Building Chemistry One Atom at a Time: An Investigation of the Effects of Two Curricula in Students’ Understanding of Covalent Bonding and Atomic Size

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BUILDING CHEMISTRY ONE ATOM AT A TIME: AN INVESTIGATION OF THE EFFECTS OF TWO CURRICULA IN STUDENTS' UNDERSTANDING OF COVALENT BONDING AND ATOMIC SIZE

A Dissertation
Presented to
the Graduate School of
Clemson University

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

by
Barbara Jeanne Bull
May 2014

Accepted by:
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ABSTRACT

Chemists have to rely on models to aid in the explanation of phenomena they experience. Instruction of atomic theory has been used as the introduction and primary model for many concepts in chemistry. Therefore, it is important for students to have a robust understanding of the different atomic models, their relationships and their limitations. Previous research has shown that students have alternative conceptions concerning their interpretation of atomic models, but there is less exploration into how students apply their understanding of atomic structure to other chemical concepts. Therefore, this research concentrated on the development of three Model Eliciting Activities to investigate the most fundamental topic of the atom and how students applied their atomic model to covalent bonding and atomic size. Along with the investigation into students’ use of their atomic models, a comparison was included between a traditional chemistry curriculum using an Atoms First approach and Chemistry, Life, the Universe and Everything (CLUE), a NSF-funded general chemistry curriculum. Treatment and Control groups were employed to determine the effectiveness of the curricula in conveying the relationship between atoms, covalent bonds and atomic size. The CLUE students developed a Cloud representation on the Atomic Model Eliciting Activity and maintained this depiction through the Covalent Bonding Model Eliciting Activity. The traditional students more often illustrated the atom using a Bohr representation and continued to apply the same model to their portrayal of covalent bonding. During the analysis of the Atomic Size Model Eliciting Activity, students had difficulty fully supporting their explanation of the atomic size trend. Utilizing the
beSocratic platform, an activity was designed to aid students’ construction of explanations using Toulmin’s Argumentation Pattern. In order to study the effectiveness of the activity, the students were asked questions relating to a four-week long investigation into the identity of an inorganic salt during their laboratory class. Students who completed the activity exhibited an improvement in their explanation of the identity of their salt’s cation. After completing the activity, another question was posed about the identity of their anion. Both groups saw a decrease in the percentage of students who included reasoning in their answer; however, the activity group maintained a significantly higher percentage of responses with a reasoning than the control group.
DEDICATION

This dissertation is dedicated to the very supportive people that have blessed my life.

To my husband, Rick and son, Ben, thank you for keeping me grounded during my journey through this process. You have helped keep a smile on my face through the difficult times.

To my parents, Bill and Jeanne, you have made all of this possible. From horseback riding lessons to support through IB classes, you have provided me every opportunity to achieve this accomplishment. I cannot thank you enough for the guidance and love that you have bestowed upon me my entire life.

To my brothers and sister, Chris and Jaclyn, and Bill Jr., thank you for all your support through the years. Jaclyn and Billy, we have had lots of brotherly and sisterly fights, but in the end, we were always there to encourage one another.
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My group has been an instrumental part in the successful collection of the data. Evy, Leah, Nicole, and Sonia, thank you for your help and encouragement throughout this process. Barbara Lewis and Dr. Dennis Taylor allowed the collection of student responses during laboratory and class time.
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CHAPTER ONE
INTRODUCTION

Countless calls for reform have been made concerning the state of general chemistry curriculum (Nakhleh, 1992; Lloyd & Spencer, 1994; Spencer, 1999; Gabel, 1999; Taber, 2001; Reid, 2008; Valanquer & Pollard, 2010). The findings of the Task Force on General Chemistry Curriculum (Lloyd & Spencer, 1994) remain true to this day. A survey was conducted of 114 colleges and universities, and the conclusion was that general chemistry curricula attempt to cover too many topics. Trying to cover a copious amount of material leaves the student with surface-level comprehension or even incorrect interpretations of material that is presented in a disjointed fashion (Lloyd & Spencer, 1994; Talanquer & Pollard, 2010).

In attempts to address the fragmented presentation of material, several publishers have started selling textbooks with an Atoms-First content arrangement. Since the atom has been labeled as the building block of matter, a curricular reform has become popular where the students are exposed to the structure of an atom prior to progressing to bonding or phase changes. Beginning with the topic of the atom requires students to discuss the existence and interaction of objects that cannot be seen. Teachers rely on different types of models to demonstrate the sub-microscopic structure as well as interaction. Studies have been completed from high school to post graduate investigating how students model their understanding of atoms (Tsaparlis & Papaphotis, 2009; Tsaparlis & Papaphotis, 2002; Tsaparlis, 1997) and how they interact (Coll & Treagust, 2001, 2002, 2003; Nicoll, 2001; Peterson & Treagust, 1989; Taber & Watts, 1996; Coll & Taylor, 2001, 2002;
Özmen, 2004); however, no research has been made available to discuss whether students apply their knowledge of an atom when discussing further chemistry concepts.

Research into meaningful learning has shown that simply exposing students to the concept of the atom first does not guarantee that the students will form a connection to the next topic taught. A new paper published by Esterling and Bartels (2013) found that students in an Atoms-First curriculum were more likely to pass the course when compared to students taking the previous curriculum. The researchers discussed the rearrangement of the curriculum; however, they compared students’ final grades at the end of each trimester. The study painted with a broader brush since some of the topics in the Atoms-First were taught in a different trimester. The research project presented here investigates students’ understanding of specific chemical principles regardless of the grade earned in the course. Two core questions lead this research project:

1) How do students’ mental models of atomic structure affect comprehension of covalent bonding and atomic size?

2) How does the Chemistry, Life, the Universe and Everything (CLUE) curriculum, with a focus on learning progressions of atomic structure and bonding, affect students’ understandings of covalent bonding and atomic size?

First, I hope to determine whether the students understand the connection between the atom and the other concepts. Since atoms are too small to see, scientists have used experimental results to adjust and refine the scientifically accepted atomic model. The hope is that students can achieve a level of expertise where they understand the purpose of generating models and which situations to apply a particular model. Secondly, I aim to
evaluate the effect of two different curricula on the students’ comprehension. Most chemistry curricula have not changed even with the chemical education and learning sciences research findings into alternative conceptions and how people learn. With recent curricular reform at the university, the effectiveness of these new approaches has to be assessed.

Recently, a large southeastern institution began to offer two versions of a general chemistry curriculum to the science and engineering majors. The first version was considered the traditional chemistry curriculum while the second was an experimental curriculum designed by a chemical education faculty member. The approaches of the two curricula were widely different and are described below.

The traditional chemistry curriculum began teaching from an Atoms First edition of McMurry and Fay’s *General Chemistry* (2010). The version reorders the first seven chapters to start with building atomic structure and discussing characteristics and bonding. Although some chapters were reordered, several topics remained fragmented, such as the coverage of thermodynamic topics being split between first and second semester. Since the chapters were not revised but remain as before in a new order, the professors did not have to alter their instruction materials or methods. The traditional chemistry classroom continued with the teacher-centered lecture while some utilize i-Clicker questions to gauge student understanding during class. The instructor poses a multiple choice question to the class, and the students are able to answer the question without the rest of the class knowing their choice. The instructor can view a bar graph of the students’ responses and gauge their understanding of the concept. Assessment of
student understanding continued with online homework being completed through *Mastering Chemistry* and exams containing a majority of algorithmic multiple choice questions.

A second curriculum, Chemistry, Life, the Universe and Everything (CLUE), was funded by National Science Foundation and also taught at Clemson University. The curriculum incorporates research on how people learn and how to improve problem-solving into the classroom. CLUE takes the teacher out of the focal point and places the attention on the student through active participation in classroom discussion. The students engage in discourse that encourages them to analyze their prior knowledge and how it could be useful to the topic at hand. The text builds chemistry from the atom up commencing with atoms and atomic theory as well. CLUE focuses on student understanding of energy, structure and function with each topic and the reflection on how prior topics learned influence further concepts. The second semester of the curriculum focuses on systems thinking where the students analyze how the core concepts that have been discussed throughout the first semester work together in everyday life to produce the world around them (e.g., phase changes and chemical reactions).

Assessments are an integral part of the CLUE curriculum. In order to monitor student learning, worksheets are utilized to gather student ideas pre- and post-discussion while i-Clickers are an essential tool during class time to assess real time understanding. Homework comes in the form of worksheets or interactive applets for the students to explore. The exams have both multiple choice and short answer questions. The use of
short answer allows the instructor to investigate understanding of the fundamental concepts.

The following chapters are used to inform the audience of the tools I used to address the core questions of my research project. The theoretical frameworks that guided the research project as well as the development of three model eliciting activities that were administered throughout the semester are outlined in Chapter II and III. Chapters IV and V discuss and analyze the results from the model eliciting activities. Chapter VI addresses using argumentation to help students provide a more complete answer. Chapter VII provides the overall conclusions and possible future work to further the research project.
CHAPTER TWO
THEORETICAL FRAMEWORKS

Throughout the learning process, students use different methods to evaluate the world around them. Students construct models and learn scientific explanations in order to define and understand the things they experience daily. Through meaningful learning, students are able to develop robust models and coherent explanations that can be articulated to their peers and teachers.

From grade school, students are made aware that the world is composed of atoms. Students find themselves memorizing the types of bonds that form between atoms or the periodic trends that change across a row. This is a result of the difficulty in crafting a meaningful connection between atoms and the ideas of bonding and periodic trends. In order for students to provide a logical and conceptually sound explanation of these phenomena, educators must promote how the atomic structure influences the formation of bonds and dictates the periodic trends. However, students must choose to incorporate this knowledge meaningfully into their comprehension of atoms and atomic interactions. Examining how students utilize their atomic model in drawings and explanations will help determine how students chose to understand the material. In this chapter, I will discuss how mental models, meaningful learning, and explanation provide the scaffold for my research and how they were instrumental in focusing my investigation.
Mental Models

Throughout their education, instructors expose students to different types of models. From physical to mental, scientific models are powerful tools that allow the connection of the abstract with the concrete (Oh & Oh, 2011; Justi & Gilbert, 2002a, 2002b; Gilbert & Boulter, 2000; Khan, 2007). In a review of models by Oh and Oh (2011), the researchers focus on five topics that describe the nature of a model. First, a model represents a phenomenon or concept. A model can be used as an analogy to aid comprehension of a target concept. Next, modeling allows the learner to describe, explain or predict ideas. A learner relies on their model to understand how to interpret new situations through the manipulation of their existing representation. Third, there can be several models to explain a single concept. The individual must understand the limitations of each model since several models may be needed to fully explain the overall concept. Also, models are always changing due to the nature of science. New experiments and scientific discoveries can alter the parts of the accepted or preferred model. Finally, teachers use models in the classroom to explain the difficult topics. A complicated topic may be broken down into several models to aid students in understanding the complete concept. Gilbert and Boulter (2000) propose that “a model can be defined as a representation of objects, phenomena, process, ideas and/or their systems.” This definition encompasses the different facets of science as well as indicating how a model is generated from the perspective of the individual, not a duplicate of the target object.
When discussing models, several different types of models are defined. A scientific model expresses the scientifically tested and accepted model of a concept or phenomenon; whereas, teaching models were developed to aid student learning of the concept (Chittleborough, Treagust, Mamiala, & Mocerino, 2005). Mental models, on the other hand, are representations that the learner constructs in order to explain a concept or phenomenon (Greca & Moreira, 2000; Bodner, Gardner, & Briggs, 2005). As soon as an individual describes or draws their mental model, it is considered an expressed model.

Since the atom is not visible, students have to rely on their instructor and textbooks to provide models of the atom (Niaz & Coştu, 2009; Justi & Gilbert 2001; Rodríguez & Niaz, 2002; Niaz, 1998). Ideally, students would construct a useful mental model to explain how an atom might behave under different circumstances, such as how adding an electron would affect the atom. A model is useless if the student is unable to connect the model with further concepts. In order to determine the usefulness of an individual’s model, instructors must elicit their mental models by asking them to draw and describe in words how they envisage an atom. Determining students’ mental model of the atom is the first step in exploring how students use those models to explain further related chemical phenomena.

**Meaningful Learning**

Ausubel (1968) outlines the characteristics of meaningful and rote learning along with the benefits and drawbacks to the two approaches to learning. He states that a task has two factors that determine whether it can be learned meaningfully. It must have logical meaningfulness and the learner must have relevant content available in their
cognitive structure (p. 37, 38). Ausubel continues by summarizing the process of meaningful learning as the process of relating new information to existing ideas. Through this connection, the learner constructs various kinds of significant relationships. The progression of rote learning differs because it is composed of discrete and isolated ideas that are integrated into the learner’s cognitive structure in a verbatim fashion. The ability to anchor the concept to relevant existing cognitive structure allows meaningfully acquired information to become an integral part of the student’s understanding. Learning and retention are no longer reliant on the limitations of the short term memory, which occurs with isolated rote learned knowledge. The new material will be organized within the information in which it was incorporated. The human mind is not equipped to efficiently store verbatim material for a long period of time. The association of the data to existing understanding is necessary for basic learning-retention mechanism (pgs. 107-110).

Novak provides his interpretation of Ausubel’s Assimilation Learning Theory where meaningful learning is described as an active process where individuals integrate new concepts to relevant prior knowledge. This is vastly different from rote learning which occurs during the memorization of verbatim facts forming no links with previous ideas. He also introduces the idea that learning is not dichotomous, being either meaningful or rote. Novak (1977) proposed that learning lies more on a continuum with meaningful and rote learning being at each of the extremes and variations between the two. The degree to which meaningful learning occurs varies with the quality and quantity
of the current knowledge and the effort that is exerted to incorporate the new concept into the existing cognitive structure.

**Explanation**

The science community has been in discussions concerning the relationship between explanations and arguments (Osbourne & Patterson, 2011; Berland & Reiser, 2009). According to Osbourne and Patterson (2011), an explanation and an argument are two distinct entities. A key feature of an explanation is the use of scientific facts to describe a phenomenon and increase understanding while an argument has a claim that is to be justified or to persuade an audience. Osbourne and Patterson (2011) continue to point out instances of conflation between arguments and explanations throughout science education. Using the strict interpretation, Osbourn and Patterson saw the terms claim, evidence and reasoning as argumentation terms and should not be used while defining a scientific explanation and considered the use of those terms in reference to an explanation a conflation.

Berland and Reiser (2009) discuss how argumentation and explanation are complementary. When posing a question to a class, the student discourse may begin as an argument with a few students that disagree with what is occurring. In the end, the students leave the discussion with a deeper scientific understanding of the event. Berland and Reiser refer to the combination of argumentation and explanation as “constructing and defending scientific explanations” (p. 28). The goals of both explanation and argumentation are aligned because the end result is to make sense of an event, convey comprehension and convince others using science.
When scientists provide an answer to a question, the statement contains a claim with supporting data as well as a reason for how that data proves their conclusion. As they are introduced to science and scientific inquiry, students should also be exposed to how scientists respond to problems as well as how they answer them (Obsorne, Erduran, & Simon, 2004; Newton, Driver, Osborne, 1999; Erduran, Simon, & Osborne, 2004; Brockriede & Ehninger, 1960). A classically defined argument has at least three parts: a claim that asserts to the audience where you stand on a topic, a piece of data that provides evidence for what is said in the claim, and a warrant which explains why the data supports the claim (Brockriede & Ehninger, 1960). These parts to an argument were outlined by Toulmin and have become known as Toulmin’s Argumentation Pattern.

Students are still trying to comprehend the world around them. Toulmin’s Argumentation Pattern provides students with a way to articulate to others their understanding of the world around them. When posed with a question and probed to explain why, a student supplied claim without support of data or reasoning shows a superficial comprehension of the concept; however, a student who supplies a claim supported with evidence and reasoning exhibits a better grasp on the material. Students do not always have the correct claim, but a complete answer highlights the areas the student is having difficulties. As students become more familiar with the types of information that should be included within an explanation, the rigid structure of Toulmin’s Argumentation Pattern becomes unnecessary.
CHAPTER THREE
DEVELOPMENT OF MODEL ELICITING ACTIVITIES

Models are meant not only to explain a concept but also to predict how that phenomenon would behave in different situations. In chemistry, the atom is described as the basic building block of matter. As students are introduced to various representations of the atom, they generate their own mental model. Ideally, individuals would utilize their atomic model to understand how atoms interact and what characteristics one would expect different elemental atoms to have.

The chapter outlines how we designed three Model Eliciting Activities to investigate students’ understanding of atoms, bonding and atomic size. Our goal was to determine whether students’ made the connection between these topics. Before constructing these activities, we reviewed the literature to establish what researchers had already found and where we could answer the remaining questions.

Literature Review

Complicated mathematical explanations, such as the Schrödinger model, and the potential to promote barriers for future learning, such as the Bohr model, have led researchers to question whether some historical models should be taught. The difficult mathematical derivations that are associated with the Schrödinger model have been found problematic, and some researchers have concluded that it is not necessary to teach quantum mechanics during high school (Tsaparlis & Papaphotis, 2009; Tsaparlis & Papaphotis, 2002) or even senior level university chemistry majors (Tsaparlis, 1997). Park and Light (2009) identified the atom as a threshold concept for chemistry,
specifically the barriers of probability of finding an electron and energy quantization. It is these two concepts that students must comprehend in order to progress towards the higher-level Schrödinger model.

The Bohr model of the atoms was once thought to be an obstacle to understanding more advanced models; however, McKagan, Perkins and Wieman (2009) demonstrated that it was not a barrier when taught appropriately. A curriculum that compares and contrasts all of the historic atomic models (Taber, 2003; Justi & Gilbert, 2001; Harrison & Treagust, 1996) enabled students to understand the limitations of the models. The students were able to use the Bohr model as a tool in discussing the electron energy level diagram in the hydrogen atom and the Schrödinger model when discussing the distance between the nucleus and electron.

In the same manner as atomic models, the research on chemical bonding has focused mainly on students’ comprehension as well as their mental model of bonding. Several studies have been focused on investigating students’ conceptions of bonding (Coll & Treagust, 2001, 2002, 2003; Nicoll, 2001; Peterson & Treagust, 1989; Taber & Watts, 1996; Coll & Taylor, 2001, 2002; Özmen, 2004). Peterson and Treagust (1989) conducted a study that highlighted eight common misunderstandings relating to bond polarity, shape of the molecules, polarity of the molecule, intermolecular forces, and the octet rule. They developed a two-tiered assessment to investigate the alternative conceptions. In the research conducted by Coll and Treagust (2002), students were asked to describe the bonding in a sample of iodine and chloroform. The depictions the student drew were labeled as their preferred mental model of bonding, the model that came to
mind most easily. The descriptions the students provided of bonding occurring in the two molecules also became labeled as their mental model of bonding. By having the students describe what their model represents to them, the interviewers were able to determine the students’ comprehension of bonding. The undergraduate and graduate students interviewed relied on models that used the sharing of electrons to form the stable octet to explain the bonding between the atoms.

Researchers have explored how students understand the particulate nature of matter and bonding (Othman, Treagust, & Chandrasegaran, 2008). Othamn et al. (2008) conducted a study on K-12 students and tested lower level understanding of the concepts of melting and boiling. Students showed a lack of understanding of the particle nature of matter because they were not connecting those concepts with the chemical bonding questions. The research has not extended to investigate students’ use of their atomic models to explain bonding.

The research on periodic trends focuses on student views of ionization energy. Taber (1998) examined student inability to use physics in their chemistry explanations. During interviews intended to elicit students’ ideas of bonding, Taber learned that students thought there was a conservation of forces where all electrons were attracted equally to the nucleus and lacked comprehension of the repulsive forces experienced between the electrons. This would cause problems in their explanation of ionization energy since the core electrons would not be seen as compact and close to the nucleus.

Wheeldon (2012) examined how pre-service teachers view atomic models when explaining subsequent ionization energy. The teachers were provided with pictures of the
atomic models to probe the teachers’ ideas of not only the atom but the representations as well. Next, a graph displaying the successive ionization energy values for an oxygen atom was utilized to investigate their explanation for the variation. The last question focused on which models the teachers found useful and how the model aided their description of the ionization energy values. The order of the beginning questions was reversed to investigate how question order affects the justification of ionization energy value. All 31 teachers indicated that the Bohr, Schrödinger or combination of those models were advantageous in explaining the successive ionization energies of oxygen. When the Bohr model’s limitations were not taken into account, the study found that the interviewee’s responses were restricted to discussion of electrostatic attraction. Only twelve subjects discussed electron-electron repulsion; however, all relied on the Schrödinger model for that part of the explanation. Of the twelve subjects, only one person chose the Schrödinger model solely. The proposed research is different from this study because the emphasis is placed on student constructed models of the atom and how, or if, they use those models to understand ionization energy and other periodic trends.

**Research goals**

Most of the investigations I read focused on a single topic; however, these concepts are not segregated pieces of chemical understanding, contrary to how they may be taught. My research aims to investigate the connections, if any, that students make between atomic structure and bonding and/or periodic trends. In this chapter, I will outline the development of a series of Model Eliciting Activities to investigate whether students are aware of the connection between atoms and their interactions in covalent
bonding as well as atoms and the periodicity, or characteristics, found on the periodic table. The motivating questions behind these activities were:

1) How do students depict their model of an atom?

2) How do students explain and depict their model of covalent bonding, and do they build upon their atomic model?

3) In what ways do students explain the periodic trend of atomic radius, and do they use an appropriate model for the trend they discuss?

**Activity Design**

This section presents the development of each of the three Model Eliciting Activities: Atomic Model Eliciting Activity, Covalent Bonding Model Eliciting Activity and Atomic Size Model Eliciting Activity. The activities were aligned with the instruction to gather a pre- and post- instruction response from the students for the Atomic and Covalent Bonding Model Eliciting Activities as seen in Figure 3.1. This order was determined during the development of the activities and will be discussed in further detail later in the chapter.

![Figure 3.1](image)

*Figure 3.1*: The order of administration for the Model Eliciting Activities
Atomic Model Eliciting Activity

During the Fall 2009 semester, we created a worksheet for the beginning of first-semester general chemistry that asked students to identify evidence for the existence of atoms and what aspects of their life depended upon the reality of atoms. The last question on the worksheet (Figure 3.2) was of particular interest because we wanted to identify how students’ depict their model of the atom. The purpose of the question was to elicit how students pictured the atom in their mind before learning about it in class. Based on the students’ responses, we found that there were a variety of representations. During instruction, students would be exposed to several models of the atom as they covered the atomic theory. Students can see how science is an iterative process, and how different scientific models were used to convey different ideas about the atom. It is imperative that students understand the limitations of the different models since several models can be used to illustrate an atom; however, certain models better explain different characteristics or phenomena that occur. Therefore, the evolution of these representations was monitored over the course of the semester.

Given what you know about atoms, please draw a picture/diagram of what you think an atom would look like (if you could see them) and briefly explain what it represents. (Use the back of the sheet if necessary)

Figure 3.2: Original question on Atoms, an introductory worksheet

The worksheet was transformed into an assessment activity developed to further investigate students’ understanding of atoms (Figure 3.3). There were three parts to the
Atomic Model Eliciting Activity. The first part asked students to depict their image of the lithium atom. Lithium was chosen to evaluate if students understood the concept of quantized energy levels, while still being fairly simple. That is students would have to indicate more than one atomic orbital since Lithium is in the second period of the periodic table; however, the atomic orbitals are both s-orbitals so the students did not have to distinguish between different shapes of orbitals for the ground state. The second part of the question asked students to explain what they were thinking about when they were constructing their atom, while the third part of the activity provided information about what the students did not represent or had difficulty depicting in their drawing because they were unsure of how to incorporate it.

Please read and answer each question thoroughly.

1. In the space provided, draw what you imagine a Lithium (Li) atom and all of its components would look like if you could see it. Please be sure to label all important parts in your drawing so that it is clearly understood what you are representing.

2. What concepts did you use/think about while constructing your depiction of a Li atom?

3. Was there anything that you were not able to show in your drawing? Please explain.

Figure 3.3: The first version of the Atomic Model Eliciting Activity

When the activity was complete, it was administered to the same general chemistry class during the Fall 2009 semester. Because of the design of the curriculum, the students had not yet discussed quantum chemistry. We administered the activity to these students and noticed that students were simply listing the concepts that they were
using to construct their atom when answering part 2. This previous addition to the activity did not prove to be helpful in determining if students understood the meaning of these terms. A student stating “electron cloud” and drawing their electrons on an orbit does not indicate what the student does or does not understand about the electron cloud.

We intended for the students to provide a brief description of the concept or at least why they found the idea useful in constructing their atom. Therefore, to address these concerns, the activity was revised (Figure 3.4)

<table>
<thead>
<tr>
<th>Please read and answer each question thoroughly.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. In the space provided, draw what you imagine a Lithium (Li) atom and all of its components would look like if you could see it. Please be sure to label all important parts in your drawing so that it is clearly understood what you are representing.</td>
</tr>
<tr>
<td>2. Briefly explain the concepts you use/think about while constructing your depiction of a Li atom?</td>
</tr>
<tr>
<td>3. Was there anything that you were not able to show in your drawing? Please explain.</td>
</tr>
</tbody>
</table>

**Figure 3.4:** The second version of the Atomic Model Eliciting Activity

The second version of the Atomic Model Eliciting Activity was piloted with a cohort during the Spring 2010 semester. When drawing their model, some students were cautious and noted the correct number of subatomic particles while others did not. Specifying an element proved to be an obstacle for some students. In order to remedy this, the first part was revised to include asking the students to “draw and describe” and to label “so that someone else could understanding what you are representing” as seen in Figure 3.5.
Please read and answer each question thoroughly.

1. In the space provided, **draw and describe** what you imagine an atom and all of its components would look like if you could see it. Please be sure to label all important parts in your drawing so that someone else could understand what you are representing.

2. Briefly explain the concepts you use/think about while constructing your depiction of an atom?

3. Was there anything that you were not able to show in your drawing? Please explain why.

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*Figure 3.5: The final version of the Atomic Model Eliciting Activity*

**Covalent Bonding Model Eliciting Activity**

This assessment activity was designed similarly to the Atomic Model Eliciting Activity in that students were asked to depict the covalent bond between two hydrogen atoms (Figure 3.6). The students were also asked to explain what they drew and provide any details they had difficulty including in their depiction. Our focus of this activity was on covalent bonding due to the type of atomic interaction. The descriptions of the overlap of the orbitals or sharing of electrons can be drawn easily using several different models. Ionic and metallic bonding are not as easily portrayed using different models. We wanted to specify the elements to be used, unlike the Atomic Model Eliciting Activity, since the second row elements would add more orbitals and the possibility of multiple bonds. Therefore, hydrogen atoms were chosen because of their diatomic nature and their simplicity due to having a single electron. Because of these characteristics, hydrogen atoms are only able to single bond through the overlap of the s-orbital.
Originally, the activity was given to the students after they had been instructed on covalent bonding. The students were given the entire Covalent Bonding Model Eliciting Activity (Figure 3.6) including the questions about what they thought happened to the energy of the system during bond formation. Looking at the responses, most of the CLUE students provided a potential energy curve with respect to distance. However, the traditional students tended to redraw their depiction of bonding that they had included during the first part of the activity. This is not surprising, although the traditional textbook has a figure and caption about the potential energy curve little emphasis is placed on the meaning of the curve. As a result, we decided to no longer include those questions as part of the activity. The CLUE curriculum emphasizes energy and how it affects different aspects of chemistry.
Please read and answer each question thoroughly.

1. In the space provided, draw your understanding of what happens between two hydrogen atoms when forming a covalent bond. Please be sure to label all important parts in your drawing so that it is clearly understood what you are representing.

2. What concepts did you use/think about while constructing your depiction of a covalent bond?

3. Was there anything that you were not able to show in your drawing or had difficulty illustrating? Please explain.

4. In the space provided, draw your understanding of what happens to the energy of the system when two hydrogen atoms form a covalent bond. Please be sure to label all important parts in your drawing so that it is clearly understood what you are representing.

5. What concepts did you use/think about while constructing the energy diagram of covalent bonding?

6. Was there anything that you were not able to show in your drawing or had difficulty illustrating? Please explain.

Figure 3.6: The first version of Covalent Bonding Model Eliciting Activity

This preliminary version of the activity was pilot tested with the same general chemistry class in Fall 2009 after the students were instructed and tested on the bonding concepts towards the end of the semester. We adjusted the wording of this activity just as with the Atomic Model Eliciting Activity to ask the students specifically to “draw and describe” and labeling so another person would understand the parts of their representation in order to clarify the level of detail that they were being asked and wanted to provide.
When analyzing the students’ responses, it became apparent that it was imperative to administer this activity pre-instruction to investigate what students think bonding between two hydrogen atoms would look like prior to discussion of different bonding models. In order to have a pre-instruction activity, the post-instruction Atomic Model Eliciting Activity was revised to include having the students draw the bond between hydrogen atoms as well as indicate ideas they had difficulty including in their drawing (Figure 3.7). The part of the activity that asked students to briefly describe the concepts used was removed from both the Atomic and Covalent Bonding Model Eliciting Activity since students were asked to draw and describe their depictions. The post-instruction Covalent Bonding Model Eliciting Activity was administered along with the Atomic Size Model Eliciting Activity which is discussed next.

Please read and answer each question thoroughly.

1. In the space provided, draw and describe what you imagine an atom and all of its components would look like if you could see it. Please be sure to label all important parts in your drawing so that someone else could understand what you are representing.

2. Was there anything that you were not able to show in your drawing? Please explain.

3. In the space provided, draw and describe what you imagine the bond between two Hydrogen (H) atoms and all of its components would look like if you could see it. Please be sure to label all important parts in your drawing so that someone else could understand what you were representing.

4. Was there anything that you were not able to show in your drawing or had difficulty illustrating? Please explain.

Figure 3.7: The final version of the post-instruction Atomic Model Eliciting Activity and pre-instruction Covalent Bonding Model Eliciting Activity
Periodic Trend Model Eliciting Activity

An activity was designed to investigate how students would draw and explain a periodic trend. The initial version asked students specifically about the size change between an atom and ion of lithium as seen in Figure 3.8. Lithium was chosen to make a connection between the initial models that students used in drawing their atomic model in the beginning of the semester to the end of the first semester chemistry course. The students were asked which atomic models they were illustrating.

Please read and answer each question thoroughly.

1. In the space provided, draw what you imagine a Lithium (Li) atom and (Li\(^{+1}\)) ion would look like if you could see it. Please be sure to label and define all important parts in your drawing so that it is clearly understood what you are representing.

2. Which atomic model did you use to draw your representation? Why?

3. In the space provided, draw your understanding of what happens between two hydrogen atoms when forming a covalent bond. Please be sure to label all important parts in your drawing so that it is clearly understood what you are representing.

4. Which atomic model did you use to draw your representation? Why?

Figure 3.8: The Ionic Size Model Eliciting Activity and Post-Instruction Covalent Bonding Model Eliciting Activity

After administering this activity, lithium was determined not to be an appropriate choice. Since there is only one valence electron, it is easier for students to explain the effects of losing that electron since it would mean the loss of an electron shell, and the ion would be smaller. At this point, we shifted our focus from ionic size to atomic radius.
We decided to focus on atomic radius because it is the first trend that the students are introduced to during the discussion of periodicity of elements. The trend across the row can be the most counterintuitive trends that the students will encounter; however, it is one of the important trends to understand in order to correctly explain the remaining periodic concepts.

Please read and answer each question thoroughly.

1. Draw what you imagine a Lithium (Li) atom and Beryllium (Be) atom would look like if you could see it. Please be sure to label and define all important parts in your drawing so that it is clearly understood what you are representing.

2. Describe in detail the atomic model that you illustrated for each atom above.

3. Is there a trend in size between Lithium and Beryllium? If so, what is the trend?

4. Please explain in detail how your atomic representation in Question 1 can be used to explain the sizes of the atoms.

Figure 3.9: The first version of the Atomic Size Model Eliciting Activity

Lithium and beryllium were chosen because the smaller number of subatomic particles should have made it easier for the students to provide their models. Lithium continued to be used because of the simplicity of the atom. Not wanting to add the complexity of an additional shell or different type of orbital, we found beryllium to be the best possible choice for comparison. Since it is possible that students could use multiple models when thinking about different topics, the atom or atomic radius, it was important to ask them if they thought the representation they used to depict their atom could be used to explain the trend.
The final version of the activity (Figure 3.10) refocused on the depiction of their atom and the students’ ability to explain the trend. By asking students to explain what they were not able to show in their atomic depiction, we were able to gather a better understanding of what the students understood about the atom that they were not including in their drawing, more so than asking them to describe the atomic model they used. By separating “Is there a trend in size between Lithium and Beryllium? If so, what is the trend?” into two questions, we were hoping students would include an explanation instead of only answering the first part concerning the trend.

Please read and answer each question thoroughly.

1. Draw what you imagine a Lithium (Li) atom and Beryllium (Be) atom would look like if you could see it. Please be sure to label and define all important parts in your drawing so that it is clearly understood what you are representing.

2. Was there anything that you were not able to show in your drawing or had difficulty illustrating in your Lithium and Beryllium atoms? Please explain.

3. What happens to the size between Lithium (Z=3) and Beryllium (Z=4)?

4. Please explain why this happens to the size between Lithium and Beryllium?

5. In the space provided, draw your understanding of what happens between two hydrogen atoms when forming a covalent bond. Please be sure to label all important parts in your drawing so that it is clearly understood what you are representing.

6. Which atomic model did you use to draw your representation? Why?

Figure 3.10: The final version of the Atomic Size Model Eliciting Activity and Post-Instruction Covalent Bonding Model Eliciting Activity
Study Design

Pilot Study

The Atomic and Covalent Bonding Model Eliciting Activities were piloted during the Spring 2010 semester at a large southeastern university. Participants were enrolled in a first-semester general chemistry course for science majors. At this institution, two curricula were taught for general chemistry: a traditional curriculum using a textbook by Tro and CLUE. One class was taught the traditional lecture; however, the second class was the pilot of a new instructional curriculum, CLUE.

As previously mentioned, we determined a logical order and placement of these activities throughout the semester. We were interested in following the students throughout the semester and see how their models evolve with instruction. These activities would be administered during lecture time since the first topic, the atom, is covered within the first few days of class. At this university, laboratories do not start until the second full week of classes which is too late to assess students’ pre-instruction knowledge. Since we would be asking lecturers to give up at least ten minutes of their lecture time for each activity, we wanted to make sure we did not interfere with the progression of the class but still gather pre- and post-instruction representations (Figure 3.11).
The Atom Model Eliciting Activity (Pre-Atom) was administered during the beginning of the second day of class. The Atom Model Eliciting Activity (Post-Atom) was to be administered a second time after the students had covered and been tested on the Quantum Mechanical Atom. For the traditional class, the activity was administered after the second exam because the curriculum did not discuss the quantum mechanics until Chapter 7 (Tro, 2008). The CLUE students were given the post-instruction activity after their first exam. The Covalent Bonding Model Eliciting Activity (Pre-Bonding) was included on the same sheet as the Post-Atom as seen in Figure 3.7. By merging the two activities, we were able to compare if students used similar models. The last activity of the semester was the post-instruction Covalent Bonding (Post-Bonding) Model Eliciting Activities.

The student responses were analyzed from these activities and important revisions were made to the activities. The reference to lithium in the atomic structure question was found to not have an effect on the atom the students chose to depict. Many students
included more subatomic particles than exist in the lithium atom in their representations. For the Covalent Bonding Model Eliciting Activity, the traditional students did not seem to understand what was meant by the energy change of the system. The discussion of potential energy changes during the formation of a bond is glanced over in the traditional lecture while there are several lectures dedicated to this discussion in the CLUE curriculum. It was decided to remove that question from the activity. Along with revisions, the pilot study aided the development of the initial coding scheme that will be discussed later in this chapter.

During the summer semester, three first semester general chemistry students were recruited for think-a-loud interviews to investigate the face validity of the activity. Face validity establishes if the activity was measuring what was intended, students’ preferred models of the atom. The students were provided with the activities and asked if the wording was clear or if they had any difficulties completing the worksheet. The students were asked to further discuss how they imagined the atom to verify what the student understood compare it to how they depicted it on the activity. Also probed further was students’ understanding of bonding and the role that energy plays or is related to atoms bonding.

**Main Study**

**Participants.** The activities were distributed during chemistry class time filled with between about 110 students. The students were offered participation points for completing both the pre- and post-instruction activity in both the CLUE and Traditional classes. The instructor would stop lecture 10 minutes early providing enough time to
hand out the worksheet and the students to answer the questions. Most students finished within this time period; however, a few extra minutes were given if the student needed to finish the activity.

**Curricula Comparison.** During the Fall 2010 semester, a single class of CLUE students and three classes taught by the same Traditional professor were administered the activities. A similar order was used as in the Pilot (Figure 3.12); however, there was an additional activity included. During this semester, the periodic trends activities were piloted. The Ionic Size Model Eliciting Activity (Ionic Size) was given along with the Post-Bonding Activity. Before the end of the semester, the Atomic Size Model Eliciting Activity (Atomic Size) was also piloted.

![Diagram of CLUE and Traditional study design](image)

*Figure 3.12: Main Study Design for the Modeling Eliciting Activities*

Since the enrollment in CLUE was limited to certain biological majors, several traditional classes were included so that an equivalent cohort with similar majors and size (CLUE, N=69; Traditional, N=46) could be compared. In addition to comparing their major and gender, we used scores on the Scholastic Assessment Test (SAT) and Metacognitive Activities Inventory (MCA-I) to determine the equivalence of the groups.
A previous group member developed the MCA-I to examine students’ metacognitive skillfulness, or what students do when solving problems (Cooper & Sandi-Urena, 2009). We obtained the students’ SAT scores from the university, and the students completed the MCA-I during the first week of laboratory. The groups were considered equivalent if there was not a statistical difference between the groups. If there was a difference, a student was removed at random from the sample until the p value was greater than 0.05.

**Replication Study.** The study was replicated during the Fall 2011 semester, except the Ionic Size Activity was removed (Figure 3.13). Two CLUE classes (N=138) and five traditional classes (N=275) were examined during this study. The number of classes was expanded to include a class from each of the traditional professors. As with before, the demographics of the students were compared in order to determine equivalency. No significant differences arose prior to instruction.

![Figure 3.13: Replication Study Design for the Model Eliciting Activities](image)

The two cohorts were compared between the two semesters. A significant difference was found between the SAT scores (p<0.001, Z= -3.555, r=0.155). The SAT
scores were higher on average for the CLUE and Traditional classes in the Fall 2011 than Fall 2010 semester (Table 3.1). There was not a difference between the MCA-I or gender.

Table 3.1

*Average SAT scores for the Fall 2010 and Fall 2011 semesters*

<table>
<thead>
<tr>
<th></th>
<th>Fall 2010</th>
<th>Fall 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>University</td>
<td>1231</td>
<td>1230</td>
</tr>
<tr>
<td>CLUE – All</td>
<td></td>
<td>1249</td>
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<td>CLUE – Bio</td>
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<tr>
<td>Traditional – All</td>
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<td>1229</td>
</tr>
<tr>
<td>Traditional – Bio</td>
<td>1188</td>
<td>1197</td>
</tr>
</tbody>
</table>

**Instructor Effect.** As part of investigating the effectiveness of the curriculum, the effect of the instructors was also evaluated. The study in the Fall 2010 semester compared the Traditional and CLUE curricula as taught each by a different professor. Five different professors (Dr. B, Dr. C, Dr. D, Dr. E, and Dr. F) teach the Traditional curriculum; therefore, a class from each instructor was examined during the Fall of 2011 in order to determine if the same curriculum taught by different professors influenced students to draw different depictions of the atom. A Traditional class taught by the CLUE instructor (Dr. A) was compared from a previous semester. No significant differences were found in SAT (p=0.517, Z=4.230) or MCA-I (p=0.244, Z=6.694). There were slight differences in gender make-up between several of the classes.
Summary

A group of activities was developed to determine how students use their atomic models when discussing the more advanced concepts of covalent bonding and atomic radius. This set of three activities was designed to be given at various times during the course of the semester: Atomic Model Eliciting Activity at the beginning of the semester, Atomic and Covalent Bonding Model Eliciting Activity after atomic theory instruction, and Atomic Size and Covalent Bonding Model Eliciting Activity after instruction of periodic trends and covalent Bonding. The results from this study are presented in Chapter 5, Eliciting Students’ Mental Models of the Atom, and Chapter 6, Application of Students’ Atomic Models to Their Models of Covalent Bonding and Periodic Trends.
CHAPTER FOUR

ELICITING STUDENTS’ MENTAL MODELS OF THE ATOM

Student responses were collected from the administration of the series of Model Eliciting Activities. First, we analyzed the Atomic Model Eliciting Activity since we first must understand how the students were representing their atoms before we could determine whether it was utilized in the further activities. In this chapter, I will discuss how the Atomic Model Eliciting Activity responses were analyzed as well as discuss the following questions:

1) How do students represent their models of an atom? Being exposed to several modes of expressing their ideas of atomic structure, we analyzed the responses to determine how students depict the atom.

2) How does students’ choice of atomic model differ in the two general chemistry curricula, CLUE and an Atoms First version of General Chemistry (McMurry, 2010)?

3) In what ways does the instructor influence the students’ choice of atomic depictions? Since CLUE is a new curriculum, it is important to evaluate the effectiveness. Since the curriculum is currently being taught by one professor, the extent that the learning gains are from the curriculum or are the result of an instructor effect have to be determined.
Data Analysis

This section is separated into two parts: qualitative and quantitative. The qualitative analysis of the student depictions informed the quantitative comparison of the code frequencies for the different curricula, majors and instructors.

Qualitative Methods

Park and Light (2009) developed a coding scheme for students’ depictions of the atom during interviews they conducted. The coding scheme had two approaches: scientific models and levels of understanding. The scientific models corresponded to the historical scientific models, the Particle model, the Nuclear model, Bohr’s model and the Quantum model. Using textbook, instructor’s notes and pre- and post-questionnaire responses, researchers had determined the content and order of the items into 13 levels of understanding. There were several levels of understanding that correspond with each model.

We analyzed several depictions using this scheme; however, the scheme proved to be too detailed for the responses that we were gathering using the activity. Unlike Park and Light, we were unable to probe students’ understanding further, so we used their scientific model coding scheme to frame the development of our own coding scheme. First, we used the historical atomic models as the guides for the codes and included a different level if the student indicated that the energy levels were quantized and a letter for how the electrons are organized, i.e. orbit or cloud. A post-doctoral researcher, another graduate student, and I decided to focus on how the student chose to depict the
energy levels and electrons since it is through the electrons that atoms interact and can be manipulated.

There was a distinction made between students who represented the atom as spheres with no indication of subatomic particles (Ball) or those who were unsure of the organization of the subatomic particles (Plum Pudding) and students who drew there electrons in an orbit (Bohr) or an diffused area (Cloud). Depicting electrons on quantized energy levels shows a higher understanding than drawing all electrons on the same orbit. Electrons that were on the same orbital or area were labeled with a “2” while those that showed electrons on different energy levels were given a “3”. The letter “a” was given to those choosing an orbit and the letter “b” was assigned to those placing their electrons in a cloud. As seen in Table 4.1, there are two ways students can depict the electrons on an orbit, on the same orbit (2a) or energy levels (3a). We asked students about what they weren’t able to represent so that we could use what they wrote when coding their responses.

After several iterations, we agreed on the final coding scheme (Table 4.2). Next, we had to establish reliability of the codes. A post-doctoral researcher, graduate student and I coded several depictions individually and blindly before discussing the examples. We came to an agreement about different characteristics for each code. These characteristics are outline in the detailed coding definition list which can be found in Appendix A.

Students who had completed both activities were included in the analysis. New depiction codes had to be included for students who chose not to draw an atom and those
who used the atomic symbol to illustrate their atom. The students who chose to draw nothing were just as important to include as those who drew something. Students expressing a lack of understanding where they did not attempt to draw an atom were given the “Nothing” code. The students who used the atomic symbol or drew a Lewis Structure were included in the “Symbolic” code. We wanted to keep the distinction between solid ball illustrations and those that indicated subatomic particles. 1a and 1b were relabeled as Ball and Plum Pudding respectively. The distinction between single orbit and quantized energy levels was removed to focus on the model students used. 2a and 3a became labeled Bohr, and 2b and 3b were now considered Cloud. By simplifying the codes, we were able to apply the same coding scheme throughout the different activities. Another motivation for this redesign of the codes was the decision to focus on how students displayed their electrons whether on a set orbit or within an area.
Table 4.1

The First Version of the Coding Scheme developed for the Atomic Model Eliciting Activity

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Billard Ball</td>
<td>![Billard Ball Image]</td>
</tr>
<tr>
<td>1b</td>
<td>Thompson Plum Pudding</td>
<td>![Thompson Plum Pudding Image]</td>
</tr>
<tr>
<td>2a</td>
<td>Nuclear Model with electrons on orbits</td>
<td>![Nuclear Model Image]</td>
</tr>
<tr>
<td>2b</td>
<td>Electron cloud with not quantization</td>
<td>![Electron Cloud Image]</td>
</tr>
<tr>
<td>3a</td>
<td>Bohr</td>
<td>![Bohr Image]</td>
</tr>
<tr>
<td>3b</td>
<td>Electron Cloud illustrating knowledge of quantization</td>
<td>![Electron Cloud Image with Knowledge of Quantization]</td>
</tr>
</tbody>
</table>
Table 4.2

*Final Version of the Atomic Model Eliciting Activity Coding Scheme*

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Nothing</td>
<td><img src="image1" alt="Nothing Diagram" /></td>
</tr>
<tr>
<td>B</td>
<td>Ball</td>
<td><img src="image2" alt="Ball Diagram" /></td>
</tr>
<tr>
<td>P</td>
<td>Plum Pudding</td>
<td><img src="image3" alt="Plum Pudding Diagram" /></td>
</tr>
<tr>
<td>S</td>
<td>Symbolic</td>
<td><img src="image4" alt="Symbolic Diagram" /></td>
</tr>
<tr>
<td>O</td>
<td>Bohr</td>
<td><img src="image5" alt="Bohr Diagram" /></td>
</tr>
<tr>
<td>C</td>
<td>Cloud</td>
<td><img src="image6" alt="Cloud Diagram" /></td>
</tr>
</tbody>
</table>
Quantitative Methods

Once the activities had been analyzed, statistical comparison of the code frequencies was conducted to determine if the groups were significantly different. SPSS 21.0 was used to complete the statistical analysis. When calculating statistics, the p-value and the effect size are the important values to consider when determining the effect of a treatment on the population. P-values less than or equal to 0.05 were considered significant findings. To indicate on the graphs the level of significance, bolded red asterisks (*) will be used: a single asterisk (*) for $p \leq 0.05$, two asterisks (**) for $p \leq 0.01$ and three asterisks (***)) for $p \leq 0.001$. The effect size was calculated to determine “the degree to which the phenomenon is present in the population” (Cohen, 1988). According to Cohen, an effect size of 0.1 signifies a small, 0.3 a medium and greater than 0.5 a large effect.

**Wilcoxon signed rank test.** When comparing the depiction frequencies, each depiction was given its own column. A one was used to indicate presence of the depiction code and a zero for the absence of that depiction. Students were given a single code for their depiction. In order to compare student depictions pre- and post-instruction, we used the Wilcoxon signed rank test. The test is used for related samples that are assumed to be non-parametric. The data was assumed to be non-parametric because student responses normally do not have a Gaussian distribution. The analysis was being completed on the same group of student responses pre- and post-instruction. The effect size, reported as $r$ for the Wilcoxon signed rank test, was calculated by dividing the $z$-value by the square root of the number of observations (Cohen, 1988). Since the comparison was between
pre- and post-instruction depictions for each student, the population was multiplied by two to determine the total number of observations.

**Chi-square test.** The Chi-Square test was used to determine the difference between groups when the data was categorical. A Chi-Square test determines if there is a relationship between two categorical variables. The effect size, denoted by phi (φ), was calculated dividing the $\chi^2$ value by the number of observations and taking the square root of the result (Cohen, 1988).

**Results**

**Curricula Comparison.** We administered the activity prior to instruction and again the student had been tested. The students’ responses were analyzed, and the code frequencies were compared from the pre- and post-instruction activities (Pre- and Post-Atom) between the curricula (Figure 4.1). The frequencies were also compared for each curriculum between the pre- and post-Atom (Figure 4.2).

![Figure 4.1: The Pre- and Post-Instruction Comparison between the Fall 2010 Traditional and CLUE Frequency Percentages](image)

**Figure 4.1:** The Pre- and Post-Instruction Comparison between the Fall 2010 Traditional and CLUE Frequency Percentages
No significant differences were found when comparing the pre-instruction code frequencies from the students (p>0.05, Figure 4.1). The students in both curricula chose to illustrate their atom similarly prior to instruction. The Traditional students had no significant differences in the code frequencies between the two administrations of the activity (Figure 4.2). That is, the Traditional students were not likely to use a different model after instruction. However, the CLUE students had differences in almost every code, including Plum Pudding (p=0.046, Z=2.000, r=0.170), Symbolic (p=0.046, Z=2.000, r=0.170), Bohr (p=0.003, Z=2.921, r=0.249) and Cloud (p<0.001, Z=4.536, r=0.386) as seen in Figure 4.2. When comparing the post instruction depictions in Figure 4.1, the difference in utilizing the cloud model of the atom was proven to be significant (p=0.040, $\chi^2=4.211$, $\varphi=0.191$). The CLUE students were more likely to represent the atom with the electrons in a cloud around the nucleus when comparing their own responses and comparing their responses to the Traditional curriculum.
**Replication Study.** In Fall semester 2011, we administered the activity prior to instruction, and the students’ responses were analyzed. The pre- and post-instruction activities’ code frequencies were compared (Pre- and Post-Atom) between the curricula (Figure 4.3). The frequency differences between the pre- and post-Atom were also compared for each curriculum (Figure 4.4)

*Figure 4.3: The Pre- and Post-Instruction Comparison between the Fall 2011 Traditional and CLUE Frequency Percentages*

*Figure 4.4: The Comparison of the Fall 2011 Traditional and CLUE Frequency Percentages*
The pre-instruction depictions were analyzed and compared between the curricula with no significant differences (Figure 4.3, p>0.05). Table 4.3 displays the statistical comparison between pre- and post-instruction representations for each of the curriculum, and the significance was indicated in Figure 4.4. Again, we found several types of depictions that changed significantly between the two administrations. This time the Traditional curriculum students had increased their use of the Cloud depiction in the post activity although the effect size was small. Again, the CLUE curriculum showed large effect sizes when comparing the pre- and post-instruction activity Bohr and Cloud depictions. The majority of CLUE students had decided to depict the atom with a cloud of electrons. Next, the post-instruction depictions (Figure 4.3) were compared between the curricula. Significant differences between Bohr and Cloud illustrations were found with p-values <0.001 and φ= 0.416 and 0.405 respectively.

Table 4.3

*Statistical Comparison between the Depiction Frequencies for All Fall 2011 Student Depictions*

<table>
<thead>
<tr>
<th>Depiction</th>
<th>Traditional (N=275)</th>
<th></th>
<th></th>
<th>CLUE (N=138)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p value</td>
<td>Z value</td>
<td>r value</td>
<td>p value</td>
<td>Z value</td>
<td>r value</td>
</tr>
<tr>
<td>Nothing</td>
<td>0.317</td>
<td>-1.000</td>
<td></td>
<td>0.157</td>
<td>-1.414</td>
<td></td>
</tr>
<tr>
<td>Ball</td>
<td>&lt;0.001</td>
<td>3.606</td>
<td>0.154</td>
<td>0.014</td>
<td>-2.449</td>
<td>0.147</td>
</tr>
<tr>
<td>Plum Pudding</td>
<td>0.004</td>
<td>2.887</td>
<td>0.123</td>
<td>0.58</td>
<td>-1.897</td>
<td></td>
</tr>
<tr>
<td>Symbolic</td>
<td>1.000</td>
<td>0.000</td>
<td></td>
<td>0.317</td>
<td>-1.000</td>
<td></td>
</tr>
<tr>
<td>Bohr</td>
<td>0.144</td>
<td>-1.463</td>
<td>0.173</td>
<td>&lt;0.001</td>
<td>-6.975</td>
<td>0.420</td>
</tr>
<tr>
<td>Cloud</td>
<td>&lt;0.001</td>
<td>-4.061</td>
<td>0.173</td>
<td>&lt;0.001</td>
<td>-8.333</td>
<td>0.502</td>
</tr>
</tbody>
</table>
There were several differences found comparing the same curriculum over the two different years. When comparing the atom depiction frequencies for the traditional curriculum during Fall 2010 and Fall 2011 semesters, the only difference was found in the Pre-Atom activity code frequency (Symbolic: All students (N=321), \( p<0.001, \chi^2=24.215, \varphi=0.275 \); Biological Sciences Majors (N=116), \( p=0.023, \chi^2=6.304, \varphi=0.233 \)). Figure 4.5 displays the comparison between the semesters for the traditional group. The students have entered the course with a difference in SAT score but complete the course with similar atom depictions. When comparing the CLUE students between semesters, there are slight differences in their pre-instruction depictions while significant differences in their post representation frequencies (Figure 4.6). The pre-instruction differences (Symbolic: \( p=0.043, \chi^2=4.094, \varphi=0.141 \); Cloud: \( p=0.043, \chi^2=4.094, \varphi=0.141 \)) were not present when comparing similar majors between the semesters. The Post-Atom depictions (Figure 4.6) were significantly different between the two semesters regardless of major (All (N=207): Bohr, \( p<0.001, \chi^2=26.175, \varphi=0.356 \); Cloud, \( p<0.001, \chi^2=23.472, \varphi=0.337 \); Biological Sciences Major (N=169): Bohr, \( p<0.001, \chi^2=20.245, \varphi=0.346 \); Cloud, \( p<0.001, \chi^2=17.468, \varphi=0.322 \)). The differences in Post-Atom depiction frequencies for Bohr and Cloud between the two semesters may be explained through the design of CLUE. With the second year of implementation, the curriculum had been revised from the previous semester. The curriculum has several formative assessments to inform the instructor of students’ progress which allowed for the improvement of the instruction materials between classes as well as years.
Figure 4.5: Comparison of Pre-Atom and Post-Atom Frequencies between the Semesters for the Traditional Curriculum

Figure 4.6: Comparison of Pre-Atom and Post-Atom Frequencies between the Semesters for the CLUE Curriculum
Instructor Effect. An instructor’s style and emphasis on certain topics can have an effect on how and what students learn (Wagner & Koutstaal, 2002). To address this, student depictions were collected from each of the six instructors all teaching a traditional curriculum. Dr. A taught the CLUE curriculum during the academic years of 2010 and 2011; however, in Fall 2009 semester, this professor also taught a traditional section of general chemistry. Dr. B, Dr. E, and Dr. F have been teaching at the university for greater than ten years whereas Dr. C and Dr. D were newly hired lecturers. Between the Fall 2009 semester and Fall 2010 semester, the traditional curriculum decided to change their textbook to an Atoms First version. To create this Atoms First version, the chapters of McMurry and Fay’s General Chemistry (2008) were reordered to create General Chemistry. Atoms First (2010)

During the comparison of the pre-instruction depictions, differences were found between a few of the classes. No differences were found between Dr. A and Dr. F as well as no differences between Dr. B, Dr. C, Dr. D, and Dr. E; however, Dr. A and Dr. F had differences between the remaining professors (Ball: Dr. A vs Dr. C, $p=0.032$, $\chi^2=5.526$, $\varphi=0.225$; Dr. A vs Dr. D, $p=0.009$, $\chi^2=6.832$, $\varphi=0.261$; Plum Pudding: Dr. D vs Dr. F, $p=0.033$, $\chi^2=5.015$, $\varphi=0.224$; Dr. E vs Dr. F, $p=0.028$, $\chi^2=5.899$, $\varphi=0.234$; Bohr: Dr. A and Dr. D, $p=0.021$, $\chi^2=6.008$, $\varphi=0.245$). Figure 4.7 displays the Pre-Atom frequencies for all of the professors.
Figure 4.7: Comparison of Pre-Atom Depiction Frequencies for Different Instructors Teaching the Traditional Curriculum

The differences seen in the Pre-Atom for the Ball and Plum Pudding depictions frequencies was not seen in the Post-Atom depictions. Figure 4.8 displays the frequency percentages for the Post-Atom depictions for each professor. The only difference that remained from the Pre-Atom depictions was between Dr. A and Dr. D and the Bohr depictions ($p=0.015$, $\chi^2=5.964$, $\varphi=0.244$). Dr. A’s student depictions changed with instruction to a larger percentage of Cloud depictions while Dr. D’s student depictions did not, which may explain the difference persisting. While no significant differences were found again between the atom depiction frequencies of Dr. B, Dr. C, Dr. D and Dr. E and the depiction frequencies of Dr. A and Dr. F, there were differences between the two groups (Table 4.4). Dr. A and Dr. F had a higher percentage of students who illustrated their atom as a Cloud. The instructor does effect the students’ representations.
of the atom. Depending on the topics that the professor emphasizes, the students have a tendency to illustrate their atom in a particular way.

Table 4.4

*Statistical Comparison of Dr. A and Dr. F to the Other Professors*

<table>
<thead>
<tr>
<th>Professors</th>
<th>p-value</th>
<th>$\chi^2$-value</th>
<th>$\phi$-value</th>
<th>p-value</th>
<th>$\chi^2$-value</th>
<th>$\phi$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. A &amp; Dr. B</td>
<td>0.009</td>
<td>6.837</td>
<td>0.233</td>
<td>0.009</td>
<td>6.837</td>
<td>0.233</td>
</tr>
<tr>
<td>Dr. A &amp; Dr. C</td>
<td>0.001</td>
<td>11.644</td>
<td>0.327</td>
<td>0.001</td>
<td>11.644</td>
<td>0.327</td>
</tr>
<tr>
<td>Dr. A &amp; Dr. D</td>
<td>0.015</td>
<td>5.964</td>
<td>0.244</td>
<td>0.015</td>
<td>5.964</td>
<td>0.244</td>
</tr>
<tr>
<td>Dr. A &amp; Dr. E</td>
<td>0.001</td>
<td>11.138</td>
<td>0.321</td>
<td>&lt;0.001</td>
<td>12.576</td>
<td>0.341</td>
</tr>
<tr>
<td>Dr. F &amp; Dr. B</td>
<td>&lt;0.001</td>
<td>16.069</td>
<td>0.357</td>
<td>&lt;0.001</td>
<td>16.069</td>
<td>0.357</td>
</tr>
<tr>
<td>Dr. F &amp; Dr. C</td>
<td>&lt;0.001</td>
<td>22.021</td>
<td>0.449</td>
<td>&lt;0.001</td>
<td>22.021</td>
<td>0.449</td>
</tr>
<tr>
<td>Dr. F &amp; Dr. D</td>
<td>&lt;0.001</td>
<td>13.76</td>
<td>0.371</td>
<td>&lt;0.001</td>
<td>13.76</td>
<td>0.371</td>
</tr>
<tr>
<td>Dr. F &amp; Dr. E</td>
<td>&lt;0.001</td>
<td>21.304</td>
<td>0.444</td>
<td>&lt;0.001</td>
<td>21.304</td>
<td>0.444</td>
</tr>
</tbody>
</table>

*Figure 4.8*: Comparison of Post-Atom Depiction Frequencies for Different Instructors Teaching the Traditional Curriculum
The differences between the two CLUE semesters were already discussed; however, the comparison of Dr. A’s traditional class and the CLUE classes has not been discussed (Figure 4.9). There were differences between the classes with concern of the Ball depiction (Fall 2009 vs Fall 2010: \( p=0.001, \chi^2=10.531, \varphi=0.290 \); Fall 2009 vs Fall 2011: \( p=0.028, \chi^2=5.876, \varphi=0.174 \)). Fall 2009 semester also had differences in the Bohr depiction as well (\( p=0.029, \chi^2=4.751, \varphi=0.195 \)); however, neither differences were seen in the Post-Atom between the Fall 2009 and Fall 2010 semesters. Post-Atom differences were seen with Fall 2009 and Fall 2011 semesters in the Bohr and Cloud depictions (Bohr: \( p=0.001, \chi^2=11.083, \varphi=0.239 \); Cloud: \( p=0.002, \chi^2=9.381, \varphi=0.220 \)). Even though these classes were taught by the same professor, students’ representations were affected differently by the curriculum. The changes made to the CLUE curriculum augmented the differences between student utilization of the Bohr and Cloud models when comparing the Fall 2009 and Fall 2011 atomic depictions.
Little difference was seen between the traditional Fall 2009 semester and the CLUE Fall 2010 semester during the post-instruction depictions. The instructor was still developing and refining the course materials during the initial full year of CLUE. The benefits of having a research based curriculum stem from the ability to adapt to the needs of the students during the semester and make adjustments for the following year. The Fall 2011 showed improvement not only over the traditional Fall 2009 semester but the Fall 2010 semester as well. Between Fall 2009 and Fall 2010, the order of the material was changed with the implementation of the new curriculum. The textbook for the new curriculum has more narrative and has less examples and figures. CLUE has more interactive applets available for the students to explore and manipulate. Between the Fall 2010 and Fall 2011, the textbook was finalized and new activities were added to the curriculum. These improvements were seen in the students’ depictions of the atom. The
students were better able to convey the Schrödinger model, the current understanding of the atom.

Since there is an instructor effect, the comparison between CLUE and each traditional professor would not be useful. If each professor was given the opportunity to teach a CLUE class, then a comparison between each professor’s CLUE and traditional class could illustrate further the effect of the curriculum on students’ atom depictions.

Conclusions

The Atomic Model Eliciting Activity was used to gather students’ depiction of the atom. An examination of students’ depiction frequencies between two curricula, CLUE and Traditional, was utilized to determine the effectiveness of conveying Atomic Theory. The CLUE students had higher frequency of the cloud depiction than the Traditional students. The comparison was completed taking major as well as instructor into account. Each time the CLUE students provided the Cloud depictions at a significantly higher occurrence. A small instructor effect led to some of the difference in depiction frequencies; however, large differences were still apparent when comparing the same instructor teaching the two curricula.

Even more enlightening than the instructor effect was the ability of instructional materials to alter students’ models. Based on educational research, CLUE was designed to be adaptive to the needs of the students. Formative assessments keep the instructor informed of any difficulties students were having with topics. Between the Fall 2010 and Fall 2011, the professor was able to make adjustments to the instructional materials that were seen in the students’ models of the atom. There were significant differences
between the students’ atomic models between the semesters. The Fall 2011 semester students were more likely to use the Cloud model when illustrating their atom.

However, just because students chose to represent their atom using one model or another, does not mean that the students will apply the model to further chemistry concepts. We developed an activity that allows us to collect student depictions of the atom. The next step was to investigate how students explain further chemical concepts and whether they refer to their atomic model to do so.
CHAPTER FIVE
APPLICATION OF ATOMIC MODEL TO COVALENT BONDING AND ATOMIC SIZE

With the development of the activities previously discussed, this chapter will provide the analysis of student responses to the Covalent Bonding and Atomic Size Model Eliciting Activities. We had collected their atomic depictions in the Atomic Model Eliciting Activity; therefore, the next step was to determine if the students were utilizing their atomic model when discussing further chemistry concepts. We used these responses to answer these research questions:

1) How do students picture bonding, and what are students’ preferred models of bonding?

2) How do students’ depictions of their atoms forming covalent bonds compare to their individual atoms representation before and after instruction?

3) How do the students represent two atoms on the same row and are they able to explain the trend in atomic size?

4) How does the experimental CLUE curriculum influence students’ representations of bonding and understanding of atomic size?

5) Across the three activities, have students represented their atom with the same model? If not, was there an activity that students were more likely to illustrate their atom using a different model?
Data Analysis

Qualitative Methods

The anonymous responses were coded blind to remove potential researcher biases. Since more research had been conducted on student models of atoms and bonds, we were able to adapt a coding scheme that had previously been developed. The Atomic Model Eliciting Activity coding scheme was applied to the depictions on the Covalent Bonding and Atomic Size Model Eliciting Activities; however, because of the type and array of responses students provided for their explanation of the atomic size trend on the Atomic Size Model Eliciting Activity, we had to take a different approach to coding. We utilized constant comparison (Dye, Schatz, Rosenberg & Coleman, 2000) where the data was clustered into categories based on common ideas in order to determine if any patterns or themes emerged out of the data. Because the question asked students to explain, we were not sure what types of information the students would choose to include. Detailed below is the data analysis for both the Covalent Bonding and Atomic Size Model Eliciting Activities.

Covalent Bonding Model Eliciting Activity. We first tried using a coding scheme focused on how students displayed the interactions between the two atoms. Since some form of a contact would be made between two atoms for a bond to form, we were interested to see how students explained what was causing the interaction to occur. Since few students provided details about the interactions between the two atoms, the coding scheme had to be revised to be more representative of the student responses. We found the most common ways students depicted forming a bond utilized how different atomic
models would interact. This was useful because we could apply the coding scheme that we had previously developed to this new activity. We did not want to assume that we could relate the atomic model coding scheme to this activity. Table 5.1 includes examples of student work for each code.

Table 5.1

The Final Coding Scheme for the Covalent Bonding Model Eliciting Activity

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Nothing</td>
<td><img src="example1.png" alt="Example" /></td>
</tr>
<tr>
<td>B</td>
<td>Ball</td>
<td><img src="example2.png" alt="Example" /></td>
</tr>
<tr>
<td>P</td>
<td>Plum Pudding</td>
<td><img src="example3.png" alt="Example" /></td>
</tr>
<tr>
<td>S</td>
<td>Symbolic</td>
<td><img src="example4.png" alt="Example" /></td>
</tr>
<tr>
<td>O</td>
<td>Bohr</td>
<td><img src="example5.png" alt="Example" /></td>
</tr>
<tr>
<td>C</td>
<td>Cloud</td>
<td><img src="example6.png" alt="Example" /></td>
</tr>
</tbody>
</table>

When analyzing qualitative data, personal biases can influence the coding process. To limit these biases, the coding scheme was discussed with another graduate student. We co-coded several depictions until we reached agreement on how different
representations should be labeled. A detailed coding description is included in Appendix B. For example, students started using the letter “H” to indicate the nuclei which lead to a discussion of when it was appropriate to give that representation a different code than Symbolic. We agreed that the “H” was accepted as the nucleus when students drew electrons in a cloud or orbit. We also relied on the students own words which were an important resource when trying to understand what they meant with their drawing. In describing their representation, we were able to determine how the student saw their depiction.

**Atomic Size Model Eliciting Activity.** We continued to use the coding scheme established through the Atomic Model Eliciting Activity in order to evaluate the atomic depictions the students provided in the Atomic Size Model Eliciting Activity since the wording of the question was similar. Using the same codes allowed us to determine if the students continued to use the same model to depict their atom when discussing the periodic trend.

The initial version of the Atomic Size Model Eliciting Activity asked students to explain the trend and if they were able to use their atomic model. The responses proved difficult to code since students either provided an explanation for the trend or whether their model could be used to explain the trend but rarely both. This prompted revisions to the activity and returned the focus to how the students explained the atomic size trend.

The responses were open coded, and we found that Toulmin’s Argumentation Pattern (Brockriede & Ehninger, 1960) could be used as a method to group the codes and compare student responses. The three main parts of Toulmin’s analysis are claim, data
and warrant. The claim refers to the students’ initial response to the question of atomic size. The data is the support the student uses for their claim while the warrant connects the data to the claim. For the course of this dissertation, the warrant is referred to as the reasoning. I found that the term “reasoning” better describes what we want the student to provide. They would provide a reason why the data confirms the claim.

As the codes were placed within the categories, codes with less than 4 total occurrences were removed from the sample. The students provided two types of claims: correct and incorrect. There were a couple students who thought the size would stay the same or discussed how the cation size would be affected; however, the number of students who made these claims was less than 1% of the population. The majority of students were aware that the atomic size decreased across the row; however, as the students tried to explain the trend, they provided a variety of responses.

The codes that indicated “more” or an “increase” of something were grouped into the Data Category. Responses such as stating the periodic trend for atomic size were also considered data. The Reasoning category has responses that explain “why” the atom would be larger or smaller. Some codes can be seen as both data and reasoning. The distinction was made depending on how the individual student used the information in their response. For example, the statement that the effective nuclear charge increases can be used as data or as reasoning depending on where student uses this knowledge. The coding scheme found in Table 5.2 displays codes with at least 20 total occurrences with an extended and detailed coding scheme provided in Appendix C.
Table 5.2

Coding Scheme for the Atomic Size Model Eliciting Activity with Frequencies

<table>
<thead>
<tr>
<th>Theme</th>
<th>Category</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claim</td>
<td>Incorrectly identifies the trend</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Correctly identifies the trend</td>
<td>329</td>
</tr>
<tr>
<td>Data</td>
<td>Be has more electrons</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>Be has more protons/nuclear force</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Correct statement of periodic trend</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Be has larger effective nuclear charge</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Be has more electrons and protons</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Electrons are pulled towards/more attracted to nucleus</td>
<td>45</td>
</tr>
<tr>
<td>Reasoning</td>
<td>Attraction/pull between electrons and protons</td>
<td>109</td>
</tr>
</tbody>
</table>

Quantitative Methods

The code frequencies were compared using SPSS version 21.0. When the same group of students is compared between activities, a Wilcoxon signed rank test was conducted to determine significance. The comparison of two different groups was completed using a Chi-Square test. When completing these statistical tests, the null hypothesis was rejected, or the groups are considered significantly different, when the p-value was less than 0.05. After determining that the groups are different, the effect size indicates the extent the groups diverge from the null hypothesis.

Results

Covalent Bonding Model Eliciting Activity

Comparison of Bonding Depictions. After the students had been introduced to atomic theory, the students were asked to complete this activity and were administered
the same activity days after completing the exam on the topic of bonding. After the representations were analyzed, the code frequencies were compared from the pre- and post-instruction activities (Pre- and Post-Bonding) for each curriculum (Figure 5.1) and between the curricula (Figure 5.2).

**Figure 5.1:** Comparison of the Depiction Frequencies for the Covalent Bonding Model Eliciting Activity for the Fall 2010 Traditional and CLUE students

The Pre- and Post-Bonding depictions for each curriculum were compared to determine what effect instruction had on the students’ representation of bonding. The Traditional students utilized the Symbolic (p=0.007, Z=2.683, r=0.280) and Cloud (p=0.014, Z=2.449, r=0.255) representations while moving away from using the Bohr (p<0.001, Z=3.900, r=0.407) for the Post-Bonding representation. The increase in Symbolic representations could be explained by the amount of focus placed on how to draw Lewis Structures. Similar to the Traditional students, the CLUE students...
represented their bonding model using more Cloud depictions (p<0.001, Z=4.382, r=0.373) and less Bohr illustrations (p<0.001, Z=4.017, r=0.342). Interestingly, the CLUE students chose to portray their ideas of bonding using the Cloud model more often than how they decided to represent their interpretation of the atom. Even more students were using the Cloud representation of the atom in their depiction of bonding than the students that had utilized it in their Post-Atom activity.

![Figure 5.2: Comparison of the Depiction Frequencies for the Pre-Bonding and Post-Bonding for Fall 2010 semester](image)

The student depictions were then analyzed for differences between the curricula. Small differences were seen in the pre-instruction bonding (Pre-Bonding). As seen in Figure 5.2, differences were found between the cloud depiction frequencies (p=0.006, \( \chi^2=7.629, \phi=0.258 \)) as well as the symbolic depictions (p=0.024, \( \chi^2=5.085, \phi=0.210 \)) between the Pre-Bonding representations of the two groups. These differences were
accentuated after instruction (Cloud: $p<0.001$, $\chi^2=19.498$, $\phi=0.412$; Symbolic: $p<0.001$, $\chi^2=18.771$, $\phi=0.404$). The CLUE students had multiple discussions concerning atomic interactions and bonding including an interactive applet that was utilized to describe how potential energy changed throughout the bond formation process. Another interesting difference is the CLUE curriculum’s examination of atomic interactions prior to instruction on Lewis structures. The Traditional curriculum teaches the students what a covalent bond is followed immediately with rules on how to construct Lewis Structures.

The revision of the CLUE curriculum for the Fall 2011 semester proved to have an effect on the students’ atomic models. The students in Fall 2011 showed a higher preference for the cloud model to depict their atom. We were interested to see how this would impact their Pre-Bonding and Post-Bonding depictions (Figure 5.3).

![Graphs showing depiction frequencies for Pre-Bonding and Post-Bonding models for Traditional and CLUE students](image)

*Figure 5.3: Comparison of the Depiction Frequencies for the Covalent Bonding Model Eliciting Activity for the Fall 2011 Traditional and CLUE students*
Also, the Traditional students did not rely on their Symbolic depictions this semester. The students’ Cloud depictions almost doubled after instruction (p<0.001, Z=3.638, r=0.155) with a small effect size. There were differences between Ball (p=0.041, Z=2.043, r=0.087) and Plum Pudding (p=0.035, Z=2.111, r=0.090) representations; however, the effect sizes indicate that the effect is less than small (r < 0.1). The CLUE students’ depiction percentages remained similar between Pre- and Post-Bonding except for a slight difference between Symbolic (p=0.025, Z=2.236, r=0.135).

The depictions for Fall 2011 semester displayed a much wider array of differences between the groups (Figure 5.4). Every category besides “Nothing” had a significant difference (Ball: p<0.001, χ²=10.07, φ=0.156; Plum Pudding: p=0.019, χ²=5.671, φ=0.117; Symbolic: p<0.001, χ²=38.713, φ=0.3062; Bohr: p=0.001, χ²=11.390, φ=0.166; Cloud: p<0.001, χ²=131.33, φ=0.564); however, the two categories with the largest effect sizes were “Symbolic” and “Cloud”. These were the same categories that were significant in Fall 2010 semester depictions.
Comparison between Semesters. Given there were differences found between the CLUE students’ atom depictions between the semesters, we were interested in how the bonding depictions compared between the two semesters for both curricula (Figure 5.5 and 5.6). We compared the Pre-Bonding and Post-Bonding depictions for each respective curriculum between the Fall 2010 and Fall 2011.

*Figure 5.4:* Comparison of the Depiction Frequencies for the Pre-Bonding and Post-Bonding for Fall 2011 semester
Figure 5.5: Comparison of Pre-Bonding and Post-Bonding Depiction Frequencies between the Semesters of Traditional Students

Figure 5.6: Comparison of Pre-Bonding and Post-Bonding Depiction Frequencies between the Semesters for the CLUE Students

There were small differences between the Pre-Bonding (Bohr: $p=0.008$, $\chi^2=7.020$, $\phi=0.148$) and Post-Bonding (Symbolic: $p=0.003$, $\chi^2=8.900$, $\phi=0.167$) for the Traditional
students with small effect sizes. The traditional curriculum used the same book for the second year, and little different arose between student depictions. Conversely, the CLUE curriculum was revised between the two semesters to utilize the research findings from the first iteration of the curriculum which may have contributed to the larger differences in the students’ Post-Atom depictions. The differences were carried over to their Pre-Bonding depictions as well (Ball: p<0.001, $\chi^2=15.184$, $\varphi=0.271$; Symbolic: p=0.042, $\chi^2=4.731$, $\varphi=0.151$; Bohr: p<0.001, $\chi^2=13.508$, $\varphi=0.256$; Cloud: p<0.001, $\chi^2=35.888$, $\varphi=0.416$); however, there were no differences in the Post-Bonding depictions.

**Comparison between Activities.** The goal of the activities was to collect the students’ preferred models when discussing atoms and bonding. The Pre-Bonding was purposefully combined with the Post-Atom to investigate whether students would use similar models when describing these two concepts. The depiction frequencies for the Traditional and CLUE curricula were compared in Figure 5.7 for Fall 2010 and Figure 5.8 for the Fall 2011 semesters.
Figure 5.7: Comparison of the Fall 2010 semester Traditional and CLUE Students’ Depiction Frequencies for the Post-Atom and Pre-Bonding

For the Fall 2010 semester, the majority of Traditional and CLUE students preferred to use either the Bohr or Cloud models for their atoms on the Post-Atom depiction. This was not the case for the Pre-Bonding depictions. Both Traditional and CLUE students moved away from using the Cloud model (Traditional: p=0.001, Z=3.317, r=0.346; CLUE: p=0.001, Z=3.411, r=0.290) and more students used the Ball (CLUE: p=0.003, Z=3.000, r=0.255) or Symbolic (Traditional: p=0.004, Z=2.887, r=0.301; CLUE: p=0.025, Z=2.236, r=0.190) depictions for the Pre-Bonding.
Figure 5.8: Comparison of the Fall 2011 semester Traditional and CLUE Students’ Depiction Frequencies for the Post-Atom and Pre-Bonding

The depictions for the Fall 2011 semester did not follow the same pattern. The Traditional students’ depictions were different for each code. The Cloud ($p<0.001$, $Z=7.233$, $r=0.308$) and Bohr ($p<0.001$, $Z=4.619$, $r=0.197$) depictions decreased while the rest increased (Nothing: $p=0.014$, $Z=2.449$, $r=0.104$; Ball: $p<0.001$, $Z=5.099$, $r=0.217$; Plum Pudding: $p=0.004$, $Z=2.887$, $r=0.123$; Symbolic $p<0.001$, $Z=8.660$, $r=0.369$).

During the Fall 2010 semester, depictions were collected from classes taught by one professor. The data collected during the Fall 2011 sampled a class from each professor and captured a better representation of Traditional students’ portrayal of atoms during bonding. Although there were slight differences with small effect sizes between the Bohr ($p=0.020$, $Z=2.335$, $r=0.141$) and Cloud ($p=0.006$, $Z=2.744$, $r=0.165$) depictions, the CLUE students mostly continued to use the same depictions for both concepts. This
suggests that the revisions to the CLUE curriculum enabled students to apply their image of an atom to the concept of covalent bonding.

**Atomic Size Model Eliciting Activity**

**Atomic Depictions.** Students were asked to provide their mental image of a lithium and beryllium atom. Although few students indicated a size difference in their drawings, we examined how they decided to draw their atoms again. We wanted to compare those depictions with their post-instruction atom representation. With the progression of the semester and their understanding of chemical concepts, we investigated how the students chose to illustrate their atom.

The traditional students (Figure 5.9) did not have significant differences between the two sets of depictions. The Cloud representation had a slight difference (p=0.033); however, the effect size was less than 0.1 so the difference is not considered as significant. The CLUE student depictions had several differences (Figure 5.9) including the depictions using Ball (p=0.046, $\chi^2=2.000$, $\phi=0.120$), Bohr (p<0.001, $\chi^2=3.592$, $\phi=0.216$), and Cloud representations (p<0.001, $\chi^2=4.644$, $\phi=0.280$).
Figure 5.9: Comparison of Traditional and CLUE Atomic Depiction Frequencies on the Post Atom and Atomic Size Model Eliciting Activities

Even though the frequency of the Cloud representation decreased for the CLUE students, it remained larger than the frequency for the traditional students. The Bohr (p<0.001, $\chi^2=38.161$, $\varphi=0.304$) and Cloud depictions (p<0.001, $\chi^2=32.202$, $\varphi=0.280$) had the most significant differences with a slight difference in the Ball representation (p=0.045, $\chi^2=4.937$, $\varphi=0.109$). The CLUE students continued to choose to represent their atom using the Cloud model more than the traditional students.

The CLUE students had continued with the Cloud model of the atom throughout the semester. The Atomic Size Model Eliciting Activity probed further and asked students to express the size trend between two atoms. We moved on from analysis of which atomic model students illustrated to how they discussed the atomic size difference between two atoms.
**Providing a Claim.** Looking at the students’ responses, 99% of both classes included a claim in their response as seen in Table 5.3. The students who were not included either did not know the trend or discussed the formation of cations. With the activity’s administration close to the discussion of ionic size, the students may have assumed the activity was referring to ionic instead of atomic size. The comparison was continued using the students who provided a response corresponding with atomic size. We compared the correctness of the claims provided as well as the types of depictions students chose to utilize.

Table 5.3

*Atomic Size Model Eliciting Activity Categories with Frequencies*

<table>
<thead>
<tr>
<th>Category</th>
<th>Traditional Frequency (%) (N=303)</th>
<th>CLUE Frequency (%) (N=152)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claim</td>
<td>299 (99)</td>
<td>150 (99)</td>
</tr>
<tr>
<td>Data</td>
<td>275 (91)</td>
<td>134 (88)</td>
</tr>
<tr>
<td>Reasoning</td>
<td>76 (25)</td>
<td>62 (41)</td>
</tr>
</tbody>
</table>

Between the two curricula, there were no differences between the frequencies of claims. Students in both curricula would at least provide a claim when asked a question. Interestingly, a high percentage of students were able to provide the correct claim that beryllium is smaller than lithium for this in-class activity. In fact, 82% of CLUE students provided a correct claim while only 67% of traditional students said that lithium would be larger than beryllium or beryllium would be smaller (p=0.005, $\chi^2=7.760$, φ=0.137).
When we compared the frequency of correct claims and depiction between the two groups, significant differences were found between those using the Bohr (p<0.001, $\chi^2=32.474$, $\varphi=0.336$) and Cloud (p<0.001, $\chi^2=26.984$, $\varphi=0.306$) representations and correctly identifying the atomic size trend (Figure 5.10). This can be explained since the traditional students utilized the Bohr model more for their atom illustration whereas the CLUE students used the Cloud model. Conversely, there were no significant differences in the types of depictions students used when stating an incorrect claim.

![Bar chart comparison between Correctly and Incorrectly identified atomic size trends](image)

*Figure 5.10: Comparison between the Atomic Depiction Frequencies of Students that Correctly and Incorrectly Identified the Trend*

**Including Data.** We wanted to examine what types of information students were including in their explanations. The CLUE students had a lecture at the beginning of the semester about the importance of providing evidence when explaining a scientific concept. The students were not specifically instructed on the argumentation framework; however, they did discuss how they should have a conclusion, some evidence to support
that conclusion, and a reasoning to tie them together. Although the instructor periodically would ask the students what the evidence and reasoning were for different scientific conclusions, this was the only formal lecture on the topic. The traditional curriculum was not introduced to these ideas during Chemistry lecture.

We compared whether or not students provided a piece of data in addition to their claim. Regardless of how many pieces of data the student included in their response, the students were counted as either having or not having data. There were no significant differences in the number of students who provided evidence with their claim with 91% of the traditional students and 88% of the CLUE students (Table 5.3).

When analyzing the types of data the students included, all data coded was included in the following analysis. Each data code was compared individually to determine if there was a difference between the types of data the students in each curriculum chose to include (Table 5.4) because some responses could have multiple pieces of data. The curricula used similar types of data when discussing the trend in atomic size.
Table 5.4

The Traditional and CLUE students’ frequencies for the Data codes

<table>
<thead>
<tr>
<th>Code</th>
<th>Traditional (N=303)</th>
<th>CLUE (N=152)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be has more electrons</td>
<td>73</td>
<td>49</td>
</tr>
<tr>
<td>Be has more protons/nuclear force</td>
<td>33</td>
<td>23</td>
</tr>
<tr>
<td>Correct statement of periodic trend</td>
<td>51</td>
<td>15</td>
</tr>
<tr>
<td>Be has larger effective nuclear charge</td>
<td>46</td>
<td>42</td>
</tr>
<tr>
<td>Be has more electrons and protons</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>Electrons pulled towards/more attracted to nucleus</td>
<td>28</td>
<td>17</td>
</tr>
</tbody>
</table>

Not all responses that focused on the increase of protons or electrons concluded that the size would increase. It was thought that students who solely relied on the number of subatomic particles would conclude that the size would increase. More subatomic particles would take up more space; therefore, the atomic size would be larger; however, this was not the case. For example, Alex (all names are pseudonyms) stated that “Beryllium gets smaller than lithium due to a greater positive charge. There are more protons in beryllium than lithium.” Alex did not explain why the increased positive charge would cause the atom to be smaller. Increased subatomic particles leading to a smaller size is counterintuitive unless students comprehend the attraction and shielding that is occurring or they have memorized the trend correctly. Sara determined that “the size decreases. When another electron is added, Zeff (effective nuclear charge)
increases.” Although not fully complete, Sara uses the increased effective nuclear charge to connect why increased number of electrons would cause a decrease in the atomic size.

Jeff focused on the attraction and repulsion as well as a complementary trend. He responded that “beryllium is smaller than lithium. The electrons feel more attraction from the added proton than repulsion from the surrounding electrons. This increase \( (Z_{\text{eff}}) \) draws the electrons closer to the nucleus.” Jeff’s response is an example of a response that has more than one piece of data, attraction/pull between protons and electrons and effective nuclear charge increases across the row.

Alice stated “by knowing the size trend on the periodic table, I can tell that they decrease in size from Li to Be.” Sometimes students rely on the location of the element on the periodic table and how they drew the arrows on their periodic table when learning the trends. Memorizing the direction of the trend did not prove to help all the students. Several traditional students \( (n=9) \) indicated that the trend increased across the period.

**Supplying a Reasoning.** To compare between the curricula whether the students supplied a piece of reasoning as part of their responses, the students were labeled as either providing or not providing a reasoning. As shown in Table 5.3, we found that 41% of CLUE students included a piece of reasoning while only 25% of Traditional students did \( (p<0.001, \chi^2=14.912, \varphi=0.190) \).

Next, we compared the types of reasoning used by students so each piece of reasoning was treated individually. The comparison between the reasoning codes was carried out in the same manner as with the data codes. The students tended to focus on the attraction/pull between electrons and protons. Of the traditional students, 18% used
this reasoning in their response while 36% of the CLUE students utilized the same reasoning.

Comparison of Student’s Atomic Depictions throughout the Semester

Gathering atomic depictions throughout the semester has allowed the examination of how students illustrate the atom in different scenarios. I took all of the post-instruction depictions and compared the atomic model used by the students when drawing the atom. Because there is an unimaginable number of combinations of models the students could have used throughout the three activities, I started by looking at the students who maintained the same model of the atom in the post-instruction Atomic and Covalent Bonding Model Eliciting Activities as well as the Atomic Size Model Eliciting Activity (Figure 5.11).

![Comparison of the Traditional and CLUE percentages of students who utilized the same models throughout the various activities](image)

*Figure 5.11: Comparison of the Traditional and CLUE percentages of students who utilized the same models throughout the various activities*
The traditional students chose to use the same atomic model more when drawing their atom on the post-instruction Atomic and Atomic Size Model Eliciting Activities (p<0.001, Z=6.694, r=0.285) while the students use a different atomic model to represent bonding (p=0.047, Z=1.99, r=0.085). Both the Atomic and Atomic Size Model Eliciting Activities posed the question of how students would draw their atom, and interestingly, the traditional students tended to utilize the same model on these two activities. It was when asked to draw their understanding of covalent bonding that students were inclined to provide a different model. However, the CLUE students utilized the same model between the post-instruction activities (Atomic and Covalent Bonding Model Eliciting Activities: p=0.001, Z=3.405, r=0.205; Atomic and Atomic Size Model Eliciting Activities: p<0.001, Z=4.256, r=0.256; Covalent Bonding and Atomic Size Model Eliciting Activities: p=0.006, Z=2.724, r=0.164). When comparing the two curricula, CLUE students were more likely to use the same model on the Atomic and Covalent Bonding Model Eliciting Activities (p<0.001, \( \chi^2 = 14.631 \), \( \varphi = 0.188 \)) and on the Covalent Bonding and Atomic Size Model Eliciting Activities (p=0.015, \( \chi^2 = 5.934 \) \( \varphi = 0.120 \)). Finally, the models were compared across all three activities. Of the traditional students, 63% utilized a different model on at least one activity while the CLUE students were split in half about whether they would use the same model or not on all activities (between curricula: p=0.013, \( \chi^2 = 6.147 \), \( \varphi = 0.122 \)).

Further investigation was conducted to determine which activity students chose to illustrate their atom differently (Figure 5.12). This analysis further supported that the Traditional students utilized a different model of the atom to describe their understanding...
of covalent bonding because the Covalent Bonding Model Eliciting Activity was statistically different from both the Atomic (p<0.001, Z=5.32, r=0.113) and Atomic Size (p<0.001, Z=6.739, r=0.128) Model Eliciting Activities. The Covalent Bonding Model Eliciting Activities (p=0.001, χ²=10.505, φ=0.159) and Atomic Size Model Eliciting Activities (p=0.018, χ²=5.628, φ=0.117) were different between the two curricula.

![Figure 5.12](image)

*Figure 5.12: Comparing which Activity the Students Used a Different Atomic Model to Express Their Understanding*

**Conclusions**

The activities were administered to two groups of general chemistry students, one traditional and one CLUE lecture, over the course of two Fall semesters, 2010 and 2011. Throughout the semesters, we collected their depictions of an atom during different situations: isolated, bonded and size comparison.
Instruction had an enormous impact on how students illustrated their atom throughout the activities. These differences were not only evident between the traditional and CLUE curricula but also between semesters. Even with all the differences, the CLUE students tended to illustrate their atom using the Cloud model while the traditional students relied on the Bohr model.

Students showed an elementary understanding of the process of bonding. Most students drew their atoms’ outer layer overlapping whether using orbits, orbitals or clouds. Little indication was made about what caused the interaction between the two atoms or mention of the change in energy. The question did ask the students to provide their understanding of what happens between the two atoms; however, the question was not able to elicit a more sophisticated comprehension of atomic interactions so we focused on how students used their atom to represent the formation of the bond and whether they maintained the same model throughout instruction.

When it came to student representation when discussing atomic size, the traditional students illustrated their atoms using the Bohr model. The limitations of the Bohr model were not considered as the atomic size should not change with the addition of an electron since it would be added to the 2s subshell. On the other hand, the Cloud model accounts for the electron shielding that occurs between the core and valence electrons allowing for the correct identification of the size decreasing. The students drew the Bohr model when providing their rationale for the size decreasing which indicated that they adapted the model to be able to explain the trend instead of choosing a more suitable model.
As far as the explanation of the atomic size trend, we were able to compare whether the students provided a claim, data and reasoning. Surprisingly even though the Traditional students had not been introduced to the idea of scientific explanation during chemistry lecture, most were able to provide a claim with data. Almost 43% of CLUE students provided a reasoning with their response which is double the percentage of Traditional students. We were interested in helping students better express what they understand about the topic. In order to accomplish this goal, we developed an activity to expose the Traditional students to scientific explanation through the incorporation of Toulmin’s Argumentation Pattern. Through this activity, we hope the exposure to making an argument will help the students provide a clearer indication of what the students understand leading us to whether they are using their atomic model appropriately. The activity development and analysis of the results are outlined in the Chapter 6.
CHAPTER SIX
UTILIZING A BESOCRATIC ACTIVITY ON ARGUMENTATION TO AID STUDENTS’ EXPLANATIONS

Previously, we determined that the majority of students offer data as a way to support their claim (as seen during the discussion of the Atomic Size Model Eliciting Activity in Chapter 5). Nevertheless, we also found that students did not always provide reasoning to link their data and claim. Reasoning is often thought as the crucial connection that tells readers why the data verifies the specific claim.

This chapter presents two main objectives: (1) the development of an interactive activity, using the beSocratic platform, focused on argumentation and (2) a study to determine whether the activity improved students’ understanding of how to construct a complete argument regardless of curricula. Since argumentation is now part of the Next Generation Science standards (Pratt, 2011), instructors are looking for ways to communicate to students what an argument is and how to construct them. We are aware that many instructors do not have the authority to rearrange their curriculum so we wanted to investigate other adjustments that instructors could make to improve students’ understanding of how to construct a complete scientific argument.

Activity Design

This activity was designed using beSocratic (Appendix D) as a way to purposefully allow students to explain their responses to different situations (either scientific or not). Designed and programmed at Clemson University, beSocratic provides a platform for free-form student assessment (Bryfczynski, 2012). Instructors can build activities using
“steps” which are similar to slides in a presentation. On each step, a variety of modules, both interactive and non-interactive, can be arranged to the discretion of the instructor (Bryfczynski, 2012; Bryfczynski, Pargas, Cooper, Klymkowsky, 2012). The interactive modules have the opportunity to convey feedback to aid students in obtaining a correct answer. The non-interactive modules help instruct students or collect student responses for manual analysis.

As previously stated, upon examination of students’ responses given on the Fall 2011 administration of the Atomic Size Model Eliciting Activity, we determined that students seemed to provide an answer, but they did not always provide an explanation. As such, we decided that for this specific activity we wanted to target the construction of a complete scientific argument. Since the goal of this activity is to help students understand the topic and not assess them, we designed the activity with guiding questions that allowed students the opportunity to be metacognitive about what is it that they are being asked to complete and to reason through the process. Brown authored the most common description of metacognition defining it as “knowledge and regulation of one’s own cognitive system” (Brown, 1987). Students simply going through the motions will not retain the material meaningfully; however, allowing student to reflect on the material that they were just presented provides an opportunity for the information to be connected with appropriate and related knowledge. This can permit the student to use prior experiences to rationalize through the problem.
Activity Description

Using the beSocratic system, an activity was constructed that asked students to answer an initial question. As one progressed through the slides, the parts of an argument were introduced as well as an example from biology. The students were asked to identify the parts of the argument within the example. After they dissected the argument, the students were able to compare their answer to our analysis of the response. The students revisited the initial question and were asked to provide their claim, data, and any reasoning necessary to answer the question on separate steps. At the end of the activity, their original response was presented, and the student could choose to edit or leave their original response as it was. Depending on the design of the study, an additional question could be asked on a similar topic to investigate whether the students would apply argumentation to a new situation.

The argumentation activity was piloted with a section of second semester general chemistry students during Spring 2012. The activity required students to explain the trend of atomic radius across a row. After the pilot of the activity with second semester, we administered the activity to the target audience, first semester general chemistry students, during the Spring 2012 semester. The activity was given at the end of the semester as a way to ensure that students had been tested on the material and should have been reviewing for their final exam. We found that the students’ responses were not as complete as the second semester students’ answers. In order to improve the activity, several slides were reworded in order to aid student interaction with the activity.
**Final Version of the Activity**

The revisions started with the introduction to argumentation step (Figure 6.1). We wanted to articulate to the students why argumentation is important and how it is useful. Going back to the ideas of meaningful learning, students have to see the information as useful so we provided a short paragraph on how scientists use argumentation to convey to students a practical application. We also made the three parts of the argument more explicit. The students did not have to question what the three parts were; they were presented with a short definition. The example was also improved (Figure 6.2). We included a scenario about a student answering a question on their biology exam. By changing the language of the last statement from “can” to “try”, we were indicating to the students to explicitly point out what they thought the claim, data and reasoning in the example were. During earlier testing, a few students would simply answer that “yes they were able to identify the parts” but did not go into more detail.

<table>
<thead>
<tr>
<th>Constructing a Scientific Argument</th>
</tr>
</thead>
<tbody>
<tr>
<td>The function of a scientific argument is to coordinate a conclusion with available evidence. A scientist evaluates possible arguments and determines which provides the most plausible explanation for a given scientific phenomenon.</td>
</tr>
<tr>
<td>There are three main components in an argument:</td>
</tr>
<tr>
<td><strong>Claim:</strong> The claim is your conclusion.</td>
</tr>
<tr>
<td><strong>Data:</strong> The data is the evidence that is used to support the claim.</td>
</tr>
<tr>
<td><strong>Reasoning:</strong> The reasoning explains the relationship between the claim and the data.</td>
</tr>
</tbody>
</table>

*Figure 6.1:* Revised introduction to argumentation slide
A student, Becky, was asked on her biology exam to describe and explain the color of a plant's leaves during the summer. Below is her response.

"A plant's leaves are green in the summer because they contain chlorophyll. Chlorophyll is a natural pigment that absorbs all wavelengths in the visible spectrum except green. The reflected green light is the color our eyes see."

Try to identify the claim, data and reasoning Becky used in her response.

Main Study

We tailored a study to examine students’ ability to defend the identification of their unknown inorganic salt’s cation and anion. We used questions concerning a project they were completing in laboratory to provide the students with a topic that is current and relevant. Because they were conducting the experiment, the students would have the necessary data to support their claim. The activity aimed to help the students put all of the pieces together into a complete defense of their unknown’s identification in preparation of their laboratory report.

Experimental Design

This concurrent explanatory mixed methods study was conducted at a southeastern public research university. The experimental design for the pilot and main studies comprised of a nonequivalent control-group quasi-experimental design. In this approach, we usually have two non-randomly selected groups of students with one group
being administered the activity (a treatment) and both control and treatment groups were administered post-test assessments (Creswell, 2009). Both the assessments and activities were administered outside of the lecture setting and instead were conducted inside the laboratory as a way to avoid the priming effect (Wagner & Koutstaal, 2002). The post-tests as well as the treatment activity were administered at the beginning of a specific laboratory period.

Participants in the control and treatment groups for the studies were determined to be statistically equivalent using their SAT and MCA-I scores. The 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). The groups were considered equivalent if there was not a statistical difference between the groups. If there was a difference, a student was removed at random from the sample until the p value was greater than 0.05. All of the participants included in these groups signed an informed consent form (Appendix E).

**Data Collection**

The activities were conducted during the laboratory time with at most 24 students in each section. Students were offered participation credit for completing various activities throughout the semester including the ones described above. Before the teaching assistant began class, the students used their personal computers to access the beSocratic webpage and complete the activities. A Chemical Education group member was available to help remedy any issues that may arise. The students completed the activities within the first 20 minutes of the 3 hour laboratory period.
To investigate the effects of the argumentation activity on students’ explanations, a cohort was asked questions relating to the laboratory experiment they were conducting. Six lab sections taught by the same teaching assistant were chosen to be split into two activity groups, Activity Group 1 (N=39) and Activity Group 2 (N=43), and a control group (N=33). The two activity groups were given the same activity and were used to determine reproducibility of the results. The activity groups answered the same questions as the control group; however, they completed the argumentation activity as well. Initially, the question posed was “What is the identity of the cation in your unknown compound? How do you know?” The follow-up question was worded “Keeping in mind what you just learned, what is the identity of the anion in your unknown compound? How do you know?”

The students performed various experiments over the course of 4 weeks in order to identify and confirm the composition of an unknown inorganic salt given to them by their teaching assistant. Several different tests were available to conduct in order for the student to ascertain the identity of their compound. The activity was administered during the week of the laboratory that the students were to present a poster summarizing their findings to the teaching assistant (Figure 6.3). Prior to their presentation, the students were asked to complete the activity without looking at their posters or their laboratory notebook.
Figure 6.3: Study design for the Laboratory themed Argumentation Investigation

Data Analysis

Qualitative Methods

beSocratic has a text coding analysis tool within the system. Student responses for each step are displayed (Figure 6.4). beSocratic is able to display a number instead of the students’ name by selecting the “Anonymous” checkbox at the top of the submission window. The responses were coded blind. Again, the use of constant comparison was employed to capture the uniqueness of the students’ wording used in their responses. To distinguish different ideas within a response, a code can be assigned a color that will highlight the text. Prior to analysis using beSocratic, students who had not completed all parts to the study were removed. This allowed for comparison across the different questions that were asked over the few weeks of the investigation.
All 195 responses were made anonymous and randomized. The coder did not know whether the response was from an activity group or control group student as well as whether the response was pre- or post-activity. At first, the responses were coded simply for claim, data, and reasoning. We looked at the frequencies to determine whether the students were providing a more complete response after the activity as compared to the control group.

The cation and anion codes were developed separately, and the descriptions were refined through discussions with a post-doctoral researcher. Several responses were analyzed and discussed until agreement was reached. The themes and categories that emerged are seen in Table 6.1 for cations and 6.2 for anions for the entire sample of students. We found the codes separated into different categories within the major themes of claim, data and reasoning. These categories were then used to determine the quality of the students’ responses. A detailed code depiction can be found in Appendix F.
Table 6.1

*Theme and Category Frequencies for Student Explanations of their Unknown’s Cation*

<table>
<thead>
<tr>
<th>Theme</th>
<th>Category</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claim</td>
<td>Identified a Cation</td>
<td>178</td>
</tr>
<tr>
<td></td>
<td>Identified an Anion</td>
<td>18</td>
</tr>
<tr>
<td>Data</td>
<td>Experimental Data</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>Facts</td>
<td>14</td>
</tr>
<tr>
<td>Reasoning</td>
<td>Theoretical reasoning</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Comparison against known</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Experimental reasoning</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Definitions</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 6.2

*Theme and Category Frequencies for Student Explanations of their Unknown’s Anion*

<table>
<thead>
<tr>
<th>Theme</th>
<th>Category</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claim</td>
<td>Identified an Anion</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>Identified a Cation</td>
<td>8</td>
</tr>
<tr>
<td>Data</td>
<td>Experimental Data</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>Facts</td>
<td>7</td>
</tr>
<tr>
<td>Reasoning</td>
<td>Comparison against known</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Experimental Reasoning</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Definition</td>
<td>3</td>
</tr>
</tbody>
</table>

Under Claim, most students identified an anion or cation. A single student identified their entire compound. During coding, we coded those who did not support
their claim separately from those that included data or data and reasoning. This was useful when comparing the pre- and post-activity responses as well as comparing the three groups.

The data responses sorted into two categories: experimental data and facts. The types of responses that were considered experimental data were those containing their observations from their experiments. Christina (all names are pseudonyms) included in her response that “when the flame test was conducted the result of my compound was inconclusive, so an ammonium test was conducted, producing the smell of ammonium.” This student included two pieces of experimental data. First, she stated flame test results as inconclusive and then she described the ammonium test producing a smell.

The facts were pieces of information that could be found in their textbook. Alex supported his anion choice by stating that “Cl has a charge of -1 and K has a charge of +1.” This was not the type of data we were expecting the students to include. This may have been due to the phrasing of the question: how do you know? Alex knew because chlorine had the negative charge so it is his anion. The goal of the activity was to encourage students to use the experimental data that they had collected during their investigation.

The reasoning used by the students varied and was the part we were most interested to analyze. The majority of students compared their unknown to a known sample whether it was experimentally by conducting the experiment again with an identified sample or by referring to the table in their manual. Meredith stated how her group “used a known potassium in the flame test, it created a violet flame.” By
investigating the flame color a potassium salt would emit, Meredith and her group were able to compare the flame color of their unknown sample to the potassium sample, and they were able to conclude that their cation was potassium. Other students would use what we called experimental reasoning. Mark’s answer identified his group’s anion as sulfate. His group formed a precipitate with Lead Nitrate and explained that “the double displacement reaction separated out the sulfate, causing a white precipitate.” He used the reaction with lead nitrate causing a white solid to connect the white precipitate to their unknown containing sulfate.

April chose to take a different approach to link the claim that her cation was potassium and data that her compound was potassium chloride. She relied on definitions in chemistry to ascertain which element would be the cation. April knew that “K is the positively charged ion in the compound.”

Only a few students had a more sophisticated reasoning, and those students were explaining how the color was caused by excited electrons. Owen eloquently stated how:

“When the electrons are energized they jump to higher energy levels and emit photons at a wavelength specific to that element as they return to their original energy level. The purple flame produced is a result of this emission (sic) of photons and is characteristic of magnesium.”

Owen was able to explain how the color was produced to support his claim that it was potassium that produced the purple flame. The quality of the student arguments will be discussed in the findings of the Laboratory Activity.
We were able to export the student responses from Activity Group 1 & Activity 2 pre- and post-activity responses and use the “compare” option in *Microsoft Word* to reveal how the students edited their answers after completing the activity. The pre- and post-activity responses were saved in separate word documents, and under *Review*, the Compare feature allows the side by side evaluation of any differences between the two documents. In our case, the answers could be analyzed for changes the students made after the activity.

**Quantitative Methods**

The code frequencies were compared using SPSS version 21.0. When the same group of students is compared between activities, a Wilcoxon signed rank test was conducted to determine significance. The comparison of two different groups was completed using a Chi-Square test. When completing these statistical tests, the null hypothesis was rejected, or the groups are considered significantly different, when the p-value was less than 0.05. After determining that the groups are different, the effect size indicates the extent the groups diverge from the null hypothesis.

**Findings**

The identities of the students were revealed and separated into the three groups, Activity Group 1, Activity Group 2 and Control Group. First, we investigated whether frequency of claim, data, and reasoning in the students’ responses were similar at the start of the activity to the control responses (Figure 6.5). The correctness of their statement was not taken into account because the activity’s purpose is to help students construct a complete argument. The students had been given no feedback as to the correctness of
their statements during the activity. We found no significant differences between the three groups in the parts of an argument they chose to include in their initial answer. We examined how the two activity groups’ responses changed after completing the activity for the cation question. Both Group 1 ($p=0.001$, $Z=3.317$, $r=0.376$) and Group 2 ($p=0.020$, $Z=2.324$, $r=0.254$) had a significant increase in the number of responses that included a reasoning into their response. The Activity was able to produce similar effects between two independent groups of students.

**Activity Group 1**

<table>
<thead>
<tr>
<th></th>
<th>Frequency Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claim</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td></td>
</tr>
<tr>
<td>Reasoning</td>
<td></td>
</tr>
</tbody>
</table>

**Activity Group 2**

<table>
<thead>
<tr>
<th></th>
<th>Frequency Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claim</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td></td>
</tr>
<tr>
<td>Reasoning</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.5: Comparison of the Activity Groups 1 & 2 in their initial and revised answers

The post-activity responses for Activity Groups 1 & 2 were compared to the Control Group’s responses. In Figure 6.6, the post-activity responses between the two activity groups continued to not have a significant difference; however, when comparing the control and activity group as a whole, there was a significant difference found between the use of reasoning in their responses ($p=0.015$, $\chi^2=5.914$, $\varphi=0.227$).
Because we used the copy previous option in beSocratic during this activity, we explored how the students chose to edit their responses. Examining all the responses for the activity group, we found that the majority of students did edit their response in some way. 71% of students edited their response after completing the activity which is a significant percentage of activity students (p<0.001, Z=7.616, r=.594). Of the students who edited their response, 41% of students added information that strengthened their response while 52% of the students did not improve or weaken their argument. The remaining 7% removed material that was important to their argument therefore diminishing its effectiveness.

After going through the activity, some students were able to provide a more complete answer with edits that added to the student’s argument. To denote the pieces of
their argument that were added or deleted, additions to the student’s answer is bolded while any portions that were removed are in italics. George’s response is an example of an improved argument:

“The identity of the cation in unknown compound "B" was Potassium. We conducted a flame test with the unknown to determine the cation. The flame burned a low intensity violet indicating Potassium was present, because Potassium gives off a low intensity violet flame. Therefore, we could conclude the compound contained Potassium, K.”

By clarifying that potassium gives off a purple flame, George was able to include support through comparing his results to a known fact. He made the connection between potassium and a violet flame more explicit.

The other half of the students made edits that did not affect the completeness of their arguments as can be seen with the addition that Miranda made, “The identity of the cation in my unknown is potassium. I know this because I performed a flame test and it burned a purple flame. indicating the presence of a potassium cation.” We were coding for explicit statements that the students made. It could be assumed that Miranda looked at her manual to determine the correct flame color for potassium, but this would be an implicit code. This example continued to have only a claim and data with no support to connect the ideas.

After the students finished the activity, an additional question was included that asked the students to explain how they knew the identity of their compound’s anion. By incorporating this question, we wanted to assess the students’ ability to apply what they
had learned during the activity to a related situation. Figure 6.7 displays the analysis for the control group’s cation and anion responses as well as the activity group’s post-activity cation and anion responses. Even with a significant decrease in students’ incorporation of reasoning in their anion responses when compared to their revised cation replies ($p=0.008$, $Z=2.646$, $r=0.207$), the activity group still provided answers with a reasoning more often than the control group ($p=0.031$, $\chi^2=4.640$, $\phi=0.201$).

![Figure 6.7: Comparison of the percentages of responses that contained claim, data or reasoning between the cation and anion questions](image)

**Conclusion**

The activity was designed to help students construct a more complete answer to a question. Utilizing a laboratory experiment that the students were conducting, the Argumentation Activity was successful in assisting students in the addition of reasoning into their responses. The activity group provided revised responses and answered a
related question with a more complete answer than the control students. The activity was able to convey to students the three parts of an argument and compel the majority of students to incorporate them into their response.

Other measures that could be investigated to determine their effect on students’ answers would be to include student evaluation of other arguments for completeness. By providing students the opportunity to read arguments, they would determine whether the individual provided a sound argument. This would empower the students and strengthen their confidence in knowing what types of information should be used as data or reasoning. The examination could encompass other students’ responses to related questions or isolated topics.
CHAPTER SEVEN
CONCLUSIONS AND FUTURE WORK

Conclusions

Two research questions framed the determination of students’ use of their atomic models when discussing further chemical concepts. First we had to determine whether the students’ mental model of atomic structure affected their understanding of covalent bonding and atomic size. The second question examined the effect of an alternative instructional approach (CLUE) would have on students’ utilization of their mental models and understandings of the two concepts – covalent bonding and atomic size. In order to answer these questions, three model eliciting activities were designed, piloted, and revised to collect student depictions of an atom, covalent bond and atomic size. Through analysis of these activities, we hoped to answer the above research questions.

Most of the studies that discussed students’ models of atoms and covalent bonding were qualitative studies with a handful of students (Park & Light, 2009; Coll & Treagust, 2001, 2002, 2003; Nicoll, 2001; Peterson & Treagust, 1989; Taber & Watts, 1996; Coll & Taylor, 2001, 2002; Özmen, 2004). For our study, we were developed a method that would allow the collection of a larger number of students but trying to maintain the detail that would be found during an interview. There were characteristics that were imperative for successful model eliciting activities: open-ended questions that allowed for multiple forms of expression and free form input. We designed the activities with open-ended questions because we did not want to constrain or influence the student response. The word choice can have an effect on the information that students provide;
therefore, the questions were revised to ensure that the request was concise and clear without giving too much detail. We also provided that the students could response in a form that they were comfortable, whether it was an illustration or words. Another feature that proved to be important and informative was providing students the opportunity to discuss topics they were unable to depict or had difficulty showing. Students were able to clarify what was meant by their “electron cloud” or discuss the repulsion between electrons on the same shell. Allowing students the ability to include concepts they felt were important but were unsure if they clearly displayed in their image. Asking students to take a three-dimensional picture as well as additional interconnected ideas and place them on a two-dimensional surface, we knew that some pieces would not transfer as the student had intended so this question provided a space where they could share that with us. Through these activities, we were able to successfully gather students’ depictions of atomic structure, covalent bonding and atomic size.

Analysis of the students’ atomic structure mental models showed that the majority of students relied on either the Bohr or Cloud model of the atom after instruction. These results aligned well with what has been found in the literature (McKagan, Perkins, & Wieman, 2008; Coll & Treagust, 2002, Park & Light 2009). Even though the instructors discussed Rutherford’s and Dalton’s models, students preferred Bohr’s or Schrödinger’s models when depicting the atom. Responses were collected from students enrolled in two general chemistry curricula. The students taking the CLUE curriculum more strongly favored Schrödinger’s model while the traditional students drew Bohr’s model more frequently. The instructor affect could not be completely eliminated within the data that
was presented in this research. When comparing the same professor in Figure 4.9, an increase in the occurrence of the Cloud model can be seen during the second year of the curriculum implementation; however, this instructor had a higher percentage of students preferring the Cloud model while teaching the traditional course. Without comparison to another instructor teaching CLUE, we cannot completely dismiss the instructor affect.

Once we had investigated students’ atomic structure representations, we examined how the students applied those depictions to covalent bonding. The students did not change their covalent bonding model preference between pre- and post-instruction administration of the Covalent Bonding Model Eliciting Activity during the Fall 2011 semester. The conclusions are drawn from this semester because it included a more representative sample of traditional students as well as the second year the two curricula had been implemented allowing for the instructors and students to adjust. The bonding instruction had little affect on students’ depiction of covalent bonding. The CLUE students drew mostly the Cloud model for displaying their mental model of covalent bonding which aligned with their atomic structure depictions. The traditional students used a larger variety of models including Symbolic, Bohr and Cloud models. The differences found in the instructional approach could explain the students’ choice of representation. The topics do not have to be taught necessarily one after the next; however, it is the reflection upon the prior knowledge that helps the students develop a robust understanding. The CLUE curriculum discusses the origin of the atom between discussion of the Schrödinger model and formation of a chemical bond while the traditional curriculum covers several more topics including periodicity and ionic bonding.
The separation is not the difference; however, the CLUE instructor used small group discussion to have the students talk about what they think would happen when two atoms interacted and what parts of the atom were interacting. Taking the discussion of covalent bonding further than just the heuristic that covalent bonds share electrons, the students were required to answer why the bond forms and think about what is happening to the atom during this interaction. This connection can be seen since the majority of CLUE students continue to use similar models throughout the three activities. With the large instructor-centered classrooms of the traditional curriculum, the students were shown pictures of covalent bonds and lectured on the same material of why bonds form; however, they did not seem to make the same connections between atoms and covalent bonds that the CLUE students made.

Next the investigation led us to examine how students applied their atomic structure mental models to the concept of atomic size. Both curricula saw a decrease in the amount of students that chose to use the Cloud model. The question was worded to have the students depict what they thought two different atoms would like. It is unclear whether the students made the connection between drawing these two atoms and the difference in size that occurs between them. The difference in depiction could be a result of students returning the model that they are most comfortable utilizing since it had been several months since the discussion on atomic structure. The goal was not to influence the students to draw a certain picture; however, how the question is worded does have an impact on how the students choose to portray their models. If the question referring to covalent bonding was worded in terms of atoms interacting, it may have persuaded the
students to provide representations that were more consistent to their atomic structure models. As far as depicting atomic size, the majority of the students’ representations were similar with their atomic structure model.

Along with the portrayal of atomic size, we also analyzed how the students explained the trend. The goal was to answer the main question of students’ use of their atomic models in other chemical concepts. In reading the students responses, we were finding students were not providing enough information in their responses to determine whether they were referencing their atomic structure model when forming their explanation. The majority provided what the trend did and a piece of data. Of the students, 41% of CLUE and 25% of traditional students provided a reason for the change in atomic size. We were unsure if the lack of support was due to students’ ability to explain the trend or if they were unaware of what was expected when asked for an explanation. The Argumentation Activity was designed as a way of conveying to the students a method of responding to questions that asked them to explain. The activity outlined the parts of a response that are expected when students are asked to explain, especially if it is a scientific phenomenon. The activity was tested on students during their laboratory. The activity group of students edited their cation question to produce a more complete response, and even with a slight decrease in reasoning, the activity students continued to provide a more complete answer than the control group.

Overall, the students who used their atomic model when depicting covalent bonding or atomic size tended to have a more robust understanding of the topics. The CLUE students utilized similar models throughout the three activities. The students used
similar models to predict covalent bonding as they did to discuss atomic structure and that model was persistent through bonding instruction. Although some students did change models for atomic size representation, the CLUE students were more successful at identifying the correct trend as well as providing an explanation for its occurrence.

**Implication for Instruction**

During the course of this research project, we investigated the effects two curricula had on students’ understanding of atomic models and its application in future concepts. The two curricula covered the same topics in similar order; however, the delivery and focus were different. The student-centered classroom and focus on structure, function and energy of CLUE provided an environment that assisted student comprehension.

The entwining of structure, function and energy throughout instruction provided the students with a solid foundation to comprehend the atom and apply those ideas to covalent bonding. When discussing bonding, the students were reminded of the atomic structure: Where are the electrons? What is their charge? The next focus was what function would bonding hold: Why would atoms want to form bonds? The CLUE curriculum spends several class periods and an activity illustrating how potential energy is a factor during atomic interactions and bonding: What happens when two atoms approach each other? By working through these questions and focusing on these three pillars, the students develop a deeper understanding of the concept through the connections made between topics.
Since not all instructors have the capability to adopt a new curriculum, the teachers have the capability to incorporate some of the approaches that were used in the CLUE curriculum. One of the fundamental changes that were made in the curriculum was an active student-centered classroom. Actively engaging students in the classroom has been shown to promote student learning (Cooper, 1995; Case, Cooper, & Stevens, 2007; Dougherty et. al., 1995). Class discussions and/or small group discussions were a part of most classes. Having the students express their ideas and thoughts allowed the students to reflect on the concepts they understood or compare their knowledge of the topic of discussion with their peers. Since class time is limited and material is vast, a short five minute block can allow students time to exchange ideas, but not enough time to go off task. Encouraging note taking and an open invitation for questions can produce an environment that will ease students’ anxiety about challenging what the instructor was conveying to the students or asking the instructor to explain a topic again.

Another characteristic of the CLUE classroom that can be adopted is the focus on meaningful learning. Although the instructors may not be able to reorder the topics that the students are covering, they can help anchor the new material to topics they have previously covered. Even if the discussion of atoms and covalent bonding are chapters apart, instructors can remind the students about the atom and get them discussing what would happen if they were to interact so they can begin to apply their ideas of atoms with this new idea of covalent bonding. In order for students to develop a robust understanding of chemistry topics, they must understand how these topics are interrelated. Chemistry
can be taught out of any textbook; it is the instructor that must help erect the scaffold so that students can build their understanding.

**Future work**

The scope of this research focused on the general chemistry students, specifically first semester. An investigation into students’ use of atomic structure mental model as they progress through the levels of chemistry could provide information into how the model is affected during the different topics. When discussing organic chemistry, professors use mostly Lewis Structures. Would organic students rely on symbolic structures if asked how they picture the atom? By examining the depictions at different levels, we may be able to determine the influence of the topics has on students’ preferred model of the atom. In addition, we could establish at what point in their chemistry career students begin to use their atomic structure mental models to understand chemical concepts.

To further the impact of this work, an in-depth qualitative examination of students’ description of how they view the atom and its relevance to the topics of covalent bonding and periodic trends should be conducted. The activities were effective to collect a large number of students’ superficial depictions, but interviews would allow follow-up questions to obtain the fine details of students’ comprehension. The students who were not providing full explanations of atomic size could be asked supplementary questions to probe their understanding or determine what was causing their difficulties.

The student depictions of covalent bonding were collected and analyzed; however, the concept of covalent bonding goes further than the illustration. To provide a
more thorough discussion of students’ use of atomic structure and understanding of bonding, students need to be questioned about what causes a bonding to occur. We know that some students will rely on the octet rule to discuss the formation of a bond. By having the students’ depiction of atomic structure and covalent bonding, we can establish if there is a connection between the illustration and how the student chooses to explain how a covalent bond is formed.

Exposing students to Toulmin’s Argumentation Pattern in the Argumentation Activity may have been sufficient when they were discussing a laboratory experiment they had conducted; however, it is unclear that a single activity would provide students enough understanding to apply argumentation to chemistry concepts. While I was researching argumentation, it took several papers and discussions with other group members to grasp the concept. Providing the students with more of an opportunity to sharpen these new skills and discuss further examples may provide the experiences necessary for students to determine what information is required to assemble a complete response. In turn, a more descriptive response would enable the determination of whether students are using their atomic model when discussing atomic size or other periodic trends.

Instead of limiting the periodic trend to atomic size, students’ comprehension of the other periodic trends that are discussed during general chemistry could be investigated. By inquiring about effective nuclear charge and ionization energy, we could determine which trends the students were having the most difficulty comprehending. Atomic size may be the only trend that the student understood or had trouble explaining.
It would have been informative to ask a truly open ended question of the students concerning their understanding of the periodic trends. Determine which trends the students find most important and which ones they are able to explain. Also, the students’ ability to apply the periodic trends to determine properties, like melting and boiling point and polarizability, can be examined. The periodic trends provide information that can be used to determine other characteristics of atoms and compounds than simply size and electronegativity.
APPENDICES
APPENDIX A

Atomic Model Code Descriptions

No depiction (N) = the student does not draw anything and states that they are unsure what an atom looks like. Also included in this category was a student who drew a cell instead of an atom.

“Yes, everything because I have not had chemistry in three years, sorry”
“l really do not know what to draw. I know an atom has protons, neutrons, electrons, and orbitals, but I’m not quite sure what to draw. I had an A in my high school chemistry, but the teacher wasn’t very good and even got fired the next year.”

Symbolic depiction (S) = Students rely on Lewis Structures or the chemical symbol to express their ideas

“I wasn't able to show anything because my mind needs a little review exercise”

Billiard Ball depiction (B) = Simply show the atom as a ball. There is no indication of subatomic particles

These students have circles that they labeled with atomic symbols to represent their atoms.
Plum Pudding depiction (P) = Several types of depictions fell into this category. Depictions similar to Billiard Ball (B) except there are indications of subatomic particles. These students did not provide any difficulties that they had depicting their atom. These representations do not belong in Billiard Ball because they indicate an understanding that atoms have smaller subatomic particles.

This description also includes depictions that have placement problems. These are students who have the protons and electrons around the nucleus whether drawn in an area or on an orbit. Like Thompson’s Plum Pudding model, there is a sea of positive and negative charges.

Example of student who had protons and electrons in an area.

The student had difficulty showing: "I had trouble drawing neutrons, just because I don't know where they are in relation to the atom. I do know the have neither a positive or no charge"

Orbit depiction (O) = the electrons are shown on a set path. Students who label the set path electron cloud without defining somewhere what they mean by electron cloud.

Example of a student who labeled paths of electrons as "electron cloud" without further definition

The student wasn't able to show: "the three-dimensional part of it because I'm not a good drawer and it's been a while since I've had chemistry"
The electrons are placed on a path around the nucleus.

**Cloud depiction (C)** = the electrons are in an area around the nucleus; these depictions can have electrons on an orbit if the student drew “clouds”/shading over the orbits. If a student describes how they were not able to show the electrons in a cloud or how their path is not set, the depiction was also given the "Cloud" code.

A. B.

Two versions of students showing an electron cloud. A has a “cloud” around the nucleus while B has the electrons in an area around the nucleus.

This is an example of where the student’s explanation of what they had difficulty showing helped us code their depiction properly.

The student wasn't able to show: "I wasn’t able to depict that the electrons don't necessarily orbit in a distinct path but that they have hasty, nondefined paths."
Appendix B

Bonding Model Code Descriptions

The coding scheme focuses on the way students decided to depict their atoms bonding. The coding scheme for students’ representations of atoms was extended to describe how students chose to represent their atoms during bonding.

**No depiction (N)** = These responses are blank or have “I don’t know” written in the space. Some students explain further that they are unsure of where to start.

“I honestly have no idea”

**Symbolic depiction (S)** = Students rely on Lewis Structures or the chemical symbol to express their ideas

![Symbolic depiction](image)

This student chose to use a line between the two symbols

**Billiard Ball depiction (B)** = Simply show the atom as a ball. There is no indication of subatomic particles

![Billiard Ball depiction](image)

The atom is depicted with an “H” in the center with a circle around it. There is no mention of orbitals or subatomic particles when asked if there is anything they could not show.

The same for this depiction the main difference was their decision to have the two atoms touching.
The same for this depiction the main difference was their decision to have a dotted line portray the bond.

**Plum Pudding depiction (P)** = These representations were

![Plum Pudding depiction](image)

What sets this depiction apart from the depiction above in the Ball depiction is that the student stated that they had trouble illustrating “the location of the electrons and protons, neutrons”

At first glance, the representation would be given a “Ball” code; however, the indication of a charge on the atoms warrants the Plum Pudding depiction.

The student doesn’t show understanding that the neutron is in the nucleus with the proton.

**Orbit depiction (O)** = the electrons are shown on a set path. Students who label the set path electron cloud without defining somewhere what they mean by electron cloud.

The student indicates that the electrons are found on these set paths that overlap

![Orbit depiction](image)

The electrons are shared in the center with an orbital for each touching.
**Cloud depiction (C)** = the electrons are in an area around the nucleus; these depictions can have electrons on an orbit if the student drew “clouds”/shading over the orbits. If a student describes how they were not able to show the electrons in a cloud or how their path is not set, the depiction was also given the "Cloud" code.

Students used shading to indicate the electron cloud.

Students also had the electrons in an area around the nucleus to illustrate their electron cloud.
Appendix C

Atomic Size Explanation Code Descriptions and Frequencies

What happens to the size between Lithium (Z=3) and Beryllium (Z=4)? Please explain why this happens to the size between Lithium and Beryllium?

- Claim – Incorrectly identifies the trend = student identified the trend as increasing or staying the same
  “Li is smaller than Be because it holds fewer electrons. So, as you go down the row the size increases”
  “they are basically the same size”
  “the addition of the electrons creates more space and therefore a larger atom”
  “beryllium gets larger than Lithium”
- Claim - Correctly identifies the trend = student identifies that the atomic size decreases
  “Atomic radius decreases from Li to Be”
  “lithium is larger than Be”
  “beryllium should be smaller”
- Data – Incorrect information – Be has less valence electrons = students incorrectly identified Be as having less electrons
- Data – Incorrect information – Li has greater effective nuclear charge = state that Be has smaller effective nuclear charge
- Data – incorrect information – periodic trend backwards = student states that the trend increases from left to right
- Data – Be has more electrons = student discusses an increase in the number of electrons
  “because Be has more electrons, they are more "scrunched down" to the nucleus. Therefore it's smaller”
  “An added electron means bigger atomic radius”
- Data – Be has more subatomic particles = student references an increase in all three subatomic particles
- Data - More protons/nuclear force = student discusses an increase in the number of protons
  “Beryllium is smaller than lithium because it has more protons and holds its electrons more closely”
- Data – Correct statement of periodic trend = stated the periodic trend or location on periodic table
  “b/c as you move left to right across the periodic table, atomic radius decreases”
• Data – Be has larger effective nuclear charge = stated the effective nuclear charge trend
  "the effective nuclear charge of beryllium is larger than that of lithium so the electrons are more attracted to the nucleus and therefore more compact"
• Data – Be has more electrons and protons = student refers to the increase of both protons and electrons
• Data – electrons pulled towards/more attracted to nucleus = student points out an attraction or pull between protons and electrons
  "size Be < size Li, the electrons and protons have a stronger pull on each other (tighter)"
• Data – states effective nuclear charge = the response has no indication of the direction or change in effective nuclear charge
• Data – states electron shielding = no discussion or further detail the student simply stated electron shielding
• Data – Be has greater mass = the student indicated that Be has larger weight
• Reasoning – scrunched down = the student used the phrasing to discuss the electrons
• Reasoning – attraction/pull between electrons and protons = the reasoning focuses on the interaction between electrons and protons
  "this happens because the effective nuclear charge of Be is greater than that of Lithium, allowing it to attract electrons more tightly toward the nucleus"
• Reasoning – holds electrons more strongly = student had no indication of what was holding the electrons
  "because charge increases which means tighter grip on e- (electrons)"
• Reasoning – created more space/takes up more space/bigger = mention the subatomic particles or cloud taking up more space.
• Reasoning – larger repulsive forces = discussion of increased electrons causing increased repulsive forces
• Reasoning – Be has greater effective nuclear charge = use greater effective nuclear charge to connect claim and data.
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Appendix D

What is beSocratic?

Designed and programmed at Clemson University, beSocratic provides a platform for free-form student assessment (Bryfczynski, 2012). Instructors can build activities using “steps” which are similar to slides in a presentation. On each step, a variety of modules, both interactive and non-interactive, can be arranged to the discretion of the instructor (Bryfczynski, 2012; Bryfczynski, Pargas, Cooper, Klymkowsky, 2012). The interactive modules have the opportunity to convey feedback to aid students in obtaining a correct answer. The non-interactive modules help instruct students or collect student responses for manual analysis.

For the Argumentation Activity, the text modules conveyed information and collected student responses. “Display Text” is used to provide directions to the student while “Text Input” allows students to respond in the activity. The text can be formatted in respect to font, font size, color whereas the box’s size and outline and fill colors can be customized. Copy previous is an option that can be applied to text and graph responses. This option is especially useful in this project for their text responses. Once the individual has interacted with the activity, the initial response can be copied to the end, and the individual can edit their original answer. Copy previous allows for an internal check to investigate what the student learned during the activity.

Along with text, other types of responses that may be useful during an investigation are illustrations. beSocratic has “Chalkboard”, a module that records students’ free-form drawings. The student has the ability to choose draw, erase or reset. It is easiest to use a finger or stylus to draw in the area; however, a mouse or track pad can be used if the screen is not touch enabled. The “Chalkboard” area can be drawn to any size on a step, and scroll bar can be enabled to allow students a larger workspace to illustrate everything that they feel is necessary.
Appendix E

Informed Consent Form

CONSENT TO PARTICIPATE IN A RESEARCH STUDY
Clemson University

DEVELOPMENT OF TECHNOLOGY BASED ASSESSMENTS IN CHEMISTRY

Description of the research and your participation

You are invited to participate in a research study conducted by Melanie M. Cooper (Principal Investigator). The purpose of this research is to conduct research into how students learn to solve problems. Approximately 1300 students per semester will be involved in this research.

Your participation will involve working a series of web-based chemistry problems. The program you will be using keeps track of the information you utilize to solve the problems and allows us to compare your strategies with those of your peers. Part of the information collected will be in the form of surveys and/or scales administered before or after your working on the web based problems. Random short interviews may be used to collect additional information.

The amount of time required for your participation will be part of the regular time you need to dedicate to your Chemistry Lecture and Laboratory work. You will not need to allocate additional time to participate of this project. You will work on web based problems approximately four times during the semester.

Risks and discomforts

There are no known risks associated with this research.

Exclusion requirements

Students under 18 years of age will not participate in this research study.

Potential benefits

The potential benefits from this research include: improved problem solving skills and improved content mastery. It is not possible to predict whether or not any personal benefit will result from your participation in this study. You understand that the information that is obtained from this study may be used scientifically and may be helpful to others.
**Protection of confidentiality**

We will do everything we can to protect your privacy. Any statements or actions on your part will not be identified by your name or any other identifier to anyone outside the project, and your participation in this project will be held in confidence, however results of the project may be published. Your identity will not be revealed in any publication that might result from this study. Any results from this project will not contain information by which you may be identified.

**Voluntary participation**

Your participation in this research study is voluntary. You may choose not to participate and you may withdraw your consent to participate at any time. You will not be penalized in any way should you decide not to participate or to withdraw from this study.

**Contact information**

If you have any questions or concerns about this study or if any problems arise please contact Melanie M. Cooper at Clemson University at 864-656-2573. If you have any questions or concerns about your rights as a research participant, please contact the Clemson University Institutional Review Board at 864.656.6460.

**Consent**

I have read this consent form and have been given the opportunity to ask questions.

A copy of this consent form should be given to you.
Appendix F

Laboratory Activity Code Descriptions

What is the identity of your cation? How do you know?

- Claim - Cation = identified x as the cation "Magnesium is my cation"
- Claim - Anion = identified x as the anion "The cation of my unknown is Chloride"
- Claim - Compound = The student identifies the entire compound "My compound was potassium chloride"
- Claim - Cation - Unsupported = only state cation, no data or reasoning
- Claim - Anion – Unsupported = only state anion, no data or reasoning
- Claim – No Cation – confuse negative results with not having a cation
  - “I did not have one. There was no reaction from the mixing test. The results of the flame test was a bright orange flame, but the metal that the compound was on also burned bright orange, so this data was thrown out.”
- Data – Experimental – Flame Color = state that ran flame test as well as resulting color
  - “The cation was Magnesium. I know this through the flame tests, where the flame had no coloration which told me that the compound contained magnesium” here they discussed the lack of color given off in the flame and would still be coded as Flame Color.
- Data – Experimental – Flame Color - Flame inconclusive = The student states that the color is inconclusive. This is different from the “no color” that appears with magnesium and ammonium. The student was unable to determine if the flame changed color or not.
- Data – Experimental – Smell = provides that an odor/lack of odor was produced when performing the Ammonium test
  - “NH4—when the flame test was conducted the result of my compound was inconclusive, so an ammonium tests was conducted, producing the smell of ammonium, thus leading to the conclusion that ammonium was present in my unknown compound.”
- Data – Experimental – Smell – procedure = student provides information concerning the chemicals added to perform the Smell test
- Data – Experimental - formation of precipitate = state that precipitate is formed; no detail about what was mixed
  - “The cation of my unknown compound is chloride. I mixed my unknown compound with multiple cations to find one that formed a white precipitate” there is little detail about what was being mixed and solely discussed mixing things and finding one that was not soluble.”
- Data - Experimental – formation of precipitate - procedure = detail into what was added or formed in the reaction to give or not give a precipitate.
“chloride, shown by mixing it with HNO3 and finding a precipitate” detail into what they did to get a precipitate besides running a test”

- Data – Experimental - Ran Tests = no results just stating which tests were run, mixing compounds together to determine reactivity
  - “Potassium. Flame tests indicated presence. When tests of known reactions verse unknown reactions were compared all reactions matched” States that flame test was run but no statement of color of flame.

- Data – Experimental – ran tests pos or neg = discuss ran these tests and it was positive or neg
  - “The identity of the cation in the unknown compound was magnesium. This can be determined because it failed every other test” More detail than simply that tests were run

- Data – Experimental – Unknown reacted, reactivity tests = student refers to the tests as “reactivity tests” or discusses reactions that were conducted
  - “The cation of my unknown compound was potassium. I reached this conclusion by preforming a series of tests in which I mixed my unknown compound with other compounds and noted which compounds my compound reacted.”

- Data – non-experimental – takes electrons, positive charge = states that cations accept electrons and that gives it a positive charge
  - “Magnesium because it is an ion that takes electrons giving it a positive charge.”

- Data – non-experimental - solubility = makes reference to a compounds ability/inability to be soluble.
  - “Na. It is completely soluble and ionic in solution. Burns yellow when exposed to flame.” The response states facts about sodium. There is no reference to procedure or lack of precipitate formed. Simply stating that sodium is soluble.

- Data – Non-Experimental - Formula = says they have x for their compound
  - “The identity of the cation in the unknown compound was K. I know this because I have KCl.” The student determined the cation by looking at the formula of their known.

- Data – Non-experimental - state charges = details the ion charges for the compound, no discussion of test results
  - “K has a +1 charge and Cl has a -1 charge so therefore K is the cation”

- Data – Experimental - repeated experiment = obtained the same results after repeating the experiment
  - “The identity of the cation is potassium. I know this because we did a flame test and the result was a light intensity, pale-violet color, which indicates a potassium ion. I did the test twice to confirm.”

- Reasoning – compare against known - experimental = stating that they conducted the test to see what a positive result was; conducting the test with a known
  - “K was my cation. It reacted with a violet flame in the flame test. We used a known potassium in the flame test it created a violet flame. Therefore we can
conclude that the unknown cation was potassium” documented how they used a known potassium salt to investigate what color the flame would be.

- Reasoning – compare against known facts = reference was made to facts, including flame color of particular cations
  - “I determined the identity of this compound through many cation tests, beginning with the flame test. When burned under flame, the compound produced no apparent color, which is consistent with the properties of magnesium.” The last part where it discusses how no color is consistent with Mg would have this code because there is reference to

- Reasoning – Process of elimination = mention that since all other tests were negative, therefore it means that it should be the other one
  - “Magnesium is my cation because I performed a flame test. The flame was orange meaning that my cation was either magnesium or sodium. Because of other tests performed, sodium was ruled out. A reactivity test also confirmed the identity.”

- Reasoning - cation definition = rely on the definition to explain why x is the cation
  - “The identity of the cation in the unknown compound was K. I know this because I have KCl and K is the positively charged ion in the compound” uses the definition to explain why K is the cation

- Reasoning – electron excited, electron movement = makes reference to the fact that the electrons are excited during the flame test as part of the reason why a color appears in the flame.
  - “I identified the presence of the cation potassium via the flame test. The flame turned purple when the electrons were excited.” Goes into why the flame is purple.

- Reasoning - Compare against known – similar cation = student uses another cation in the same group to compare how it reacts
  - “The cation of my unknown compound is Magnesium. I know this because the flame test narrowed down the possibilities to Sodium and Magnesium. Then a solubility test was performed with a compound that forms a precipitate with Calcium. Since Calcium and Magnesium are in the same group and react the same way, and since this reaction formed a precipitate, it could be assumed that the unknown cation was Magnesium.”

- Reasoning – double displacement/replacement = student uses the reaction mechanism as logic for what their cation is.
  - “The cation in Potassium (K). I arrived at this conclusion first by flame testing which gave off a purple flame indicative of Potassium. To further confirm the result I performed a double displacement with my compound and silver nitrate which yielded a precipitate further confirming my result.”
My cation was Chloride. I was able to determine this by performing a precipitate test with silver nitrate. The silver nitrate performed a double replacement with my unknown compound and formed silver cloride, which precipitated in solution.

Reasoning – ammonium reacting w/NaOH to form ammonia = discuss the reaction mechanism to connect Ammonium and why that produces a smell during the test.

Ammonium is the cation. When a solution of the unknown was mixed with NaOH, the smell of ammonia resulted. The ammonium reacted with the hydroxide ion to form water and ammonia.

Reasoning – data told me/indicated/proved that x is my cation = it is not clear how the student knows that the data provides them with their cation whether it is comparing to a known experiment or fact.

The cation was Magnesium. I know this through the flame test, where the flame had no coloration which told me that the compound contained magnesium. Not clear how they knew that the flame test results indicated magnesium as the cation.

Potassium (K) When I place my substance in the flame of a bunsen burner, the flame turned a light violet, which is a sign that there was potassium present in my substance. How do they know that a violet flame is indicative of potassium?

Reasoning – wire burnt orange as well = refer to the nichrome wire burning orange during their flame test

I did not have one. There was no reaction from the mixing test. The results of the flame test was a bright orange flame, but the metal that the compound was on also burned bright orange, so this data was thrown out.

Reasoning – cations are metals = reason that if an element is a metal then it must be a cation

The identity of my unknown is potassium. I know this because my unknown is KCl (i determined this through the 10 test i conducted) and potassium is the only ionic compound in my solution. So since Cl is not a metal and potassium is the only metallic compound contained I thus have K as my cation.
What is the identity of the anion in your unknown compound? How do you know?

- Claim – Anion = the element is an actual anion
- Claim – Cation = the element is actually a cation
- Claim - Anion – Unsupported = only states anion, no data or reasoning
- Claim - contradicting claim = state that one anion is present and at the end of their explanation state that a different anion is present
  - "our anion is chlorine. We did several anion tests, including sulfate, nitrate, and carbonate testing. The sulfate test was positive so we came to the conclusion that our unknown had to be sulfate." Starts out stating chloride; however, by the end of the explanation states that anion is sulfate.
- Data - Experimental – formation of precipitate - procedure = discusses what was added to form the precipitate or identity of the precipitate
  - "The anion of my compound is chloride. I found this out by making a solution of my unknown precipitate with silver nitrate. The precipitate formed was silver chloride" This would be coded as such because details were included about the tests ran.
- Data - Experimental - flame color = performed flame test, color is stated
  - "The identity of my anion is Ammonium. I did a flame test to help determine this. The color of my flame ended up showing no distinct color. Because of this I had to do another test to determine if my anion was Ammonium or Magnesium. I mixed my unknown compound with 6M of NaOH to see if an Ammonium smell was produced.”
- Data - Experimental - smell = performed test, had ammonia smell
  - See above example
- Data - ran tests = no results just stating which tests were run, mixing compounds together to determine reactivity
  - "We know this because we ran several test to determine the identity" no detail about the tests or the results
- Data - Experimental - ran tests pos or neg = ran this test and it was positive
  - "We know this because the results for other anions all tested negative, except the one for chloride" provides which results were positive but not what occurred to give the positive results
- Data - Experimental – formation of precipitate = only mentions precipitate forming
  - "The anion in my unknown compound was Chloride. The formation of a white precipitate during a chloride test is a positive ID for chloride. Because a white precipitate formed during testing, the anion in my unknown compound was chloride.” No detail as to what the precipitate is or what was added to create the precipitate.
- Data - ion charges
  - "Cl has a charge of -1 and K has a charge of +1"
- Data – Non-Experimental – solubility facts = discusses solubility according to solubility rules
“Chloride. It forms a precipitate when an insoluble metal such as Ag or Pb is reacted with it. I is ionic. Is soluble and ionic when reacted with any other non-metal in solution.”

“The anion in my compound was a chloride ion. Chlorides are very soluble in water and precipitates in HNO₃ and AgNO₃. My compound was very soluble in water and also formed a precipitate when reacted with HNO₃ and AgNO₃.”

- Data – Experimental – solubility in water
  o “The identity of the anion in my compound was Chloride. I had to conduct several anion experiements to find out which anion was present in my compound. Only one anion test proved positive, and that was the Chloride test. My unknown compound was soluble in water, so when looking back at the table stating which compounds were soluble in water, Magnesium Chloride was one of them. This meant I had the right cation and anion.”

- Data – experimental – unknown reacts/does not react
  o “The identity of the unknown anion is chloride. When a chloride is mixed with silver nitrate or lead nitrate they tend to form a precipitate. As well as they do not react with acids or bases and tends to be neutral. The unknown when mixed with an acid or a base had no reaction and when mixed with lead nitrate and silver nitrate it formed a perchipitate. Therefore making it a chloride.”

- Data – Non-Experimental – more electrons than protons
  o “nitrate because only anions have more electrons than protons”

- Reasoning - compare to known - experimental = ran test with known compound and received the same results
  o “The anion of my unknown compound was Cl or Chloride. I know this because my unknown substance did not pass the chloride test in the first experiment, and also because my unknown showed that it reacted identically with the substance KCl.” Compares their unknown to how KCl reacts.

- Reasoning - anion definition
  o “The anion in the compound is Cl. Anions are always negatively charged. Cl has a charge of -1 and K has a charge of +1 so therefore the anion in the compound is Cl.”

- Reasoning – formation of precipitate - double displacement = use reaction as mechanism to deduce the identity of the anion
  o “The anion in my compound was sulfate. When tested against another salt such as Lead Nitrate, a white precipitate formed. The double displacement reaction separated out the sulfate, causing a white precipitate”

- Reasoning – compare to known – facts = refers to an authority figure, ie TA or lab manual; also provides statements that are accepted in the chemical community
  o “The anion in my unknown was chloride. This can be seen due to the precipitate formed in the chloride test. The chlorine reacts with silver to create AgCl.” This is an accepted solubility rule.
“The identity of the anion in my compound was Chloride. I had to conduct several anion experiments to find out which anion was present in my compound. Only one anion test proved positive, and that was the Chloride test. My unknown compound was soluble in water, so when looking back at the table stating which compounds were soluble in water, Magnesium Chloride was one of them. This meant I had the right cation and anion.” The student makes reference to looking in the lab manual for the information.

- Reasoning – process of elimination = discusses the elimination of all other options
  - “The Anion that was present in my solution was chloride. I know that it was chloride because the anion produced a white precipitate called (AgCl). None of the other anions tested produced a white precipitate.”
  - “Claim: Magnesium is the anion in my compound. Data: Tests based off of the knowledge that my cation was chloride were used to find out that magnesium was the anion. Reasoning: Because I have eliminated all other possibilities the only reasonable option left would be magnesium based off of my results.”

- Reasoning – verified anion with both sulfate and chloride test – false positive = acknowledge that chloride test can give a false positive if sulfate is present, usually seen for responses where sulfate is the anion
  - “The identity of the anion in my unknown is sulfate. I know this because a precipitate formed in the sulfate and chloride tests. I knew it was sulfate because positive results occur for both tests if the anion is sulfate, but they only occur for one test if the anion is sulfate.”

- Reasoning – gives away electrons = defines an anion as an ion that “gives” electrons away
  - “Chloride is the anion. The ion has a negative charge. Chlorine ions give away electrons because they have weak electrical bonds and Zeff”
REFERENCES


