Charlie who are both graduate students; Rose thought of Lewis structures as being “almost useless” and that they “don’t really reveal much about geometry,” while Charlie believes that Lewis structures “provide a really good picture of where the reactivity of the molecule would occur because if you explain reactivity based on valence electrons or lack of electron (so negative charges, positive charges, lone pairs), you can get a really good idea of where the reactivity may take place…if there’s going to be a reaction…and I think that’s one of the more important aspects of it” (Cooper, Grove, et al., 2010). These interviews
provided us with preliminary indications that students of all educational levels often fail to connect Lewis structures to their properties, which prompted a more focused investigation of determining how a larger population of students viewed this connection between structures and their properties.

**Development of the Information from Lewis Structures Survey (ILSS)**

**Data Collection from Free-Response Question**

The question from the interviews “What information can be obtained from a Lewis structure?” was further administered to general chemistry students, organic chemistry students, and chemistry graduate students using a qualitative software program. 

*Ed’s Tools*, shown in Figure 5.2, is a program that provides an efficient way to collect data from free-response questions for larger populations of students while aiding in the analysis process by allowing the user to code the responses before collating them automatically (*Ed's Tools*, 2009).

![Ed's Tools](image)

**Figure 5.2: An Example of the Coding Feature for Ed’s Tool**
When analyzing the students’ responses, the most common types of information stated in the students’ responses were determined and agreed upon with the help of a post-doctoral colleague. There were eleven main topics or codes that emerged from the responses, which include intermolecular forces, polarity, and reactivity. Before coding the rest of the students’ responses, it was important to determine the legitimacy of these main codes. Ten general chemistry students’ responses were selected at random and the inter-rater reliability (Cohen’s Kappa) ranged from 0.8-1 for the eleven codes. We believed that these eleven types of information could be further classified into two broad categories: structural information and property information. Tables 5.1 and 5.2 show the percentages of each group of students that stated the different types of structural and property information. It should be noted that due to the small sample size of graduate chemistry students that volunteered, the answers from the think-aloud interviews were reported within the Ed’s Tools results.

Table 5.1: Summary of Structural Information Obtained Using Lewis Structures

<table>
<thead>
<tr>
<th>Types of Structural Information</th>
<th>General Chemistry (%) (N = 32)</th>
<th>Organic Chemistry (%) (N = 134)</th>
<th>Graduate Students (%) (N = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybridization of Atoms</td>
<td>3</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Charges (Positive, Negative, or Formal Charges)</td>
<td>25</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Atomic/Molecular Shape (Orientation of Groups, Geometry, and Bond angles)</td>
<td>38</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>Types of Elements in Molecule</td>
<td>22</td>
<td>52</td>
<td>40</td>
</tr>
<tr>
<td>Location/Distribution of Valence or Lone Electron Pairs</td>
<td>94</td>
<td>69</td>
<td>70</td>
</tr>
<tr>
<td>Bonding Sequence or Types of Bonds (i.e. Single, Double, Triple, Ionic, and Covalent)</td>
<td>78</td>
<td>83</td>
<td>70</td>
</tr>
<tr>
<td>Resonance</td>
<td>0</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>
We further determined the percentage of students from each group that could state some type of information for the two categories. When the main types of information were combined in this fashion it became apparent that while every student could relate Lewis structures to some type of structural information, only half of the students could make the deeper connection of Lewis structures with their chemical and physical properties (Table 5.3) (Cooper, Grove, et al., 2010). It was even more surprising that the organic chemistry students had the lowest percentage for chemical/physical property information since most of organic chemistry is composed of the reactivity of different compounds. This could result from students’ focus shifting from the interaction of molecules to the reaction of molecules.

### Table 5.2: Summary of Property Information Obtained Using Lewis Structures

<table>
<thead>
<tr>
<th>Types of Property Information</th>
<th>General Chemistry (%) $(N = 32)$</th>
<th>Organic Chemistry (%) $(N = 134)$</th>
<th>Graduate Students (%) $(N = 10)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermolecular Forces</td>
<td>13</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Physical Properties (Boiling Point and Melting Point)</td>
<td>6</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Bond Polarity</td>
<td>35</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Reactivity</td>
<td>31</td>
<td>28</td>
<td>20</td>
</tr>
</tbody>
</table>

### Table 5.3: Students Understanding of the Utilization of Lewis Structures

<table>
<thead>
<tr>
<th>Types of Information</th>
<th>General Chemistry (%) $(N = 32)$</th>
<th>Organic Chemistry (%) $(N = 134)$</th>
<th>Graduate Students (%) $(N = 10)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Chemical/Physical Properties</td>
<td>56</td>
<td>31</td>
<td>50</td>
</tr>
</tbody>
</table>
To determine if this inability to connect structures with their properties was ubiquitous, a survey was developed for this question to allow for an easier way to collect and analyze a larger population of students’ responses.

_Pilot-Testing of the ILSS_

A preliminary version of the ILSS was constructed using the results from _Ed’s Tools_ and the interviews. This version of the survey consisted of three questions, shown in Figure 5.3. Question 1 was a multiple-answer question that asked “What information can be obtained from a Lewis structure?” The answer choices for this question contained the most commonly stated types of information from the student responses on _Ed’s Tools_. Since some students may believe Lewis structures provide little to no information, the answer choice “no information” was added to provide these students with a possible selection. This answer choice also serves as a validation measure to eliminate participants who merely check all of the answer choices. The other two questions on the survey (Q2 and Q3) contained open-ended follow-up questions that served two main purposes: 1. allowed for the input of any additional information that the students believed was absent from the list and 2. determined if any of the answer choices were unclear to the student. This first version of the ILSS was administered on paper to first and second-semester general chemistry students (_N_ = 595) and second-semester organic chemistry students (_N_ = 292) at the end of the Spring 2009 semester.
When analyzing the results from this pilot study, we noticed that students who had not been instructed on a specific topic did not choose that particular answer choice. For example, first-semester general chemistry students ($N = 47$) who had not received any instruction on resonances structures had a selection rate of less than 20% for the answer choice “resonance,” while first-semester general chemistry students ($N = 259$) who had received instruction on this topic had a selection rate of over 60%. This not only shows the predictive validity of the ILSS, but also suggested that students took this survey seriously and did not randomly choose the answer choices.

Revising the Pilot ILSS Based on Students’ Responses

The students’ responses to the follow-up questions (Q2 and Q3 in Figure 5.3) were used to modify the ILSS. When analyzing the students’ responses, it became apparent that several answer choices could have multiple meanings; for example, students...
stated that the answer choice “type of element(s)” could refer to whether an element is a metal / non-metal or to the element itself. Since students selected these answer choices for different reasons, it was important for validity and consistency reasons to alter these answer choices to have only one meaning. Other answer choices were interpreted as being too specific; for example, “melting point” and “boiling point” were changed to “relative melting point” and “relative boiling point” since students asked whether it meant exact melting and boiling points. Lastly, the answer choice “electronegativity” was removed since it is determined from the periodic table and not a Lewis structure.

Along with these changes to the answer choices in question one, there were also some changes to the wording of the questions for further clarity. For example, question one was rephrased to “What information could you obtain using a Lewis structure?” since some students had asked if it was what they personally could determine from a Lewis structure. Question three was changed to “Were any choices in Question 1 unclear? If so, which ones? Explain why you did/didn’t pick them and how you would reword them.” for several reasons. First, we wanted to give students the opportunity to reword any of these answer choices to alleviate any confusion. It was also important to remove any terms the students may be unfamiliar with, for example the word “items.”

**Final Changes and Moving the ILSS Online**

During Summer 2010, the latest version of the ILSS was administered on paper to first-semester general chemistry students ($N = 17$) and first and second-semester organic chemistry students ($N = 44$) to help determine if any additional changes were needed.
With the intention to distribute this survey to larger sample sizes, an online version was created and pilot-tested by administering it to an additional 26 second-semester general chemistry students via SurveyMonkey. To comply with IRB regulations and avoid students’ information being kept on SurveyMonkey’s database, these students were provided a survey ID (known only by the researchers) and general link to the survey. We determined that moving the survey online did not affect the students’ responses since their selections were similar to previously collected submissions. The students’ responses from the online and paper versions provided us with information about a few more changes that needed to be made. For example, following the recommendations of organic chemistry students, the answer choice “acidity/basicity” was added and the answer choice “charges” was removed since “formal charges” was also present.

Testing of the Final Version of the ILSS

The last version of the survey was administered online to general chemistry students \(N = 1717\) and organic chemistry students \(N = 470\). To verify that there were no additional student concerns about the survey, the free-response questions (Q2 and Q3) were also administered, shown in Figure 5.4. From the students’ responses, we concluded that there were no major concerns from the students for any of the answer choices in question one; therefore, all future administrations of ILSS should only include question one since questions two and three were only used for validation purposes. Appendix C shows the three different versions of question one administered along with a list of all the changes that were made during the survey’s construction process.
Grouping the Survey’s Answer Choices

In order to provide a more meaningful analysis of the survey results, the answer choices for question one were condensed into five groups based on the reasoning required to connect structures and properties, shown in Figure 5.5. The first set of reasoning requires specific knowledge for the initial construction of a Lewis structure (number of valence electrons, formal charges, type of bond(s), number of bonds between particular atoms, and element(s) present). Using the Lewis structure to determine the molecular shape of the compound, the next group consists of geometrical information (bond angle, geometry/shape, potential for resonance, and hybridization). From the molecular shape of the structure, one can then predict how the compound would interact at the molecular level (intermolecular forces and polarity), ultimately to assist in predicting both its
chemical properties (reactivity and acidity/basicity) and physical properties (relative boiling point, relative melting point, and physical properties).

![Diagram of H2O molecule with Lewis structure, molecular formula, electron pair geometry, and bond polarities.]

**Figure 5.5: The Process for Connecting Structures and Properties**

**Validity and Reliability of the Survey**

The content and face validities of this survey were determined using several methods. Content validity ensures that all aspects of an intended topic are encompassed in an instrument, while face validity depends on how the instrument is received and if it appears valid (Creswell & Plano Clark, 2007). Using the students’ responses to question two (provide additional information that could be obtained using a Lewis structure), helped us evaluate the content validity of this survey. An example of one piece of information that students believed should be added to the list of possible information was
“acidity and basicity.” It should be noted that this type of information was never stated by students for the Ed’s Tools portion of this study. For the face validity of this survey, four graduate students and one faculty member examined the survey and agreed that it was measuring its intended purposes. To further confirm the face validity of the survey, the students’ responses to question three were analyzed. The student responses to this question allowed for the modification of the survey until students no longer reported any major concerns with the clarity of the answer choices for question one.

To further validate the ILSS, the results from the survey were compared to the Ed’s Tools free-response answers (Table 5.3). Figure 5.6 shows the results from second-semester general chemistry students (CH 102, N = 744) and second-semester organic chemistry students (CH 228, N = 387) from Spring 2011. We concluded that still less than 50% of the students spontaneously state that they can obtain physical properties from Lewis structures. Students also appear to have more difficulties as they continue to move through the process of relating structures and properties. Recall that for the Ed’s Tools results acidity and basicity information was never stated by students; however, students stated that this information needed to be added to the survey construction. Therefore, the Ed’s Tools and survey responses about the types of chemical properties information that can be obtain using a Lewis structures cannot be equally compared.
The reliability of the ILSS was also evaluated. Although one of the most common ways to evaluate the reliability of an instrument is through determining test-retest correlations, we determined this type of reliability testing was not appropriate since the ILSS only contains one question. The other concern was that a closely repeated administration of the ILSS could alter students’ future responses through remembering the survey question.

Instead, the reliability of the ILSS was determined from the results of two similar groups of students that had been exposed to the same instruction and instructor (one group from Spring 2010 and the other from Fall 2010). The results from this comparison are shown in Figure 5.7. A Chi Squared analysis was performed using SPSS to determine whether or not the two groups selected similar answer choices for the types of information that can be obtained using a Lewis structure. Only three of the thirteen

![Figure 5.6: Comparing Second-Semester Organic and General Chemistry Students’ Responses to the ILSS](chart.jpg)
possible answer choice comparisons were found to have a significant difference in
selection between the two groups of students: polarity \[X^2 (1, N = 147) = 5.44, p = .020, \phi = .21\],
intermolecular forces \[X^2 (1, N = 147) = 4.64, p = .031, \phi = .20\], and formal
charges \[X^2 (1, N = 147) = 18.2, p < .001, \phi = .37\]. The phi coefficient (effect size) for
Chi Squared, denoted with \(\phi\), displays “the degree to which the phenomenon is present in
the population,” (pg. 9) where Cohen recommends that an effect size of .1 indicates a
small effect, .3 a medium effect, and .5 a large effect (Cohen, 1988). It should be noted
that since the versions of the survey for these two administrations differed slightly, a few
answer choices were omitted from this comparison such as “acidity/basicity.” For the
three answer choice comparisons that showed a significant difference between the two
groups of students, this increase could be due to a greater emphasis on the instruction of
these topics during the Fall 2010 semester. Also, a few of these answer choices
contained slightly different wording between the two administrations; for example, the
answer choice “charge(s)” from the Spring 2010 semester was changed to “formal
charges” for the Fall 2010 semester. From these results, we concluded that the ILSS
instrument was valid and reliable.
Figure 5.7: ILSS Reliability Results for Two Similar Groups of Students

Conclusions

The results from this investigation on students’ ability to link structures with their properties revealed that many students lack an understanding of the purpose of Lewis structures. Although every student can use a Lewis structure to determine some type of structural information, only about half of students have a higher level of representational competence and can deduce the deeper, more important information of physical and chemical properties. This was evident from the quantitative and qualitative studies that involved the think-aloud interviews, Ed’s Tools, and survey results. There are a number of possible answers to the question of why students do not connect the structural representation with properties.
One explanation of students’ difficulty may stem from the process of predicting properties from a chemical formula. This process consists of eight steps that differ in levels of complexity which may overwhelm the working memory capacity (Chapter 2) of some students. For example, the step going from a chemical formula to the Lewis structure is more involved than determining the polar bonds within a structure. Perhaps for the connection process, the working memory could be used more efficiently if students begin to chunk together steps such as electron pair geometry and molecular shape.

Another possibility for disconnect in students’ understanding could develop from the way the two topics (construction process of Lewis structures and the use of these structures) are taught. In general chemistry textbooks, the Lewis structure’s construction process is often followed with several chapters – stoichiometry, types of reactions (redox, acid/base, and solutions), thermochemistry, and gases – before continuing to the topic of their importance, intermolecular forces and property information. Therefore, students are not explicitly shown the relevance for Lewis structures and the link between structure and properties is not well developed.

The results from the studies on how students construct Lewis structures (Chapter 4) and use them (Chapter 5), show that students have many difficulties with both of these processes. We believe that most of students’ difficulties with representational competence for Lewis structures stem from students inability to understand these structures meaningfully. Two of the three requirements for meaningful learning to occur could potentially be influenced from the arrangement of the material. For example, one
requirement states the learner must possess relevant prior knowledge for which to anchor new knowledge upon. With the construction process of Lewis structures, this requirement is not met since the rules of construction (this new knowledge) does not rely upon any of the students’ prior knowledge; instead, students are given an arbitrary set of rules to memorize and follow. The other requirement is that new information must be perceived by the student as relevant “to other knowledge.” Again this is typically unfulfilled since students do not understand why Lewis structures are important until about five chapters after learning how to construct them. Thus, with both of these processes, students are not explicitly provided with the relevant information, in a timely fashion, about why Lewis structures are important or how they can be used to predict property information.

Chapter 6 discusses an alternate instructional method that is part of a new curriculum development project and is designed to overcome some of these problems.
CHAPTER SIX

ALTERNATIVE APPROACHES FOR THE GENERAL CHEMISTRY CURRICULUM

Education Reform

The calls for education reform are numerous and cyclical, with reports as far back as 1891 bemoaning students’ limited understanding. One example of a national education reform project is Project 2061, which is an educational reform that was initiated in 1985 to improve the scientific literacy of the United States, involving kindergarten through twelfth grade students. This project was initiated based the appearances of Halley’s Comet; in its inception in 1985, the hope was that children that were starting school at that time would be the generation charged with completing education reform at the time of its return in 2061 (Rutherford & Ahlgren, 1990). Around the same time, the National Research Council developed National Science Education Standards (National Research Council, 1996) that “requires that students combine processes and scientific knowledge as they use scientific reasoning and critical thinking to develop their understanding of science…Science as inquiry is basic to science education and a controlling principle in the ultimate organization and selection of students’ activities” (pg. 105).

Currently, a more recent reform effort is underway from the National Research Council, to develop a new framework for the Next Generation Science Standards (Pratt, 2011).

Along with this curriculum reform at the K-12 level, other smaller attempts have been made that include complete curriculum reform within a subject, reorganizing the
order of topics within a subject, and using different pedagogical techniques (e.g. (Gafney & Varma-Nelson, 2008; Moog et al., 2009; Oliver-Hoyo & Beichner, 2004; Smith et al., 2009)). Despite the attempts at reform at the post-secondary education level and the abundance of chemical education research, the same student misunderstandings observed in the 1970s persist among students today.

In the 1960s the United States tried to address the alleged threats of Russian scientific supremacy and replaced the old schemes of “preparations and properties” with ChemStudy and Chemical Bond curriculum reforms (Johnstone, 2010). That is: the old chemistry curriculum which mainly consisted of descriptive chemistry, was replaced with curricula that attempted to supply some underlying conceptual support to the subject. At the college level this meant that the curriculum became much more theoretical and mathematically “rigorous.” However, the developers of the new curricula, while well intentioned, did not have sufficient knowledge about how students learn. Subsequently, the general chemistry curriculum can be confusing to some students, which can cause them to become disinterested in the subject on top of facing learning difficulties. Reasons for this could stem from its conflicting language (for example, the meaning of the concept equilibrium for chemistry compared to physics), overwhelming extraneous requirement for the working memory (i.e. using inorganic elements such as antimony instead of common and less complicated ones such as carbon, hydrogen, oxygen, nitrogen, and sulfur), and the frequent focus on calculations (Johnstone, 2010).

Two examples of curriculum reforms for general chemistry courses are discussed in detail for the remainder of this chapter. One of the approaches is a reorganization of
the topics (*Atoms First*), while the other is a complete curriculum reform (*Chemistry, Life, the Universe and Everything – CLUE*).

**Description of CLUE and Atoms First Curricula**

*Atoms First Approach Curriculum*

One approach for trying to improve education has been to organize the material in a way to help students “think like a chemist” (Zumdahl & Zumdahl, 2011). Currently, the main sequence curriculum for the two-semester general chemistry courses at Clemson University uses an “Atoms First” approach, which is merely a rearrangement of the topic order from a more traditional curriculum. The organization of the material is described as a “chemical story (beginning with) atoms – their history, stability, electronic structure, and consequent periodicity…that follows an intuitive logic in progressing from the simplest building blocks to successively more complex concepts” (McMurry & Fay, 2009) with the goal being to build chemistry concepts from the ground (atoms) up. With the rearrangement of the material, their best intentions were to have a flow of topics that would begin with atomic structure and build from there; however, their vision was blurred with respect to keeping some related topics together such as the introduction of Lewis structures and their purpose/importance.

Neither the material itself nor the instructional methods have been changed from traditional general chemistry curriculum. For example, instructors are still able to use the same instructional materials from the previous year when a traditional general chemistry curriculum was in place. What has changed is the order of the topics in an attempt to
make a more logical flow of the material. The use of Clickers (Chapter 3) is one method utilized within the classroom setting to help engage students in their own learning process while informing the instructor of students’ uncertainties. For evaluation purposes, students are given quizzes, Mastering Chemistry homework, and multiple-choice exams. The textbook that is currently used is a custom edition of McMurry and Fay’s General Chemistry: Atoms First (McMurry & Fay, 2009) and therefore, when the term “Atoms First” is used in this chapter, it refers to the instruction at Clemson using this text since there was a slight difference between the order of the textbook and how it was covered. Although there are several textbooks available that have an Atoms First edition (Bishop, 2007; Burdge & Overby, 2011; McMurry & Fay, 2009; Zumdahl & Zumdahl, 2011), no supportive research is currently available on the effectiveness of this approach.

**CLUE Curriculum**

CLUE is an NSF-funded curriculum reform that results in part from research that indicates very successful students (those whom score above average on standardized American Chemical Society (ACS) exams and have on average an SAT score above 1200) succeed in the general and organic chemistry courses while maintaining very novice-like ideas and misunderstandings (Cooper, Grove, et al., 2010). For example, many students believe that energy is released when breaking a bond (Ozmen, 2004). This misconception has also been found with upper level students as well as graduate chemistry students (Gonzales, 2011). Another impetus for the development of a new curriculum was dissatisfaction with the topics and coverage of a traditional chemistry
course that has not changed over the past thirty years, even though there was no research-based reasoning for its initial development.

The CLUE curriculum focuses on developing students’ critical thinking skills and deeper conceptual understanding and was structured to provide students with a more meaningful learning experience through the arrangement of the material in such a way that new knowledge is explicitly linked to prior knowledge. This is accomplished with the early topics serving as a foundation for the following material to be built upon, which is a critical step for meaningful learning. Before instruction, students are typically asked questions about their understanding on the upcoming topic. This is done for several reasons: 1. to identify students’ preconceptions about the topic, since students do not come into general chemistry as a “blank slate” (Locke, 2001), and 2. to have the students take a stance on their understanding and determine what they know about the topic. During instruction, Clickers (Caldwell, 2007) are utilized within the classroom to gauge students’ levels of comprehension, along with the incorporation of group activities to reinforce the information being discussed. Typically these group activities consist of worksheets, although hands-on activities have also been widely utilized. Some examples have included using ball-and-stick models to learn about molecular shape and structure, while others involved an experiment where water was added to different types of salts (endothermic and exothermic) in a Ziploc bag to bring together the concepts of enthalpy, entropy, and Gibbs free energy. The students in this curriculum were evaluated with two-part exams consisting of a multiple-choice section and a free-response section. The purpose of administering a free-response section of the exam is to evaluate on a deeper
level how students comprehend the material while asking the students thought-provoking questions.

**Organization of Material for the Different Approaches**

Tables 6.1, 6.2, and 6.3 show the arrangement of the material for the three curricula that have been used at Clemson in the last two years. For the traditional curriculum, a custom edition of *Chemistry: A Molecular Approach* (Tro, 2008) was used, while the Atoms First textbook is a custom edition of McMurry and Fay’s *General Chemistry: Atoms First* (McMurry & Fay, 2009). Table 6.1 contains the material for the first-semester and second-semester of general chemistry for the CLUE curriculum, while Table 6.2 is the traditional curriculum and Table 6.3 is for the Atoms First curriculum. It should be mentioned that in the CLUE curriculum, each chapter contains multiple concepts. For example, Chapter One *Atoms* contains material on atoms, intermolecular forces, bonding, energy, and stoichiometry.

**Table 6.1: Chemistry, Life, the Universe and Everything Chapter Order of Material Instructed**

<table>
<thead>
<tr>
<th>First-Semester</th>
<th>Second-Semester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atoms</td>
<td>Solutions</td>
</tr>
<tr>
<td>Electrons and Orbitals</td>
<td>A Field Guide to Reactions</td>
</tr>
<tr>
<td>Elements, Bonding, and Physical Properties</td>
<td></td>
</tr>
<tr>
<td>Heterogenous Compounds: 3D realities and 2D Representations</td>
<td>How Far, How Fast</td>
</tr>
<tr>
<td>Systems Thinking</td>
<td>System</td>
</tr>
</tbody>
</table>
### Table 6.2: *Chemistry A Molecular Approach* Chapter Order of Material Instructed

<table>
<thead>
<tr>
<th>First-Semester</th>
<th>Second-Semester</th>
</tr>
</thead>
<tbody>
<tr>
<td>❖ Matter Measurement and Problem Solving</td>
<td>❖ Quantum Mechanical Model of the Atom</td>
</tr>
<tr>
<td>❖ Atoms and Elements</td>
<td>❖ Periodic Properties</td>
</tr>
<tr>
<td>❖ Molecules, Compounds and Equations</td>
<td>❖ Chemical Bonding I</td>
</tr>
<tr>
<td>❖ Quantities and Aqueous Reactions</td>
<td>❖ Chemical Bonding II</td>
</tr>
<tr>
<td>❖ Gases</td>
<td>❖ Liquids, Solids and Intermolecular Forces</td>
</tr>
<tr>
<td>❖ Thermochemistry</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 6.3: *General Chemistry: Atoms First* Chapter Order of Material Instructed

<table>
<thead>
<tr>
<th>First-Semester</th>
<th>Second-Semester</th>
</tr>
</thead>
<tbody>
<tr>
<td>❖ Chemistry: Matter and Measurement</td>
<td>❖ Radioactivity and Nuclear Chemistry</td>
</tr>
<tr>
<td>❖ The Structure and Stability of Atoms</td>
<td>❖ Chemical Equilibrium</td>
</tr>
<tr>
<td>❖ Periodicity and the Electronic Structure of Atoms</td>
<td>❖ Gibbs Free Energy</td>
</tr>
<tr>
<td>❖ Ionic Bonds and Some Main-Group Chemistry</td>
<td>❖ Acids and Bases</td>
</tr>
<tr>
<td>❖ Covalent Bonds and Molecular Structure</td>
<td>❖ Buffers and Titrations</td>
</tr>
<tr>
<td></td>
<td>❖ Electrochemistry</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 67 -
Comparing Instructional Plans for Lewis Structures and Predicting Properties

Atoms First (traditional) Approach

After the topics of ionic and covalent bonding, students are introduced to Lewis structures or Electron-Dot Structures. The traditional curriculum uses a series of rules to teach Lewis structures. Sometimes these rules may vary slightly, but the fundamental principles are typically the same: 1. write the skeletal structure, 2. count the total number of valence electrons, 3. place electrons around each atom to create an octet for every element (except hydrogen and helium, which have a duet), and 4. create any multiple bonds to use the remaining valence electrons. Along with these rules for creating Lewis structures, students are also given a list of exceptions to these rules. For example, the octet rule states that elements tend to interact in such a way to result in a Noble gas electron configuration (having eight valence electrons around each atom). Unfortunately, this rule only holds true for most second row elements on the periodic table. Beyond neon, most elements have “expanded octets” due to the addition of d orbitals and their ability to hold more than eight electrons.

Once the rules are shown to the students, it is followed by the drawing multiple examples of Lewis structures. These structures typically include those that contain a central atom, polyatomic ions, or inorganic compounds with expanded octets (ex. SbF₆). In fact there is a considerable focus on more exotic structures with expanded octets and uncommon structures. After instruction on this topic, there are four more chapters of material covered (Table 6.3) before learning about intermolecular forces and
physical/chemical properties. Therefore, it could be difficult for students to link Lewis structures and their properties when they are several weeks apart.

**CLUE**

It is clear from prior research that students have great difficulty in linking structural representations with molecular and bulk properties. The connection between the molecular level structure and the bulk properties of the substance must be explicit and strongly made. This is accomplished in the CLUE curriculum using the following instructional plan (Figure 6.1). Initially physical properties of compounds are introduced, since the ability to predict relative properties is an important skill that can be used to assess understanding. One example of how to help students visualize the dependence of physical properties on its structure is through the use of two very common substances, diamond and graphite. Even though both substances are carbon-based structures, graphite and diamond have very different physical properties (Figure 6.2), the difference being that the bonds form an inflexible three-dimensional lattice in diamonds, whereas the atoms are tightly bonded into sheets in graphite, which can slide easily over one another.
After they understand that properties are very dependent on the structure, students are then introduced to the three-dimensional models of simple molecules, such as methane (Figure 6.3). The three-dimensional structure is explicitly shown to students both as physical models and as drawings on paper or on the board. Once students understand that most molecules have a three-dimensional structure, more complex molecules are shown. It soon becomes apparent that drawing three-dimensional structures is cumbersome and time consuming. At this point Lewis structures are introduced as a way to simplify the representation of the more complex three-dimensional structure. It is
emphasized that these two-dimensional representation of molecules are not the actual depiction of these molecules, but are used since it is very difficult to represent molecules in a three-dimensional representation without computer software or model kits. To help students connect the three-dimensional and two-dimensional representations of structures, an activity was created where students first built ball-and-stick models of the given compound followed by drawing its Lewis structure before further relating the two-dimensional model to the three-dimensional model through the use of dash-wedge representations.

Figure 6.3: Three-Dimensional Representation of Methane

Once students were comfortable with the relationship between two-dimensional and three-dimensional representations, they were given guidelines (instead of rules) to help them construct Lewis structures from molecular formulas. First, when constructing the skeletal structure of a molecule, the emphasis is placed on the number of bonds each atom can typically form instead of the identity of the central atom, since most molecules do not consist of one central atom. Second, to construct the bonds between atoms, the students were given two options: 1. connect all of the atoms initially using a single bond before determining which connections need multiple bonds or 2. determine the valence electrons for each atom and place them around each atom to determine the number of bonds between each connection. Lastly, the tallying of valence electrons was used more
as a verification of the construction process than for initializing said process. The octet rule is not emphasized since many students misunderstand its use and believe that it is the reason for bond formation in the first place, Hence, students become too reliant on it and use it inappropriately (Taber, 2001), even though it is a heuristic that is quite helpful if students understand its limitations. Although these guidelines are similar to the rules traditionally given to students to construct Lewis structures, the intent is that with the CLUE curriculum students should be able to anchor these instructions to relevant previous knowledge.

Once hydrocarbons are covered in this manner, more complex compounds that contain heteroatoms are introduced in the same format (particularly nitrogen-, oxygen-, and sulfur-containing compounds). During this time, structures are related back to their properties, using the Lewis structure to predict the physical properties of the compound through the many steps shown in Figure 5.5. The process of how the molecular shape is determined for compounds was covered by having students transition among the two-dimensional and three-dimensional representations using model kits while discussing hybridization.

Expanding upon this, the topics of polarity and intermolecular forces are introduced so that students’ now have all of the knowledge necessary to predict the properties of structures. The steps required to pull all of this knowledge together can become overwhelming and impossible when lacking pieces of knowledge.

The evaluation of these two approaches for the topic of structure and property relationships for Lewis structures are discussed in Chapter 7.
CHAPTER SEVEN

EVALUATION OF STUDENTS’ REPRESENTATIONAL COMPETENCE TO DETERMINE THE EFFECTIVENESS OF THE CHEMISTRY, LIFE, THE UNIVERSE AND EVERYTHING (CLUE) CURRICULUM

This chapter consists of four main studies conducted to determine the effectiveness of the CLUE curriculum: pilot, instructor effect, main, and retention. The types of assessments evaluated for each of these studies is shown below. The pilot study compared students on their structure construction ability and representational competence for Lewis structures and the purpose of the instructor effect study was to determine if the results observed in the pilot study were because of the instructor. The main study was meant to determine if the results in the pilot study could be repeated, while the retention study evaluated how students maintained their understanding of structures and properties.

- PILOT STUDY – OrganicPad (pre- & post-test) and ILSS (post-test)
- INSTRUCTOR EFFECT STUDY – OrganicPad (post-test)
- MAIN STUDY – OrganicPad (pre- & post-test) and ILSS (pre- & post-test)
- RETENTION STUDY – OrganicPad (pre- & post-test) and ILSS (post-test)

Methodology for Pilot and Main Studies

The experimental design for the pilot and main studies comprised of a nonequivalent control-group quasi-experimental design with two non-randomly selected groups of students – where one group was administered a treatment – and both groups were administered pre- and post-test assessments (Figure 7.1) (Creswell, 2009). To ascertain how students behave in “the wild,” all evaluations were administered outside of the lecture setting, and instead were conducted inside the laboratory to obtain a naturalistic environment and to accommodate the limited resources available for
collection purposes (there were only twenty-four tablet-PCs). By administering the assessments outside of the lecture setting, it also helped avoid the priming effect, an increase in efficiency due to an earlier stimulus or experience within the same task and stimulus materials (Wagner & Koutstaal, 2002). The pre- and post-tests were administered at the beginning of the class period and typically took twenty minutes to complete. In order to avoid the interruption of their laboratory experiment, only one laboratory section within each time period of the day was selected.

![Experimental Design for the Pilot and Main Studies](image)

**Figure 7.1: Experimental Design for the Pilot and Main Studies**

Before instruction, in addition to the pre- and post-test measures regarding the students' ability to construct and understand Lewis structures, the students in both groups were evaluated on their cognitive and affective domains (Engelhart et al., 1956; Krathwohl, Bloom, & Masia, 1964). These assessments and their purposes are:

- **Metacognitive Activities Inventory (MCA-I)** – measures student's metacognitive skillfulness (regulation of cognition – planning, monitoring, and evaluation skills) for problem solving (Cooper & Sandi-Urena, 2009)
- Test of Logical Thinking (TOLT) – evaluates five modes of students’ formal reasoning abilities (controlling variables, proportional reasoning, combinatorial reasoning, probabilistic reasoning, and correlational reasoning) (Tobin & Capie, 1981)

- Shortened version of the Attitude towards the Subject of Chemistry Inventory (ASCIv2) – evaluate students’ attitude towards chemistry for two factors, Intellectual Accessibility and Emotional Satisfaction (Brandriet et al., 2011; Bauer, 2008)

- Expectancy Component: Self-Efficacy for Learning and Performance from the Motivated Strategies for Learning Questionnaire (MSLQ) – measure students’ expectation of their performance in the course as well as their evaluation of their ability to accomplish a task (Pintrich et al., 1992; Pintrich et al., 1993)

All of the analyses in this chapter consist of non-parametric measures since the data in all of these studies are not normally distributed. Three main statistical tests were used: Chi Squared tests assessed differences between two groups on dichotomous values (i.e. correctness of Lewis structures), Mann-Whitney tests analyzed results containing continuous values (i.e. overall percent correct for the structures administered), and Wilcoxon Rank Sign tests compared the same group of students pre- and post-tests measures. The effect size or power effect for results that indicated a significant difference between the two groups or within a group were evaluated; Chi Squared is reported using the phi coefficient (ϕ) while the Pearson’s (r) coefficient is for Mann-
Whitney and Wilcoxon Rank Sign analyses. For both of these measures, Cohen
recommends that an effect size of .1 indicates a small effect, .3 a medium effect, and .5 a
large effect. This is because the effect size displays “the degree to which the
phenomenon is present in the population” (pg. 9) (Cohen, 1988).

Pilot Testing of the Instructional Plan

In the Spring 2010 semester, 379 students were enrolled in the first-semester
general chemistry course, CH 101 (a majority of the first-semester general chemistry
students enroll during the fall semesters). These students were distributed between two
instructors: one instructor led a lecture section of the CLUE curriculum ($N = 47$;
treatment group), while the remaining lecture sections ($N = 224$; control group) were
taught the traditional general chemistry curriculum with the other instructor. It should be
mentioned that students involved in the CLUE curriculum were unaware of the
alternative curriculum until the first day of class. Therefore, the students were given the
opportunity during the first week of the semester to switch to the traditional curriculum if
they preferred; there were only two students that self-selected out of the alternative
curriculum. Since the lecture sections of general chemistry at this institution are not
associated with a specific laboratory section (i.e. the students from one lecture section
typically are dispersed among all of the laboratory sections available), pre- and post-
evaluations were collected from all lab sections.
Pilot Testing – Pre-Test Comparisons

Using all of the cognitive and affective measures listed above, we determined that the two groups contained similar students since all of the p-values were greater than .05. The results from all of these measures, shown in Table 7.1, were all evaluated using the “exclude cases listwise” settings so that only students that complete all of the pre-test assessments were included. An additional parameter examined was the students SAT composite scores (which includes an ACT equivalent score for students that only took the ACT); however, this analysis was performed separately since the inclusion of this measure with the other pre-test assessments excluded too many students from the analysis. This is because in the off-semester, a proportion of students have transferred from another institution and their SAT scores do not always transfer with them. For example, the control group sample size dropped from 190 to 157. The mean SAT composite score for the control group was 1194, while the treatment group’s mean was 1172 with p = .18; therefore, we concluded that the two groups were also statistically equivalent for this factor.

Table 7.1: Comparison of Pre-Test Assessments for Pilot Study

<table>
<thead>
<tr>
<th>Pre-Assessments</th>
<th>Control Group Mean ((N = 190))</th>
<th>Treatment Group Mean ((N = 42))</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCA-I</td>
<td>74.8%</td>
<td>73.2%</td>
<td>.39</td>
</tr>
<tr>
<td>TOLT</td>
<td>8.1 (out of 10)</td>
<td>7.7 (out of 10)</td>
<td>.13</td>
</tr>
<tr>
<td>Intellectual Accessibility – ASCIv2</td>
<td>47.7%</td>
<td>46.9%</td>
<td>.81</td>
</tr>
<tr>
<td>Emotional Satisfaction – ASCIv2</td>
<td>53.1%</td>
<td>48.4%</td>
<td>.11</td>
</tr>
<tr>
<td>Self-Efficacy for Learning and Performance – MSLQ</td>
<td>79.2%</td>
<td>79.1%</td>
<td>.87</td>
</tr>
</tbody>
</table>
To evaluate if the two groups were also similar in their ability to construct Lewis structures prior to instruction, we asked students to construct the Lewis structure for eight chemical formulas (NH$_3$, HCN, CO$_2$, NH$_2^-$, H$_2$O, CH$_4$O, CH$_3$OH, and C$_2$H$_6$O) using the quiz feature of OrganicPad (Chapter 3). These structures were chosen due to their variety in structural characteristics such as diversity of elements, formal charge, and structural cues. While administering this pre-test assessment, we noticed that many students appeared unsure about Lewis structures since they were asking what we meant by the term. We asked them to just do their best, which resulted in some students submitting the chemical formula as their answer. The students’ Lewis structures were classified as either correct or incorrect via the grading feature of OrganicPad (Chapter 3) and then exported into an Excel file before being further transferred into SPSS for statistical analysis. The criteria for a structure to be considered correct are: the proper atom arrangement and the appropriate number of valence electrons shown either as shared or unshared electrons (Lewis dot structures were considered correct). The percentage correct on the eight structures for each student was calculated: the mean for the control group was 7.1% and treatment group was 4.3%. This low score indicated that, just as we had suspected, most of the students were unable to construct a Lewis structure. Although this statistical analysis indicated that the two groups were different [$U = 4483.0$, $Z = -2.14$, $p = .033$] since neither of the groups’ means was above 10%, we concluded that the students’ were similar in their prior knowledge of Lewis structures.
Pilot Testing – Post-Test Comparisons

After both groups completed and were tested on the instruction of how to construct Lewis structures, we administered the first post-test. Using *OrganicPad*, we had students construct the same eight chemical formulas as the pre-test plus an additional four structures (CH₃N, CH₄S, CH₃CO₂H, and CH₃COOH). The correctness of each of the twelve structures was ascertained for each student using *OrganicPad* as described above. The control and treatment groups’ average percent correct for each structure, the overall twelve structures, and the seven less familiar / more difficult structures are shown in Figure 7.2. The seven more difficult structures (CH₄O, CH₃OH, C₂H₆O, CH₅N, CH₄S, CH₃CO₂H, and CH₃COOH) are important since they are 1. less familiar, which should exemplify students’ true understandings about constructing structures and 2. do not contain a central atom, since most compounds do not contain one single central atom. For example, acetic acid would be difficult for first-semester general chemistry students since it requires a more complex skeleton structure for which students do not have any experience. The number of asterisks in Figure 7.2 depicts the level of significance: * p < .05, ** p < .01, and *** p < .001.
Figure 7.2: Comparison of Percent Correct for the Pilot Study’s Post-Test
OrganicPad Structures

For the last two structures, chemical formulas of acetic acid, any viable structure was considered as correct (examples are shown in Figure 7.3) since at this point the students lack the knowledge of functional groups and would not gain any insight from the structural cues given. When comparing the two groups for each structure, six of the twelve structures were found to have a significant difference (Table 7.2). NH$_2^-$ was the only structure where the control group had a higher construction success rate when compared to the treatment group, which most likely results from the CLUE curriculum not covering the topic of charges since it is taught in the second-semester of the course. Although there was no significant difference between the control and treatment for the overall percent correct, the two groups were found to be statistically different for the seven less familiar or more difficult structures [$U = 3566.0$, $Z = -3.23$, $p < .001$, $r = .20$].
The initial version of the ILSS (Figure 5.3) was also administered as a post-test measure via paper and pencil immediately following the students’ completion of *OrganicPad*. We first calculated the percentage of students that selected each type of information from the survey (Figure 7.4). Six of the fifteen items resulted in significant differences between the control and treatment groups (Table 7.3). For the answer choices of “resonance” and “charges,” the difference between the two groups probably results from the CLUE curriculum since similar to the topic of charges, resonance structures was not covered until the second-semester. Likewise, the differences for the answer choices “intermolecular forces,” “melting point,” “boiling point,” and “physical properties,” stemmed from the control group not covering this material due to a lack of time in the semester. These topics are covered in the last chapter of the material in the traditional
first-semster general chemistry curriculum (Chapter 6) and all of these differences supported the predictive validity of the survey (Chapter 5).

![Histogram showing percentage of students selecting each type of information for the Pilot Study’s Post-Test ILSS](image)

**Figure 7.4: Percentage of Students that Selected Each Type of Information for the Pilot Study’s Post-Test ILSS**

<table>
<thead>
<tr>
<th>Type of Information</th>
<th>p-value</th>
<th>$X^2$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point</td>
<td>&lt; .001</td>
<td>37.21</td>
<td>0.39</td>
</tr>
<tr>
<td>Intermolecular forces</td>
<td>&lt; .001</td>
<td>30.38</td>
<td>0.35</td>
</tr>
<tr>
<td>Charge(s)</td>
<td>&lt; .001</td>
<td>34.28</td>
<td>0.37</td>
</tr>
<tr>
<td>Melting point</td>
<td>&lt; .001</td>
<td>32.00</td>
<td>0.36</td>
</tr>
<tr>
<td>Physical properties</td>
<td>&lt; .001</td>
<td>10.03</td>
<td>0.21</td>
</tr>
<tr>
<td>Resonance</td>
<td>&lt; .001</td>
<td>35.13</td>
<td>0.38</td>
</tr>
</tbody>
</table>

The students’ ILSS results were further clustered into five categories using the process described in Chapter 5: structural information, geometrical information, molecular level information, chemical property information, and physical property
information. Each of the students’ submissions were analyzed to establish if they had stated some type of information for each of the five groupings listed above; if the student selected at least one type of information from a given category, then that category was given a value of 1 and if there were not any types of information from a particular category selected, it was given a value of 0. The percentage of students in both groups that selected each cluster of information is shown in Figure 7.5. We determined that the control and treatment groups were statistically different for molecular level information \( X^2 (1, N = 262) = 4.65, p = .031, \phi = .14 \) and physical property information \( X^2 (1, N = 262) = 32.79, p < .001, \phi = .37 \). This is not surprising since the topics of intermolecular forces and boiling/melting point predictions were not covered for the control group due to a lack of time at the end of the semester.

![Figure 7.5: Percentage of Students that Selected Each Category of Information for Pilot Study’s Post-Test ILSS](image-url)
Are the Students’ Improvements Due to an Instructor Effect?

For the pilot study above, there was a treatment group (one lecture section using the CLUE curriculum with an instructor – Instructor A) and a control group (several lecture sections using the traditional curriculum with a different instructor). With observing the improvements in the students’ structure construction ability, it was imperative to determine if the increase was due to Instructor A. To evaluate this, the previous semester’s results (Fall 2009) were analyzed to compare Instructor A’s teaching effects to other instructors.

Several measures were assessed to determine if any instructor differences were present. All of these assessments were administered inside the laboratory setting, except OrganicPad for Instructor A’s students. However, these students were given their post-test structure construction evaluation during one of two afternoon sessions.

Instructor Effect – Pre-Test Comparisons

During the Fall 2009 semester, all of the first-semester general chemistry students were undergoing the traditional general chemistry curriculum. Using subsamples from the entire population, we intended to determine if there were any differences between Instructor A ($N = 39$) and the other instructors ($N = 66$). First, their students were evaluated and compared on the same pre-test assessments as in the pilot study. Although, this time two additional comprehension measures were analyzed (Exam 1 and Exam 2) since the two groups of students were taking the same multiple-choice exams. Exam 1 and Exam 2 were available for pre-instruction comparison purposes since the topic of
Lewis structures in the traditional curriculum is introduced towards the end of the first-semester. This time, the students’ SAT composite scores were left in the list-wise settings since only a few additional students were excluded. The mean scores for all of these pre-assessment measures are shown in Table 7.4.

A pre-test comparison of the students’ structure construction ability was not feasible since Instructor A’s students were not as easily assessable for collection purposes. Based on the pre-test results in the pilot study, we would suspect that the two groups would be similar in their pre-instruction ability to construct Lewis structures. The ILSS was also not developed at this time and therefore could not be used for comparison purposes. However, with the data that we had available we concluded that the two groups were comparable.

### Table 7.4: Comparison of Pre-Test Assessments for Instructor Effect Study

<table>
<thead>
<tr>
<th>Pre-Assessment</th>
<th>Other Instructors Mean (N = 66)</th>
<th>Instructor A Mean (N = 39)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCA-I</td>
<td>78.8 %</td>
<td>76.2 %</td>
<td>.30</td>
</tr>
<tr>
<td>Intellectual Accessibility – ASCIv2</td>
<td>50.9 %</td>
<td>48.5 %</td>
<td>.50</td>
</tr>
<tr>
<td>Emotional Satisfaction – ASCIv2</td>
<td>60.1%</td>
<td>56.4%</td>
<td>.51</td>
</tr>
<tr>
<td>Self-Efficacy for Learning and Performance – MSLQ</td>
<td>78.0 %</td>
<td>74.2 %</td>
<td>.33</td>
</tr>
<tr>
<td>TOLT</td>
<td>8.2 (out of 10)</td>
<td>8.3 (out of 10)</td>
<td>.98</td>
</tr>
<tr>
<td>First Exam</td>
<td>88.1%</td>
<td>87.7%</td>
<td>.47</td>
</tr>
<tr>
<td>Second Exam</td>
<td>70.2%</td>
<td>69.0%</td>
<td>.71</td>
</tr>
<tr>
<td>SAT</td>
<td>1227</td>
<td>1199</td>
<td>.27</td>
</tr>
</tbody>
</table>
Instructor Effect – Post-Test Comparisons

In order to verify that the gains observed from the CLUE curriculum were not due to an instructor effect, two measures were evaluated: 1. students’ ability to construct Lewis structures using OrganicPad and 2. the students’ third exam scores, which contained Lewis structure material. For the evaluation of the students’ construction ability, the students were asked to construct the Lewis structure for eight different chemical formulas: \( \text{NH}_3 \), HCN, CO\(_2\), \( \text{NH}_2^- \), H\(_2\)O, CH\(_4\)O, CH\(_3\)OH, and C\(_2\)H\(_6\)O. The percent of students in each group that constructed a viable structure for the different chemical formulas and their overall percent correct for the eight structures is shown in Figure 7.6. Since there was no significant difference for any of the eight structures or for the overall percent correct, we concluded that the two groups were equivalent in their post-instruction construction ability.

![Figure 7.6: Comparison of Percent Correct for the Instructor Effect Study’s Post-Test OrganicPad Structures](image)

**Figure 7.6:** Comparison of Percent Correct for the Instructor Effect Study’s Post-Test OrganicPad Structures
The other measure, Exam 3, was analyzed to further compare the two groups’ summative assessment for the topic of Lewis structures. The mean for the Other Instructors’ group was 73.0%, while Instructor A’s group had a mean of 73.2%. These findings from OrganicPad were further supported since the two groups were found to be statistically equivalent \[ U = 1282.0, Z = -.03, p = .97 \]; therefore, we established that Instructor A was comparable to the Other Instructors in their instruction of Lewis structures.

**Main Study of the Instructional Plan**

In the Fall 2010 semester, there were a total of 226 students selected for this study. The treatment group consisted of one lecture course of students undergoing the CLUE curriculum \( N = 99 \) that were selected similar to the pilot study (this time, only one student left the section when given the option the first week of class), while the control group contained specifically selected students enrolled in the Atoms First approach (traditional instruction, \( N = 127 \)). It should be noted that only students with certain biological majors were eligible to enroll in the CLUE lecture section for the Fall administration.

**Main Study – Demographic Information**

Once the students were selected, their demographic information was analyzed to verify that the two groups contained similar populations of students. Even though the two groups consisted of biological science related majors, it was important to confirm
that the distribution of each major was similar (Figure 7.7). A Chi-Squared test indicated that there were no significant differences between the two groups for any of the majors. There was also no significant difference in the distribution of sex between the two groups: control group 35.8% males vs. 64.2% females and treatment group 39.0% males vs. 61.0% females. For both of these groups, there were more females than males since biological-focused majors include health science related fields which can be primarily female.

![Figure 7.7: Distribution of the Control and Treatment Groups’ Majors for the Main Study](image)

**Figure 7.7: Distribution of the Control and Treatment Groups’ Majors for the Main Study**

**Main Study – Pre-Test Comparisons**

The same pre-test assessments were administered to evaluate the students’ cognitive and affective domains, the mean for each of these measures for the two groups
is shown in Table 7.5. The analysis showed that the two groups were statistically equivalent in their distribution of males and females, along with the pre-test measures stated earlier (SAT, TOLT, Intellectual Accessibility – ASCIv2, Emotional Satisfaction – ASCIv2, and Self-Efficacy for Learning and Performance – MSLQ). The MCA-I could not be used for comparison purposes since it was administered after all of the other pre-test assessments.

Table 7.5: Comparison of Pre-Test Assessments for Main Study

<table>
<thead>
<tr>
<th>Pre-Assessment</th>
<th>Control Group (N = 108)</th>
<th>Treatment Group (N = 80)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAT Composite</td>
<td>1188</td>
<td>1193</td>
<td>.79</td>
</tr>
<tr>
<td>TOLT</td>
<td>8.0 (out of 10)</td>
<td>8.3 (out of 10)</td>
<td>.38</td>
</tr>
<tr>
<td>Intellectual Accessibility – ASCIv2</td>
<td>46.1%</td>
<td>44.8%</td>
<td>.43</td>
</tr>
<tr>
<td>Emotional Satisfaction – ASCIv2</td>
<td>56.1%</td>
<td>55.5%</td>
<td>.83</td>
</tr>
<tr>
<td>Self-Efficacy for Learning and Performance – MSLQ</td>
<td>78.6%</td>
<td>79.7%</td>
<td>.62</td>
</tr>
</tbody>
</table>

Next, we evaluated the students’ ability to construct Lewis structures. Using OrganicPad, the students were asked to draw the Lewis structure for eight chemical formulas: \( \text{NH}_3 \), HCN, \( \text{CO}_2 \), \( \text{NH}_2 \), \( \text{H}_2\text{O} \), \( \text{CH}_4\text{O} \), \( \text{CH}_3\text{OH} \), and \( \text{C}_2\text{H}_6\text{O} \). These were the same structures from the pilot study since they elicited a range of student success and could be used for comparison purposes. The students’ submissions were first analyzed to answer two questions: 1. Are the two groups similar in their ability to construct each of the eight structures? and 2. Is the distribution of the eight structures’ success rate similar for the two groups? The former was evaluated by first marking each of the students’
eight structures as correct with a given value of 1 or incorrect with a given value of 0. We found the two groups to be statistically equivalent in their pre-instruction ability to construct each of the Lewis structures. For the second question, we found the two groups were statistically equivalent in their overall distribution of correctness for the eight chemical formulas (control group mean – 10.0% and treatment group mean – 14.0%). When counting structures that lack lone pairs (students often forget to place them on the structure), there was still no significant difference between the two groups.

Last, we evaluated the students for their pre-instruction representational competence. The final version of the ILSS was administered (Figure 5.4) using the online software SurveyMonkey, and to maintain student confidentiality, students were given survey IDs, known only to the researchers, as identifiers. The data from SurveyMonkey was collected and exported into Excel, and students responses were analyzed as previously described with the results shown in Figure 7.8. The answer choice “no information” was included since some students believe that there is no information that can be obtained from a Lewis structure and had not selected any other types of information. This is typically only the case for pre-instruction analysis since students will at least select some type of structural information after instruction. We verified that for all of these types of information, the two groups were equivalent in their pre-instructional understanding.
When clustering the students’ responses into the five groups of information as stated in Chapter 5 for the process of predicting properties from Lewis structures (Figure 5.5), we found that the majority of students have an initial understanding that these structures can give you structural information and only a few already had an understanding of the structure-property relationship. For each of these groupings of information, we concluded that the two groups were statistically equivalent in their representational competence of Lewis structures (Figure 7.9).
Main Study – Post-Test Comparisons

To evaluate how students in the control and treatment group developed after instruction, students were asked to construct Lewis structures from twelve chemical formulas using OrganicPad. Eight formulas were taken from the pre-test for comparison purposes (NH₃, HCN, CO₂, NH₂⁻, H₂O, CH₄O, CH₃OH, and C₂H₆O) and an additional four chemical formulas (CH₃CH₂OH, C₂H₇N, C₂H₄O₂, and C₄H₈O₂) were added to allow us to analyze how students handle new structures of increased difficulty. The students’ submissions were analyzed and the percent correct for each of the twelve structures along with their overall score was calculated for each group, Figure 7.10.
Each group was analyzed for their proficiency on each of the twelve structures. We found a difference between the two groups in their construction ability for six of the twelve chemical formulas (Table 7.6). It was not surprising that the two groups were equivalent for some of the structures since those were commonly seen in lecture and contain a central atom which makes the atom arrangement (skeletal structure) much easier to construct. The only structure where the control group performed significantly higher than the treatment group was the chemical formula NH$_2^\text{−}$. This could be explained from the fact that the treatment group does not cover the subject of formal charge in detail until the second-semester of the CLUE curriculum. Another possibility for this could stem from the strong emphasis on the octet rule for the control group; for example, if students are unsure about needing to add or subtract an electron due to the negative charge.
charge, they may be more inclined to add an electron to provide the nitrogen with eight electrons instead of six.

Table 7.6: Statistical Values for Main Study’s Post-Test OrganicPad Structures

<table>
<thead>
<tr>
<th>Chemical Formula</th>
<th>p-value</th>
<th>$X^2$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_2$</td>
<td>.001</td>
<td>11.4</td>
<td>.24</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>.013</td>
<td>6.2</td>
<td>.18</td>
</tr>
<tr>
<td>CH$_4$O</td>
<td>&lt; .001</td>
<td>17.1</td>
<td>.29</td>
</tr>
<tr>
<td>C$_2$H$_6$O</td>
<td>&lt; .001</td>
<td>22.7</td>
<td>.34</td>
</tr>
<tr>
<td>C$_2$H$_4$O$_2$</td>
<td>&lt; .001</td>
<td>37.2</td>
<td>.43</td>
</tr>
<tr>
<td>C$_4$H$_8$O$_2$</td>
<td>&lt; .001</td>
<td>34.9</td>
<td>.42</td>
</tr>
</tbody>
</table>

Analysis for the twelve structures overall showed that the treatment group had a significantly higher success rate compared to the control group in their construction abilities [$U = 4358.5, Z = -2.75, p = .006, r = .19$]; this was even more evident with the seven more difficult structures [$U = 3411.5, Z = -4.93, p < .001, r = .34$]. However, we still wanted to determine why the treatment group had greater success with these structures. For example, was the difference between the two groups caused by the control group forgetting lone pairs? Using OrganicPad’s tagging feature, the students’ submitted structures were evaluated based on the tags available in Figure 3.10.

Each student’s structure can potentially contain more than one type of error; therefore, in order to compare the two groups effectively, the percentage of each type of error was calculated for the seven difficult structures by dividing the frequency of a particular error by the total number of tags (Figure 7.11). For example, there were 359 student-drawn structures for the control group that had the error of “atom connection arrangement” for these seven structures. That number was divided by 1225 which is the
total number of tags for that group (this included the tag “correct”), which resulted in 29.3% of the tags for the control group from atom arrangement related issues. The treatment group had significantly fewer problems in the arrangement of their atoms (Table 7.7). We also noticed that the control group had twice as much difficulty with the arrangement of their atoms compared to the placement of lone pairs. The control group’s atom connection issues with placing too many bonds on carbon, hydrogen, and heteroatom reinforce their lack of understanding of how to arrange their atoms.

Figure 7.11: Types of Errors for the Main Study’s Post-Test Seven Harder OrganicPad Structures
Table 7.7: Statistical Values for Types of Errors on the Main Study’s Post-Test *OrganicPad* Structure

<table>
<thead>
<tr>
<th></th>
<th>p-value</th>
<th>$X^2$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atom Connection Arrangement</td>
<td>&lt; .001</td>
<td>49.0</td>
<td>.16</td>
</tr>
<tr>
<td>Too Many Bonds/e on Carbon</td>
<td>&lt; .001</td>
<td>21.2</td>
<td>.11</td>
</tr>
<tr>
<td>Too Many Bonds/e on Hydrogen</td>
<td>&lt; .001</td>
<td>17.7</td>
<td>.10</td>
</tr>
<tr>
<td>Too Many Bonds/e on N, O, S</td>
<td>.034</td>
<td>4.48</td>
<td>.05</td>
</tr>
</tbody>
</table>

To further investigate the hypothesis that the treatment group had developed a robust understanding of how to construct Lewis structures, we analyzed both groups’ construction process for CH$_4$O (this structure was chosen since it does not contain a central atom and only entails a few atoms). For this structure, we calculated the percentage of each tag (Figure 7.12). When analyzing these tags, three of the nine were found to have a significant difference between the two groups (Table 7.8). The Fisher’s exact test is used instead of the Chi Squared analysis when one of the groups has less than a frequency of 5. This proved that the students in the treatment group had significantly less problems with arranging their atoms compared to the control group.

Table 7.8: Statistical Values for Types of Errors on the Main Study’s Post-Test *OrganicPad* Structure of CH$_4$O

<table>
<thead>
<tr>
<th></th>
<th>p-value</th>
<th>$X^2$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atom Connection Arrangement</td>
<td>.001</td>
<td>10.9</td>
<td>.20</td>
</tr>
<tr>
<td>Too Many Bonds/e on Carbon</td>
<td>.036</td>
<td></td>
<td>.10</td>
</tr>
<tr>
<td>Correct</td>
<td>&lt; .001</td>
<td>29.1</td>
<td>.32</td>
</tr>
</tbody>
</table>

To better understand how the students were going through the process of constructing their structures, we used the *Markov Modeling* feature of *OrganicPad*. The control group’s Markov model for CH$_4$O is shown in Figure 7.13, while the treatment group’s Markov model is shown in Figure 7.14. The Zoom is the same for both of these
screenshots, so that the two Markov models could be compared. For Markov models, the more interconnected the students states are, the tighter the model; therefore, with this comparison, it became clear that the students in the control group varied considerably in their construction process because they were uncertain of how to construct their Lewis structure. This is shown in the size of their Markov model compared to the treatment group’s model and further verified in that the control group submitted 34 unique structures, while the treatment group submitted 19 unique structures. Therefore, we concluded that the treatment group had a better understanding of how to construct Lewis structures and demonstrated more expert-like strategies when constructing their structures compared to the control group.

Figure 7.12: Types of Errors for the Main Study’s Post-Test OrganicPad Structure of CH₃O
Figure 7.13: Control Group’s Markov Model for the Main Study’s Post-Test

OrganicPad Structure of CH₄O
Figure 7.14: Treatment Group’s Markov Model for the Main Study’s Post-Test

*OrganicPad* Structure of CH$_4$O
To further prove that the difference in the groups’ construction ability resulted from how they constructed their Lewis structures and not because the students forgot lone pairs, we reanalyzed the twelve submitted post-test structures to include structures lacking lone pairs as correct. Figure 7.15 shows the percent correct for both groups on each structure, the overall twelve structures, and the seven more difficult structures. We found that the two groups were statistically equivalent in their ability to construct Lewis structures for only three of the twelve structures (Table 7.9). It should be mentioned that these three structures (NH₃, CO₂, and H₂O) are probably the most frequently used structures in instruction due to their simplicity. Therefore, we concluded that the treatment group performed significantly higher than the control group on the twelve structures \([U = 3266.0, Z = -5.22, p < .001, r = .36]\) and the seven more difficult structures \([U = 2584.0, Z = -6.81, p < .001, r = .47]\). When comparing these results to the ones in Figure 7.10 (structures incorrect if missing lone pairs), we found that three additional structures (HCN, CH₃OH, and C₂H₇N) were found to have a significant difference between the two group, while the significant difference for H₂O disappeared. This means that for the structures of HCN, CH₃OH, and C₂H₇N, the treatment group forgot lone pairs more frequently than the control group, while for H₂O the control group forgot lone pairs more frequently.
Figure 7.15: Comparison of Percent Correct for the Main Study’s Post-Test OrganicPad Structures Including Structures Only Missing Lone Pairs as Correct

Table 7.9: Statistical Values for the Main Study’s Post-Test OrganicPad Structures Including Structures Only Missing Lone Pairs as Correct

<table>
<thead>
<tr>
<th>Chemical Formula</th>
<th>p-value</th>
<th>$X^2$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCN</td>
<td>.012</td>
<td>6.24</td>
<td>.18</td>
</tr>
<tr>
<td>NH$_2^-$</td>
<td>.040</td>
<td>4.23</td>
<td>.15</td>
</tr>
<tr>
<td>CH$_3$O</td>
<td>&lt; .001</td>
<td>27.0</td>
<td>.37</td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>.002</td>
<td>9.78</td>
<td>.23</td>
</tr>
<tr>
<td>C$_2$H$_6$O</td>
<td>&lt; .001</td>
<td>51.1</td>
<td>.39</td>
</tr>
<tr>
<td>CH$_3$CH$_2$OH</td>
<td>.024</td>
<td>5.12</td>
<td>.17</td>
</tr>
<tr>
<td>C$_2$H$_7$N</td>
<td>.003</td>
<td>9.12</td>
<td>.22</td>
</tr>
<tr>
<td>C$_2$H$_4$O$_2$</td>
<td>&lt; .001</td>
<td>42.5</td>
<td>.46</td>
</tr>
<tr>
<td>C$_4$H$_8$O$_2$</td>
<td>&lt; .001</td>
<td>35.5</td>
<td>.42</td>
</tr>
</tbody>
</table>

From all of the results of the students’ structure construction ability, the evidence indicates that the students in the CLUE curriculum have a better understanding of how to construct Lewis structures by exhibiting more expert-like strategies for their construction
process. To determine if these students also improved in representational competence, their responses to the ILSS were also analyzed.

Analysis of the data began with the calculation of the percentage of students that chose each type of information, by group, Figure 7.16. Nine of the sixteen types of information resulted in a significant difference between the two groups of students (Table 7.10). The “potential for resonance” was the only answer choice that the treatment group selected significantly less frequently than the control group, which is most likely because the term “resonance” was not introduced during instruction.

Figure 7.16: Percentage of Students that Selected Each Type of Information for the Main Study’s Post-Test ILSS
Table 7.10: Statistical Values for the Individual Types of Information on the Main Study’s Post-Test ILSS

<table>
<thead>
<tr>
<th>Type of Information</th>
<th>p-value</th>
<th>$X^2$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybridization</td>
<td>&lt; .001</td>
<td>14.4</td>
<td>.27</td>
</tr>
<tr>
<td>Polarity</td>
<td>&lt; .001</td>
<td>30.7</td>
<td>.39</td>
</tr>
<tr>
<td>Reactivity</td>
<td>&lt; .001</td>
<td>18.2</td>
<td>.30</td>
</tr>
<tr>
<td>Relative Boiling Point</td>
<td>&lt; .001</td>
<td>27.9</td>
<td>.37</td>
</tr>
<tr>
<td>Intermolecular Forces</td>
<td>&lt; .001</td>
<td>53.8</td>
<td>.51</td>
</tr>
<tr>
<td>Formal Charges</td>
<td>.015</td>
<td>5.90</td>
<td>.18</td>
</tr>
<tr>
<td>Relative Melting Point</td>
<td>&lt; .001</td>
<td>22.0</td>
<td>.33</td>
</tr>
<tr>
<td>Physical Properties</td>
<td>&lt; .001</td>
<td>17.1</td>
<td>.29</td>
</tr>
<tr>
<td>Potential for Resonance</td>
<td>.007</td>
<td>7.15</td>
<td>.19</td>
</tr>
</tbody>
</table>

When grouping the answer choices, this analysis further showed the treatment and control groups were equivalent with respect to their understanding that structural information and geometrical information are obtained using a Lewis structure. However, when continuing further in the process of connecting structures and properties, we found that there was a significant difference between the two groups in their ability to select molecular level information, chemical property information, and physical property information (Table 7.11). The percentage of both groups that selected each grouping of information is shown in Figure 7.17. Even though this post-test was given at the latest possible time in the semester, the control group was currently covering the chapter on intermolecular forces and phase changes. Therefore, we could not be certain if the differences between the two groups were caused from the CLUE curriculum or the control group currently learning the material.
### Table 7.11: Statistical Values for the Categories of Information on the Main Study’s Post-Test ILSS

<table>
<thead>
<tr>
<th>Category of Information</th>
<th>p-value</th>
<th>$X^2$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Level</td>
<td>&lt; .001</td>
<td>28.3</td>
<td>.38</td>
</tr>
<tr>
<td>Chemical Property</td>
<td>.001</td>
<td>12.1</td>
<td>.25</td>
</tr>
<tr>
<td>Physical Property</td>
<td>&lt; .001</td>
<td>31.4</td>
<td>.40</td>
</tr>
</tbody>
</table>

![Bar Chart](#)

**Figure 7.17: Percentage of Students that Selected Each Category of Information for the Main Study’s Post-Test ILSS**

In addition to this assessment, a multiple-choice question, “Lewis Electron Dot Structures can be used to determine which of the following information? Indicate all possible choices, even if this results in multiple bubbles,” was placed on the final exam. The answer choices were: (a) molecular structure, (b) boiling and melting points, (c) intermolecular forces, (d) molecular polarity and/or reactivity, and (e) resonance and/or formal charges. Upon further examination, we disregarded the answer choices “molecular structure” since it could have multiple interpretations and “molecular polarity
and/or reactivity” because it contained two different groups of information (polarity from molecular level information and reactivity from chemical property information).

The percentage of students that selected each type of information for this new question is shown in Figure 7.18. When comparing the two groups for each type of information, we concluded that the two groups were statistically different for intermolecular forces $[X^2 (1, N = 205) = 13.6, p < .001, \phi = .27]$. The answer choice “boiling and melting point” showed a borderline difference although not significant $[X^2 (1, N = 205) = 3.59, p = .058, \phi = .14]$.

![Figure 7.18: Comparison of the Control and Treatment Groups on the Structure-Property Final Exam Question](image)

The “resonance and/or formal charges” answer choice is a type of surface feature information, the lowest level of representational competence, and since every student can typically determine surface level information, it should not be surprising that there was
no difference between the groups for this option. However, the answer choice “intermolecular forces,” where the two groups selection rates were different, is a type of molecular level information, which is a higher level of representational competence and one of the more abstract concepts. Within the traditional curriculum, the process of connecting structure and property relationships is not explicit and they are only asked about the end goal, ranking boiling/melting points, which causes some students to rely on heuristics and not realize the reasons for the ranking trends. These results suggest that the CLUE curriculum may help students better understand the process of connecting structures and properties.

*Do the Students Retain the Knowledge?*

For meaningful learning to occur, students must be able to retain and use information in new situations. While these short-term assessments provide encouraging information about the efficacy of the CLUE curriculum, they are not sufficient to confirm that meaningful learning has occurred. The next stage in the evaluation project was to administer assessment activities in the second semester. Any students from the main study that were originally part of the treatment group and continued with the CLUE curriculum for the second semester or originally part of the control group and remained in a traditional curriculum instruction, were monitored through their second-semester of general chemistry. Some students in the original sample did not continue into the CLUE treatment section for a number of reasons, for example: time conflicts with scheduling, the second part of the course not being required for their major, switching majors, etc.
Fortunately 61% of the students (56 of the original 92) in the treatment group and 73% of the students (83 of the original 113) in the control group were still available for tracking purposes since these students are in biological-related majors and typically are required to take more than one semester of general chemistry.

**Retention Study – Beginning of Semester Comparisons**

Since some students did not continue onto the second-semester of general chemistry, it was important to verify that the two groups were still equivalent in their cognitive and affective domains. To determine this, the students pre-test assessments from the first-semester of general chemistry were re-evaluated since instruction could have had an effect on these domains. We found that the two groups were statistically equivalent on all of these measurements (Table 7.12).

**Table 7.12: Comparison of Pre-Test Assessments for Retention Study**

<table>
<thead>
<tr>
<th>Pre-Assessment</th>
<th>Control Group Mean $(N = 82)$</th>
<th>Treatment Group Mean $(N = 51)$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAT Composite</td>
<td>1215</td>
<td>1191</td>
<td>.38</td>
</tr>
<tr>
<td>TOLT</td>
<td>7.7 (out of 10)</td>
<td>8.2 (out of 10)</td>
<td>.24</td>
</tr>
<tr>
<td>Intellectual Accessibility – ASCIV2</td>
<td>44.6</td>
<td>40.7</td>
<td>.22</td>
</tr>
<tr>
<td>Emotional Satisfaction – ASCIV2</td>
<td>53.7</td>
<td>53.6</td>
<td>.62</td>
</tr>
<tr>
<td>Self-Efficacy for Learning and Performance – MSLQ</td>
<td>75.3</td>
<td>75.2</td>
<td>.50</td>
</tr>
</tbody>
</table>

The follow-up testing for the students’ ability to construct and relate structures and properties was administered two weeks into the beginning of the second-semester of
general chemistry. By this time, all of the students had revisited the topic of structures in a review of first-semester material. The control group also finished instruction on the last chapter of the first-semester material, Liquids, Solids and Intermolecular Forces (Table 6.3). Students were first evaluated, using *OrganicPad*, on their ability to construct the Lewis structures for twelve chemical formulas (NH$_2$, HCN, CH$_4$, C$_2$H$_6$O, CH$_3$CH$_2$OH, C$_2$H$_7$N, C$_2$H$_4$O, C$_2$H$_6$O$_2$, CH$_3$CO$_2$H, CH$_3$COOH, N$_2$H$_4$, H$_2$O), where nine of these structures were considered to be more difficult (CH$_4$, C$_2$H$_6$O, CH$_3$CH$_2$OH, C$_2$H$_7$N, C$_2$H$_4$O, C$_2$H$_6$O$_2$, CH$_3$CO$_2$H, CH$_3$COOH, N$_2$H$_4$). For comparison purposes, eight of the twelve structures administered were from the main study’s post-test (HCN, NH$_2$, H$_2$O, CH$_4$, C$_2$H$_6$O, CH$_3$CH$_2$OH, C$_2$H$_7$N, C$_2$H$_4$O, C$_2$H$_6$O$_2$).

Two questions were examined: 1. Do the students retain the knowledge from the previous semester? and 2. Is there a significant difference between the two groups in their construction ability? A Wilcoxon Rank Sign analysis indicated that both groups maintained their ability to construct Lewis structures from the end of the previous semester (control group [$Z = -0.79, p = .43$] and treatment group [$Z = -1.49, p = .14$]). To determine if there was still a significant difference between the two groups, the percent correct for each structure, overall twelve structures, and nine harder structures was calculated (Figure 7.19). This analysis showed that the students in the CLUE curriculum performed significantly higher than the students in the traditional curriculum for nine out of twelve structures (Table 7.13), the overall percent correct [$U = 1523.0, Z = -3.46, p = .001, r = .29$] and the nine more difficult structures [$U = 1321.0, Z = -4.34, p < .001, r = .37$]. Even when considering that students forget to place lone pairs on their structures,
we found the two groups were still significantly different (overall percent correct \([ U = 1051.0, Z = -5.50, p < .001, r = .47] \) and nine harder structures percent correct \([ U = 1003.5, Z = -5.72, p < .001, r = .49] \)).

**Figure 7.19: Comparison of the Percent Correct for the Retention Study’s Beginning of the Semester OrganicPad Structures**

**Table 7.13: Statistical Values for Retention Study’s Beginning of the Semester OrganicPad structures**

<table>
<thead>
<tr>
<th>Chemical Formula</th>
<th>p-value</th>
<th>( X^2 )</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{NH}_2 )</td>
<td>&lt; .001</td>
<td>15.82</td>
<td>.35</td>
</tr>
<tr>
<td>( \text{CH}_4 \text{O} )</td>
<td>.002</td>
<td>9.93</td>
<td>.28</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_6\text{O} )</td>
<td>&lt; .001</td>
<td>13.89</td>
<td>.33</td>
</tr>
<tr>
<td>( \text{CH}_3\text{CH}_2\text{OH} )</td>
<td>.048</td>
<td>3.90</td>
<td>.18</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_5\text{O} )</td>
<td>.005</td>
<td>7.84</td>
<td>.25</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_4\text{O}_2 )</td>
<td>&lt; .001</td>
<td>30.83</td>
<td>.49</td>
</tr>
<tr>
<td>( \text{CH}_3\text{CO}_2\text{H} )</td>
<td>.001</td>
<td>11.31</td>
<td>.30</td>
</tr>
<tr>
<td>( \text{CH}_3\text{COOH} )</td>
<td>&lt; .001</td>
<td>15.74</td>
<td>.35</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>&lt; .001</td>
<td>13.06</td>
<td>.33</td>
</tr>
</tbody>
</table>
Retention Study – End of Semester Comparisons

The students were further evaluated at the end of their second-semester of general chemistry. Two assessments were used: OrganicPad and ILSS. The students were asked to construct the Lewis structure for twelve chemical formulas (HCN, CH$_4$, C$_2$H$_6$O, CH$_3$CH$_2$OH, N$_2$H$_4$, CH$_3$CO$_2$H, CH$_3$COOH, C$_2$H$_4$O, CH$_3$NH$_3^+$, C$_4$H$_8$O$_2$, C$_3$H$_7$NO, and NH$_3$). Eight of these structures were previously administered in the pre-test for comparison reasons, with an additional four structures. The control and treatment groups were compared using two criteria: the overall success for the twelve structures and the ability to construct the two most unfamiliar chemical formulas, C$_4$H$_8$O$_2$ and C$_3$H$_7$NO. Since students do not have enough experience to identify the most likely structures, any viable Lewis structure were accepted, even structures considered to be less sophisticated. (e.g. a structure that contains oxygen single-bonded to another oxygen as in the example of a COOH group).

The success rate for each structure, the mean on the twelve structures, and the two unfamiliar structures are shown in Figure 7.20. For eleven of the twelve structures, we found the two groups were significantly different (Table 7.14); therefore, it was not surprising that there was a significant difference for the overall success rate between the two groups \([U = 691.0, Z = -7.10, p < .001, r = .60]\). The purpose of analyzing the two less familiar structures was to determine how students handle structures that they have not previously seen. That is: can students transfer their knowledge and skills to a new situation. There was a significant difference for these two structures between the two groups of students \([U = 1348.0, Z = -5.05, p < .001, r = .43]\).
Figure 7.20: Comparison of the Percent Correct for the Retention Study’s End of the Semester OrganicPad Structures

Table 7.14: Statistical Values for Retention Study’s End of the Semester OrganicPad Structures

<table>
<thead>
<tr>
<th>Chemical Formula</th>
<th>p-value</th>
<th>$\chi^2$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCN</td>
<td>.019</td>
<td>5.48</td>
<td>.21</td>
</tr>
<tr>
<td>CH$_3$O</td>
<td>&lt; .001</td>
<td>25.21</td>
<td>.44</td>
</tr>
<tr>
<td>C$_2$H$_6$O</td>
<td>&lt; .001</td>
<td>28.64</td>
<td>.47</td>
</tr>
<tr>
<td>CH$_3$CH$_2$OH</td>
<td>.021</td>
<td>5.35</td>
<td>.21</td>
</tr>
<tr>
<td>N$_2$H$_4$</td>
<td>.025</td>
<td>5.06</td>
<td>.21</td>
</tr>
<tr>
<td>CH$_3$CO$_2$H</td>
<td>&lt; .001</td>
<td>41.79</td>
<td>.56</td>
</tr>
<tr>
<td>CH$_3$COOH</td>
<td>&lt; .001</td>
<td>45.24</td>
<td>.58</td>
</tr>
<tr>
<td>C$_2$H$_4$O</td>
<td>&lt; .001</td>
<td>41.81</td>
<td>.56</td>
</tr>
<tr>
<td>C$_4$H$_8$O$_2$</td>
<td>&lt; .001</td>
<td>33.77</td>
<td>.51</td>
</tr>
<tr>
<td>C$_3$H$_7$NO</td>
<td>.015</td>
<td>5.97</td>
<td>.22</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>.020</td>
<td>5.37</td>
<td>.21</td>
</tr>
</tbody>
</table>
Even though the treatment group performed significantly better than the control group in their construction ability, we wanted to verify that this difference was not because the students omitted lone pairs. The percent of students that correctly drew each structure and how they performed overall for both the twelve structures and the two less familiar structures is shown in Table 7.15. The two groups were significantly different for nine of the twelve structures (Table 7.15), the overall percent correct \( U = 1474.0, Z = -7.00, p < .001, r = .59 \) and the percent correct for the two unfamiliar structures \( U = 719.5, Z = -4.26, p < .001, r = .36 \). This provides evidence that the instructional plan in the CLUE curriculum helps students develop and retain a more robust understanding of how to construct Lewis structures.

**Table 7.15: Percentage Correct and Statistical Values for Retention Study’s End of the Semester OrganicPad Structures Including Structures Only Missing Lone Pairs as Correct**

<table>
<thead>
<tr>
<th>Chemical Formula</th>
<th>Control Group Mean (%)</th>
<th>Treatment Group Mean (%)</th>
<th>p-value</th>
<th>( X^2 )</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCN</td>
<td>41.7</td>
<td>78.6</td>
<td>&lt; .001</td>
<td>17.14</td>
<td>.37</td>
</tr>
<tr>
<td>CH₃O</td>
<td>59.5</td>
<td>91.1</td>
<td>&lt; .001</td>
<td>15.11</td>
<td>.35</td>
</tr>
<tr>
<td>C₂H₆O</td>
<td>61.9</td>
<td>94.6</td>
<td>&lt; .001</td>
<td>17.50</td>
<td>.37</td>
</tr>
<tr>
<td>CH₃CO₂H</td>
<td>21.4</td>
<td>67.9</td>
<td>&lt; .001</td>
<td>28.28</td>
<td>.46</td>
</tr>
<tr>
<td>CH₃COOH</td>
<td>28.6</td>
<td>80.4</td>
<td>&lt; .001</td>
<td>34.01</td>
<td>.51</td>
</tr>
<tr>
<td>C₂H₄O</td>
<td>22.6</td>
<td>71.4</td>
<td>&lt; .001</td>
<td>30.86</td>
<td>.48</td>
</tr>
<tr>
<td>C₄H₈O₂</td>
<td>7.1</td>
<td>44.6</td>
<td>&lt; .001</td>
<td>25.28</td>
<td>.44</td>
</tr>
</tbody>
</table>

The end of semester responses to the ILSS, Appendix C, were analyzed (Figure 7.21). Six of the sixteen types of information produced significant differences between the control and treatment groups (Table 7.16). Further analysis showed: three of the six types of information involved property information (reactivity, physical properties, and
acidity/basicity). The answer choices of “relative boiling point” and “relative melting point” were the only types of property information where the two groups were statistically equivalent. One possibility for this could be that in the traditional curriculum students are typically asked to rank these properties based on their structures, which is further evident in that the answer choice “boiling point” has the highest selection rate (46.4%) for all of the property information choices.

Figure 7.21: Percentage of Students that Selected Each Type of Information for the Retention Study’s End of the Semester ILSS
Table 7.16: Statistical Values for Retention Study’s End of the Semester ILSS

<table>
<thead>
<tr>
<th>Type of Information</th>
<th>p-value</th>
<th>$\chi^2$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybridization</td>
<td>.009</td>
<td>6.76</td>
<td>.24</td>
</tr>
<tr>
<td>Polarity</td>
<td>.020</td>
<td>5.37</td>
<td>.21</td>
</tr>
<tr>
<td>Reactivity</td>
<td>.005</td>
<td>7.84</td>
<td>.25</td>
</tr>
<tr>
<td>Formal charges</td>
<td>.001</td>
<td>11.92</td>
<td>.31</td>
</tr>
<tr>
<td>Physical properties</td>
<td>.003</td>
<td>8.72</td>
<td>.27</td>
</tr>
<tr>
<td>Acidity/basicity</td>
<td>&lt; .001</td>
<td>12.15</td>
<td>.31</td>
</tr>
</tbody>
</table>

The percent of students that selected each group of information was calculated for the control and treatment groups and is shown in Figure 7.22. Only 50% of the control group showed proficient understanding of the purpose of Lewis structures, which supports our previous results (typically less than half of students exhibit a proficient representational competence with regards to Lewis structures – Table 5.3) from Ed’s Tools (Chapter 5). For “chemical property information,” the two groups were found to be statistically different in their understanding that this type of information could be obtained using a Lewis structures [$\chi^2 (1, N = 139) = 10.2, p = .001, \phi = .29$]. Although both groups gained in their understanding of chemical property information during the second-semester of general chemistry, these findings were consistent with the results from above since both of the chemical property attributes (reactivity and acidity/basicity) were found to have a significant difference between the two groups.

For the grouping “physical property information,” the treatment group had a selection rate about 15% higher than the control group, though no statistical significance was found [$\chi^2 (1, N = 139) = 1.49, p = .22$]. Although the treatment group had a small gain in their selection of this group of information, the control group had substantial gains and caught up to the treatment group at the end of the second-semester.
The greatest difference for this group of information came from the answer choice “physical properties,” which could result from the control students not fully understanding how physical properties relate to Lewis structures other than through ranking structures based on learned heuristics. For example, an organic chemistry student that was interviewed on their understanding and connection of structure and property stated that “I don’t know how you would get a boiling point or anything like that from a structure… I don’t know how you could tell a whole lot about it just based off the structure,” although he could answer every boiling point trend correctly.

Figure 7.22: Percentage of Students that Selected Each Category of Information for the Retention Study’s End of the Semester ILSS

Figure 7.22 also shows a gradual decrease in the students’ selection rate as they progressed further through the process of connecting structures and properties (Figure 5.5). For example, the treatment group has a selection rate of 100% for the structural
information, 95% for geometrical information, 93% for molecular information, 80% for chemical property information, and 64% for physical property information. This provides evidence that the structure-property relationship is not dichotomous. The example from Chapter 5 with regards to the two graduate chemistry students, one believed that no information could be obtained from Lewis structures, while the other student believed they were very valuable and that there was an abundance of information that could be obtained from them (Cooper et al., 2010). We instead suggest that the students’ representational competence is a continuum with students containing varying degrees of comprehension of the process.

Conclusions

Four main studies were conducted to evaluate the effectiveness of the CLUE curriculum to increase students’ representational competence through the encouragement of meaningful learning: an instructor effect, pilot study, main study, and retention study. For these studies, the two main measures used were to gauge students’ ability to construct Lewis structures and establish if students then connect structures to their properties.

When comparing the two groups’ ability to construct Lewis structures, the treatment group had significantly higher success rates compared to the traditional general chemistry curriculum for the pilot and main studies (Figures 7.2 and 7.10). Not only were there immediate effects on the students success, but it carried over to some extent to the end of the second-semester of the course (Figures 7.19 and 7.20). The treatment group’s higher success rates result from the students demonstrating more expert-like
strategies for their construction process. This is evident in Figure 7.11, where the
students in the treatment group had significantly less atom arrangement issues for the
seven more difficult and unfamiliar structures and further proven from the Markov
Models (Figures 7.13 and 7.14). Even when including structures that lacked lone pairs as
correct, the effects were still present (Figure 7.15 and Table 7.15). Figure 4.1 showed
that organic chemistry students’ greatest difficulty with constructing Lewis structures
stemmed from their uncertainty of atom arrangement within structures and the absence of
lone pairs. Of these two types of errors, atom connectivity is the error that is more
imperative. These organic chemistry students make the same types of errors as the
general chemistry students in these studies. By providing students with an explicit
connection between the molecular level structure and the bulk properties of the substance
instead of presenting students with a series of meaningless rules, they are more competent
in generating valid representations.

The second measure to evaluate the effectiveness of the CLUE curriculum was
the ILSS, which assesses the students’ level of representational competence for Lewis
structures. As previously found (Table 5.3), less than half of students attain a high level
of understanding and can fully relate structures to their properties (Cooper et al., 2010).
This was further confirmed in Figure 7.22 with the control group having a selection rate
of 52.4% for both chemical and physical property information. The CLUE curriculum
proved to be successful in increasing students’ representational competence since their
selection rate was 80.4% for chemical property information and 64.3% for physical
property information. Therefore, the treatment group is able to better relate structures and their properties.

Through comparing Instructor A to Other Instructors, we verified that these effects were not because of the instructor but in fact stemmed from the curriculum itself since the two groups post-instruction were statistically equivalent in their structure construction ability for the instructor effect study (Figure 7.6). Therefore, from conducting a pilot study, main study, retention studies, and concluding that the effects were not from the instructor, we believe that we have provided substantial evidence that the CLUE curriculum improves students’ understanding of how to construct and utilize Lewis structures by encouraging the students to participate in meaningfully learning.
CHAPTER EIGHT

CONCLUSIONS AND FUTURE WORK

Conclusions

There were two guiding questions used to investigate and evaluate how students develop representational competence. To determine if students’ understood the relationship of structure and property, the question of importance was: How do students construct and utilize Lewis structures? Second, we wanted to evaluate students’ ability to construct and use Lewis structures through an alternative instructional approach (Chemistry, Life, the Universe and Everything – CLUE). To better answer these two questions, four specific goals were created: 1. investigate students’ construction process of Lewis structures using a tablet-PC program (OrganicPad – Chapter 3) and think-aloud interviews, 2. investigate what students believe is the purpose of Lewis structures, 3. develop a reliable and valid survey question to assess students’ representational competence, and 4. evaluate if the CLUE curriculum, in particular the instructional plan for Lewis structures, increases students’ representational competence.

To develop an understanding of students’ construction process for Lewis structures, a sequential mixed-method study was conducted. We first analyzed, using OrganicPad, how organic chemistry students’ constructed their Lewis structures and discovered that the students had much difficulty. The most common problems that students had were proper atom connections and including lone pairs (Figure 4.1). Since these were organic chemistry students, the absence of lone pairs on their structures was not a great a cause for concern as their problems with the connectivity of atoms in the
structures. However, the omission of lone pairs could become problematic for students trying to determine the spatial arrangement of molecules for purposes such as understanding steric hindrance. The other concern was that students’ level of success decreased with the construction of a two-carbon structure compared to one-carbon structure since students in organic chemistry typically must work with compounds with more than one carbon.

The quantitative portion of this study provided evidence that students have many difficulties constructing Lewis structures. The think-aloud interviews, allowed us to develop an understanding of why students were having these difficulties. For example interviews showed that students created their own “home-grown” rules, perhaps to fill voids in their knowledge of how to construct Lewis structures. The students' self-developed rules even included a strategy for how to deal with determining the arrangement of the atoms in the structure, “just write it all out” (Chapter 4). Another rule that students stated as a guideline for their construction process was the need for “symmetry.” The students’ creation of their own rules indicated that the standard ones taught for the construction process have no underlying meaning. It was clear that the construction process for students is very difficult since they were trying to develop guidelines based on structures they have previously constructed to compensate for voids in their knowledge.

The results from this first goal led to the question of whether students understood why they were asked to construct these structures. To investigate this, we asked students (using Ed’s Tools and as part of the qualitative portion of the study above) what
The students’ responses to this question varied greatly. Some students could only focus on structural features (low level of representational competence – Chapter 2), while others could state an array of information and use different representations to gather information (high level of representational competence). For example, the quote in Chapter 5 from the two graduate students represents the two extremes. Rose had a low level of representational competence since she believed that these structures were “almost useless” and that they “don’t really reveal much about geometry;” however, Charlie had a much higher level of representational competence since he believed they “provide a really good picture of where the reactivity of the molecule would occur because if you explain reactivity based on valence electrons or lack of electron (so negative charges, positive charges, lone pairs), you can get a really good idea of where the reactivity may take place…if there’s going to be a reaction…and I think that’s one of the more important aspects of it” (Cooper, Grove, et al., 2010). In his mind he could relate the Lewis structure to a molecular level depiction to think about its reactivity.

The results from Ed’s Tools and the interviews showed that only about half of the students, regardless of level, have a deeper understanding and higher level of representational competence since they were able to relate Lewis structures to physical and chemical properties (Table 5.3) (Cooper, Grove, et al., 2010). We believe that these findings can be explained by the idea that students are not engaging in meaningful learning as they learn to draw structures. First, the construction rules do not rely on any relevant previous knowledge that the students possess. For example, students do not
understand why the least electronegative atom is placed in the center or why hydrogen is always terminal. Second, the students do not understand the importance of these structures (that is why they are learning to draw them since they typically do not relate structures to their chemical and physical properties. Therefore, students tend to learn these structures as isolated pieces of knowledge via rote memorization instead of choosing to learn meaningfully.

To better understand how a larger group of students understand Lewis structures and develop representational competence, we created the ILSS (goal three). This survey was created using the student responses from the open-ended questions on Ed’s Tools that asked about types of information that can be obtained using a Lewis structure. From the most common student responses, we created a multiple-answer question where students can select all of the information that they believe can be inferred. For beginning students who truly believe Lewis structures do not provide any information, the answer choice “no information” was added; this answer choice was also used as a verification measure for students that randomly selected answer choices or selecting every type of information. This survey was further tested for reliability and validity purposes through multiple administrations and modifications until students no longer reported any confusion about the answer choices or the addition of other types of information that could be obtained. Since the development of the survey’s final version (Appendix C), it has been administered multiple times to over 3,000 general chemistry and organic chemistry students.
The last goal for this research project was to determine if the CLUE curriculum improves students’ representational competence. The effectiveness of this new instructional plan was evaluated by investigating the students’ ability to construct Lewis structures using OrganicPad and how they link those structures to physical/chemical properties on the Information from Lewis Structures survey. From the pilot and main studies, we determined that the students in the CLUE curriculum demonstrated more expert-like strategies to construct their Lewis structures compared to the traditional curriculum. That is, the students did not randomly connect their atoms, but instead used more sophisticated arrangements. This was evident from the students in the treatment group that had a significantly higher success rate in constructing their structures compared to the control group (Figure 7.10), significantly fewer problems with the arrangements of their atoms (Figure 7.11), and the differences in the groups’ Markov models for the structure CH₄O (Figures 7.13 and 7.14). We also verified that the differences between the two groups were not caused by students forgetting to place lone pairs on their structures (Figure 7.15 and Table 7.15). This confirmed that the students in the treatment group maintained their expert-like ability to construct Lewis structures.

We also concluded from this study that the CLUE curriculum improved students’ level of representational competence compared to the students in the traditional curriculum. Figure 7.18 shows that the treatment group had a better understanding that intermolecular forces could be determined using a Lewis structure based on their final exam answers. Although the two groups demonstrated similar understanding for the last step of relating structures and properties (predicting property information – Figure 5.5),
the treatment group had a better understanding of the connection process for how the property information can be obtained. Typically in the traditional curriculum, students are asked to rank structures based on their boiling/melting point through the use of heuristics and are not explicitly instructed on the process for connecting Lewis structures and properties. When evaluating the two groups’ representational competence at the end of the second-semester of general chemistry, the treatment group still maintained a higher level. This group presented a significantly better understanding that Lewis structures could be used to obtain chemical property information and had a slightly higher understanding that they could be used to determine physical property information (Figure 7.22).

The previously-described studies (main and retention) and the study showing that the effects were not because of the instructor, provide strong evidence that the CLUE curriculum was able to improve students’ Lewis construction ability and representational competence. The students from this curriculum appear to be engaging in meaningful learning since they are able to make the connections between the information of structures and their properties.

**Implications for Instruction**

The above research shows that students have a great deal of difficulty with constructing structures and relating them to their properties; however, it appears that providing a learning environment that facilitates meaningful learning leads students to develop a higher level of representational competence. Therefore, we support Novak’s
contention that the requirements for meaningful learning should be provided when possible within instruction.

First, it is important that students possess relevant prior knowledge. It is important that students first develop an understanding about bonding and energy changes for structures, in that bonds result from the system becoming more stable and not because elements want octets. The second requirement – that the material must be perceived as meaningful by linking the new knowledge to other knowledge - means that students must be explicitly provided with the links between the “chunks” of curricular material, providing students with reasons to deem the new information important. With a foundation of understanding bonding, students can then be introduced (using computer models) to representations of molecules at the molecular level to develop an understanding of three-dimensional representations and their relationship to properties of these compounds. We suggest that students should be first introduced to simple compounds (e.g. hydrocarbons) before moving onto more complex ones (e.g. heteroatoms, multiple bonds). Next, Lewis structures should be presented as a tool for representing the three-dimensional structure of a compound since students should only learn how to construct Lewis structures to relate structures with their properties. Lastly, the students must choose to learn meaningfully. Therefore, students should be encouraged to participate in meaningful learning and be discouraged from rote memorization by providing them with an environment in which they can start to understand different representations and models to build upon/use them when necessary.
**Future Directions**

With this research project, we were able to determine if students were connecting structures with their properties; however, for the students that are going through the process, there is still the question of how these linkages are made. While our data provide quantitative evidence for the effect of a revised curriculum, the data do not tell us how students learn to make these connections. A qualitative investigation in which students are interviewed is the next step. A potential interview protocol involves asking students to: predict properties of a compound, draw the structure of that compound, and explain, using that structure, if they can determine any of the properties they just stated. By analyzing the data from both general chemistry students and organic chemistry students, a better understanding of how students visualize the reactivity and interaction of different molecules may be determined.

Another way that the findings from this research project can be further developed is to determine other methods that could also improve students’ representational competence. We recognize that a full-curriculum reform may not be attainable for every instructor and therefore want to develop potential alternative interventions. Two such programs that could be explored are: 1. the contextual feedback feature of OrganicPad, and 2. a newly developed system BeSocratic (Figure 8.1) – a web-based computer program that recognizes and responds to free-form student input. To fully engage students in meaningful learning with these programs, we believe it would be beneficial to incorporate several different activities within the traditional curriculum.
For example the *contextual feedback* feature of *OrganicPad* provides Socratic prompts designed to elicit metacognitive activity as students move through the construction process. After this instruction, students could work through the structure to property process (Figure 5.5) in a sequence of different activities using *BeSocratic*. This is a unique program that allows students to answer various formats of questions (i.e. graphical, pictorial, and free-response), while receiving constructive multiple-tiered feedback. The different activities could consist of helping students first understand that structures can provide a plethora of information, transitioning from the Lewis structure to the molecular level representations through understanding electron pair geometry and molecular shape, how to identify polarity of a molecule, and visualize depictions of the types of intermolecular forces present and how they can help predict properties.
Appendix A

OrganicPad’s User Manual

OrganicPad User Manual

Melanie M Cooper (cmelani@clemson.edu)

Sonia M Underwood (sunderw@clemson.edu)

Samuel P Bryfczynski (sbryfcz@clemson.edu)
# Table of Contents

- Basics ................................................................................................................................................. 2
- Logging In............................................................................................................................................... 7
- Making a Quiz/Tutorial.......................................................................................................................... 8
- Taking a Quiz/Tutorial.......................................................................................................................... 12
- Starting a Classroom Activity .............................................................................................................. 15
- Joining a Classroom Activity............................................................................................................... 19
- Reviewing Submissions.......................................................................................................................... 21
- Grading Submissions.............................................................................................................................. 23
- Tagging Submissions.............................................................................................................................. 25
Basics

1. Once *OrganicPad* opens, the screen below should appear and in the center of the screen is the drawing canvas.

![OrganicPad Interface](image)

2. Along the left-hand side of the window is a tool selector. Each tool controls how your strokes will be interpreted. The currently selected tool is highlighted as shown below with the “Draw” tool.

![Tool Selector](image)
3. The “Draw” tool will convert your handwritten strokes in the center drawing canvas into atoms, bonds, charges, and electrons. You must pause briefly after each structure you draw in order for OrganicPad to properly recognize what you have drawn.

4. The “Push” tool allows you draw mechanism arrows.
5. The “Erase” tool will erase the parts of your structure that you put a line through.

6. The “Pen” tool allows you to make annotations without your strokes being interpreted.
7. The “Select” tool allows for parts of your drawing to be moved and rotated. With the “Select” tool selected, dragging your cursor in the canvas will place a box around parts of your drawings. With the parts selected, you can move the box by dragging it around the screen. Dragging a corner of the box allows the selected parts to be rotated.

8. The “3D” tool converts your structure drawing into a three dimensional model. Once the model appears, it may be manipulated and displayed in several ways. Dragging with stylus or the left mouse button rotates the molecule. Holding the stylus down for a second and then dragging the stylus or dragging with the right mouse button zooms in and out. The “Labels” checkbox will determine if the model’s atoms are displayed with labels. The “Ball and Stick”, “Space Filled”, and “Electrostatic Potential Map” buttons determine how the model is displayed.
9. Along the bottom of the OrganicPad window is a list of commonly used functions. The “Reset” button clears the canvas of all the drawings. The “Check” button checks your chemical structures against a list of common chemistry rules and displays any problems that are present. The “Undo” button undoes the last drawing change. The “Clean” button changes the layout of your chemical structures to a standardized structure. The “Replay” button plays an animation of all the drawings you have made.
**Logging In**

1. When a “Login” window appears, you will need to either enter in your current information or register a new account.

2. If you are a new user, click the “Not registered yet?” button. Otherwise, enter your email and password and click “Login”.

3. Next, fill in the registration information and click “Register”. If you are registering as a teacher, select “Teacher” and fill out the additional information and click “Register”.

4. This will return you to the previous window with your email address filled in. Enter your password and click “Login”.
Making a Quiz/Tutorial
1. Once OrganicPad opens, click on “Teacher-Quiz-Create a Quiz”.

2. A “Login” window will appear. Refer to “Logging In” Section.

3. Once logged in, you will be prompted with the “Quiz Creation” window.

4. For making a question, you could use either the Text or Ink buttons to enter your question in the lower white box. The Erase button allows you to erase any ink strokes.
5. If you would like to display a picture for your students, you may insert an image by clicking the “Click to Insert an Image” button and selecting your desired image.

6. To enter another question, click the “Next” button to get a new question window. Continue this process until you are finished creating your questions.

7. If you would like to require your student to make some ink mark before continuing to the next question, check the “Expect Pen” box. Similarly if you would like to require your student to use the Draw tool before continuing to the next question, check the “Expect Draw” box.

8. When finished creating your questions, click “Upload Quiz” button.

9. Your will then be prompted with an “Atom Selection” window. Check the atoms that you would be expecting your students to draw during the quiz. Then click the “Save” button.
10. Next, you will be prompted with an “Options” window. Select a class from the “Class” drop-down box or enter a new one by entering text in the “Enter a new name” field and clicking the “Add” button. Then enter a description of your quiz in the “Description” field. If you would like to use a list of students expected to complete the quiz, leave the “Use Roster” box checked and enter the roster one of two ways. 1. Enter their email address manually by separating their email addresses with commas (ex. john.smith@email.com, jane.smith@email.com, etc) or 2. use a comma separate text file of email addresses by clicking the “Load Roster” button and selecting the desired file. If you would like to make your quiz public, uncheck the “Use Roster” box. Next, select a start and end date for your quiz to remain visible to the students and check the remaining desired options. Finally, click the “Ok” button to upload the quiz to the database. A confirmation popup will appear if the upload was successful.
Taking a Quiz/Tutorial

1. Once OrganicPad opens, click on “Student->Quiz” or “Student->Tutorial” depending on the desired action.

![OrganicPad interface showing menu options](image)

2. A “Login” window will appear. Refer to “Logging In” Section.

3. Once logged in, a “Select Quiz” window will appear. Select the quiz you wish to take and click the “Start” button.
4. Once the quiz loads, follow the teacher’s instructions in the bottom white box. Click the “Next” or “Previous” button to move between questions. Once all questions are answered, click the “Finish” button on the last question to submit your quiz. A confirmation box will appear once your quiz has been successfully submitted.
Draw a Lewis structure for $\text{H}_2\text{O}$. Quiz Submitted.

Ok
Starting a Classroom Activity

1. Once OrganicPad opens, click on “Teacher->Connect”.

2. A “Login” window will appear. Refer to “Logging In” Section.

3. Once logged in, you will be prompted with an “Options” window. Select a class from the “Class” drop-down box or enter a new one by entering text in the “Enter a new name” field and clicking the “Add” button. Then enter a description of your quiz in the “Description” field. Click the “Local” button to allow only users on the local network to be able to join. Click the “Remote” button to allow users on other networks to join. Check the “Allow Student to See Solutions” box to allow students to view the correct solutions once they have submitted. Click the “Ok” button to continue.
4. Next, you will be shown the “Teacher” window. The right hand side of the window has a “Name” box that displays all of the students who are currently signed in and their current state (Signed In, Unchecked, Correct, Incorrect). The pie chart in the top right displays the ratios of states for the entire class. For making a question, you could use either the Text or Ink buttons to enter your question in the lower white box. The Erase button allows you to erase any ink strokes. Click the “Send to Class” button to distribute the question to the all of the students.

5. Hovering over a student’s name displays a popup with whatever drawings the student has made.
6. When a student submits a structure, their state will change from “Signed in” to “Unchecked”. Clicking on a student’s name will display their submission in the central canvas.

7. For automatic checking of the students’ submissions, either draw the correct structure by hand or select one from the student list and click the “Add Solution” button. Checking the students work can begin by clicking the “Check Once” button or the “Start Checking” button to check each student’s submission against the solution(s). Each student’s state will change to reflect the results of the comparisons. The “Check Once” button performs one round of comparisons, while the “Start Checking” button will automatically reevaluate the students’ submission whenever a change is made to the solution list or the student list.
8. Checking the “Anonymous” box will mark all of the students’ names as anonymous. Clicking the “Clear” button will start a new question.
Joining a Classroom Activity

1. Once OrganicPad opens, click on “Student->Connect”.

2. A “Login” window will appear. Refer to “Logging In” Section.

3. After logging in, the “Student” window will appear. Instructions from the teacher will appear in the lower white box. Once you are finished drawing your structure, click the “Submit Molecule” button to submit your work to the teacher. A confirmation popup will appear once your submission has been received by the teacher.

4. If the teacher checks your submission, a popup will appear indicating the results of the checking.
You got the question Correct.

Would you like to view the solution(s)?  Yes  No
Reviewing Submissions

1. Once *OrganicPad* opens, click on “Teacher->Review Submissions”.

2. A “Login” window will appear. Refer to “Logging In” Section.

3. Next, you will be prompted with the “AdminTool” window. A list of all the activities you have started will appear in the left box. Clicking an activity will open a new level with the numbers of each question that was asked. Click on one of the numbers will display a list of all the students who submitted an answer to that question. By clicking a name, the student’s submission will appear on the canvas. Clicking the play button will replay the submission.
4. Checking the “Anonymous” box will replace the students’ names with their ID numbers.
Grading Submissions

1. To grade the students’ submission(s), select the question(s) that you want to grade and click the “Grade” button. To select a sequence of questions click the first question and then hold Shift as you click the last question; all of the questions between these two questions will be selected. To select (or deselect) questions individually hold Ctrl and click on each question.

2. Once you click the “Grade” button the “GraphSelector” window will open. The questions selected are listed across the top of this window while the submissions to the selected question are shown in the rest of the window (although the questions along the top of the window may not be numbered the same as in the “AdminTool” window, they will always be in the same order). The number in the upper left corner of each submission box indicates its frequency. The check box in the upper right corner is not needed for grading. Click on each submission that you want to mark as correct; when you select a submission the red outline will turn green.
3. Once you have finished selecting correct submissions click the “Done” button. The “GraphSelector” window will close and the “Grading” window will open. This window contains a grading table that indicates whether a student’s submission was marked correct or incorrect for each question: 0 means incorrect and 1 means correct. This table can be exported to a comma-separated values (.csv) file using the “Export” button.
Tagging Submissions

1. First select the question you want to tag and click the “Generate Error Chart” button in the “Admin Tool” window (tagging must be done one question at a time).

2. The “TagGeneratorWindow” will then open when the “Generate Error Chart” button is clicked. At the top of the window you will see that the “Select Correct Structures” is currently the only tab available and the submissions are displayed below. Each submission box has its frequency in the upper left corner and a check box in the upper right corner. A checked box indicates that the submission(s) will be automatically tagged. Select the correct submissions for the question: the outline of the submissions you select will turn green.
3. Click the “Next” button. You will now tag each submission that had an unchecked check box as well as each structure that has been automatically tagged as having a “Atom Connection Arrangement” problem. The tags are self-explanatory, but one of them requires some explanation:

Saturation Problem means that the structure is correct except that the total number of electrons is too high or too low (i.e. incorrect degrees of unsaturation).
4. Once you have tagged the last structure click the “Next” button again. The list of tabs at the top of the window will be populated with the automatically tagged structures, the “Results” tab, and the “User Results” tab; the “Results” tab will be selected. This tab shows the frequency of each of the tags, and the “User Results” tab shows a table indicating the errors with each structure that can be exported to a comma-separated values (.csv) file using the “Export” button while that tab is selected.

5. It is recommended that you review the automatically tagged structures before exporting the data.
Appendix B

Multi-Tiered Feedback Design

I. Correct
   1. "Congratulations, your Lewis structure was drawn correctly!"

II. Unconnected Bonds
   1. "Please make sure that every bond is connected to two atoms."

III. Molecule Atom Frequency Mismatch
   1. "You might want to consider looking at the chemical formula again."
   2. "This structure calls for … atoms."

IV. Molecule Electrons Counts (count bonds and electrons)
   IF Charged [Feedback for entire molecule]
      1. "How many valence electrons should your Lewis structure contain?
         Does your structure show that number of electrons? (Remember
         that a bond counts as two electrons.)"
      2. + : "Remember for a positive charge, an electron should be
         subtracted from the total valence electron available."
         - : "Remember for a negative charge, an electron should be added
         from the total valence electron available."
      3. “To calculate the total number of valence electrons, remember X
         has # valence electrons… (Don’t forget about what to do with the
         charge)
      4. “Your structure should show X valence electrons. Remember that
         a bond counts as two electrons.”
   ELSE Not Charged
      1. "How many valence electrons should your Lewis structure
         contain? Does your structure show that number of electrons?
         (Remember that a bond counts as two electrons.)"
      2. “To calculate the total number of valence electrons, remember X
         has # valence electrons…

V. “Your structure should show X valence electrons. Remember that a bond
   counts as two electrons.” Atom Bonds Counts Mismatch

   1. Tier 1
      H. "What is the total number of electrons that H can have in a molecule?"
      C. "How many bonds does carbon normally form?"
      O. "How many bonds does oxygen normally form?"
      N. "How many bonds does nitrogen normally form?"
      S. "How many bonds does sulfur normally form?"
2. Tier 2
   H. "Remember, hydrogen is small and only can hold two electrons."
   C. "Carbon typically forms 4 bonds."
   O. "Oxygen typically forms 2 bonds."
   N. "Nitrogen typically forms 3 bonds."
   S. "Sulfur typically forms 2 bonds."

VI. Atom Electron Counts Mismatch
1. "X has Y valence electrons"
2. - : Remember that adding a negative charge adds an electron to the valence count.
   +. Remember that adding a positive charge removes an electron from the valence count
   >. You may want to consider removing lone pairs until you reach the total number of valence electrons.
   <. You may want to consider adding lone pairs until you reach the total number of valence electrons.
Appendix C

Versions and Changes for the Information from Lewis Structures Survey

**Version I of the survey**

What information can be obtained from a Lewis structure? (Mark all that may apply)

<table>
<thead>
<tr>
<th></th>
<th>Hybridization</th>
<th></th>
<th>Intermolecular forces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polarity</td>
<td></td>
<td>Charge(s)</td>
</tr>
<tr>
<td></td>
<td>Type of element(s)</td>
<td></td>
<td>Melting point</td>
</tr>
<tr>
<td></td>
<td>Reactivity</td>
<td></td>
<td>Geometry/shape</td>
</tr>
<tr>
<td></td>
<td>Type of bond(s)</td>
<td></td>
<td>Physical properties</td>
</tr>
<tr>
<td></td>
<td>Boiling point</td>
<td></td>
<td>Number of electron(s)</td>
</tr>
<tr>
<td></td>
<td>Electronegativity</td>
<td></td>
<td>Resonance</td>
</tr>
<tr>
<td></td>
<td>Bond angle</td>
<td></td>
<td>No information</td>
</tr>
</tbody>
</table>

**Revisions:**

Type of element(s) → Element(s) present
Melting point → Relative melting point
Boiling point → Relative boiling point
Number of electron(s) → Number of valence electrons
Resonance → Potential for resonance
Electronegativity removed

What information can be obtained from a Lewis structure → What information could you obtain using a Lewis structure?

**Version II of the survey**

What information could you obtain using a Lewis structure? (Mark all that may apply)

<table>
<thead>
<tr>
<th></th>
<th>Hybridization</th>
<th></th>
<th>Intermolecular forces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polarity</td>
<td></td>
<td>Formal charges</td>
</tr>
<tr>
<td></td>
<td>Element(s) present</td>
<td></td>
<td>Relative melting point</td>
</tr>
<tr>
<td></td>
<td>Reactivity</td>
<td></td>
<td>Geometry/shape</td>
</tr>
<tr>
<td></td>
<td>Type of bond(s)</td>
<td></td>
<td>Physical properties</td>
</tr>
<tr>
<td></td>
<td>Relative boiling point</td>
<td></td>
<td>Number of valence electrons</td>
</tr>
<tr>
<td></td>
<td>Number of bonds between particular atoms</td>
<td></td>
<td>Potential for resonance</td>
</tr>
<tr>
<td></td>
<td>Bond angle</td>
<td></td>
<td>Charge(s)</td>
</tr>
<tr>
<td></td>
<td>No information</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Revisions:**

Charge(s) removed
Acidity/basicity added
**Version III (final version) of the survey**

What information could you obtain using a Lewis structure? (Mark all that may apply)

<table>
<thead>
<tr>
<th></th>
<th>Hybridization</th>
<th></th>
<th>Intermolecular forces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polarity</td>
<td></td>
<td>Formal charges</td>
</tr>
<tr>
<td></td>
<td>Element(s) present</td>
<td></td>
<td>Relative melting point</td>
</tr>
<tr>
<td></td>
<td>Reactivity</td>
<td></td>
<td>Geometry/shape</td>
</tr>
<tr>
<td></td>
<td>Type of bond(s)</td>
<td></td>
<td>Physical properties</td>
</tr>
<tr>
<td></td>
<td>Relative boiling point</td>
<td></td>
<td>Number of valence electrons</td>
</tr>
<tr>
<td></td>
<td>Number of bonds between particular atoms</td>
<td></td>
<td>Potential for resonance</td>
</tr>
<tr>
<td></td>
<td>Bond angle</td>
<td></td>
<td>Acidity/basicity</td>
</tr>
<tr>
<td></td>
<td>No information</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


The impact of tablet PCs and pen-based technology on education: Going mainstream, (pp. 3-10) Purdue University Press.


Hillsdale, New Jersey: Lawrence Erlbaum Associates.


*OrganicPad*: An interactive freehand drawing application for organic chemistry. 


