I would like to thank Dr. Lang for working with me throughout this project and making sure that I was able to finish my degree. She even drove to meet me near my home while I was teaching school, so that I would not have to drive all the way to Muncie. Thank you, Dr. Lang, for all of your assistance in helping me to fulfill this goal.

I would like to thank the members of my committee for their valuable input and their attendance at many meetings: Dr. Patricia Lang, Dr. Tom McConnell, Dr. Joel Bryan, Dr. Scott Pattison, and Dr. Kristie Speirs-Neumeister. I have appreciated your suggestions and comments to make this project better. Thank you also, to Dr. Ashley Versprille for acting as a consultant for this project.

Dr. Kianre Eouanzoui did the statistical analysis for my project. He worked many hours with me, running the statistics and helping me understand it meant. He was extremely knowledgeable about what I needed to accomplish with statistics. I appreciate all of the time he spent with me and the excellent advice he gave.

The project could not have been completed without the assistance of two of my colleagues. Mr. Kyle Booher taught both methods when I was working out the details. He also recorded the videos that we used when teaching the methods, collected all of the consent forms, and conducted the interviews. He was also an invaluable source when I needed suggestions or advice. Thank you, Kyle, for assisting in so many areas and for being willing to help. Mr. Layne Maki taught both methods to his classes over the course of two years. Thank
you, Layne, for allowing me to use your students and for spending the time to complete the data collection. I appreciate you both.

My parents helped me in numerous ways, by providing dinner, taking care of my children, and being generally supportive. Thank you, Mom and Dad. You set an example for me to value education and to continue to graduate school, even while I was working full-time and being a mother to four children. Thank you.

My family has been supportive throughout this project – my husband Brad, and my children Rachel, Daniel, Sarah and Andrew. Thank you for allowing this change in our schedule for the past few years in order for me to complete this degree. I love you!
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Lewis structures are two-dimensional models of molecules that show all of the valence electrons as either bonding or non-bonding electrons (Harrison & Treagust, 1996). According to Lewis theory, a bond contains a pair of electrons that are spinning in opposite directions and are attracted to the atomic nuclei that they connect. Each atom in the bond tends to mimic and attain the same electron configuration as the noble gases that contain eight electrons, or an octet (Ahmad & Zakaria, 2000).

The majority of structures that a high school chemistry student will encounter are Lewis structures (Zandler & Talaty, 1984). Although there is some question as to whether we should be teaching Lewis structures at all (Logan, 2001), many believe they need to be able to draw the structures correctly so that they can correctly predict physical properties such as acidity and basicity, resonance, molecular geometry, structural isomerism and reactivity (Ahmad & Omar, 1992; Brady, Milbury-Steen, & Burmeister, 1990; McGoran, 1991; Nassiff & Czerwinski, 2015; Pardo, 1989; Purser, 2001; Shultz & Gere, 2015; Zandler & Talaty, 1984). Not all of those topics will be in a typical first-year chemistry course, but students will encounter them in a second year or Advanced Placement (AP) course.

In Indiana, since Lewis structures are not explicitly listed in the Indiana Academic Science Standards (Indiana Department of Education, 2016b), Indiana high school teachers may not teach them until AP Chemistry. However, Lewis structures could be taught to meet the following Indiana Chemistry 1 content standards:
• **C.2.3** Write the full and noble gas electron configuration of an element, determine its valence electrons, and relate this to its position on the periodic table.

• **C.2.4** Use the periodic table as a model to predict the relative properties of elements based on the pattern of valence electrons and periodic trends.

• **C.3.2** Compare and contrast how ionic and covalent compounds form.

• **C.3.6** Use structural formulas of hydrocarbons to illustrate carbon's ability to form single and multiple bonds within a molecule.

• **SEPS.2** Developing and using models and tools (Science and Engineering Process Standards): A practice of both science and engineering is to use and construct conceptual models that illustrate ideas and explanations. Models are used to develop questions, predictions and explanations; analyze and identify flaws in systems; build and revise scientific explanations and proposed engineered systems; and communicate ideas. Measurements and observations are used to revise and improve models and designs. Models include, but are not limited to: diagrams, drawings, physical replicas, mathematical representations, analogies, and other technological models (Indiana Department of Education, 2016b).

I believe that Lewis structures should be taught in the high school classroom. Knowing how to draw and interpret Lewis structures lays the foundation for advanced learning in additional science courses (Shultz & Gere, 2015).

However, students struggle drawing the structures (Ahmad & Omar, 1992; Carroll, 1986; Cooper, Grove, Underwood, & Klymkowsky, 2010; Lever, 1972; McGoran, 1991; Miburo, 1998;
Nassiff & Czerwinski, 2015; Snadden, 1987). The study by Cooper et. al (2010) showed that the task of drawing Lewis structures was made more difficult in the following circumstances: (a) increasing molecular complexity, from a one to two carbon species, and (b) giving a formula without structural cues. Students were frustrated when they could not determine the correct attachment of atoms, and they did not know what to do when presented with a cation or anion.

Experts can draw Lewis structures easily because they can recognize the pattern in many structures, but beginning students struggle (Carroll, 1986). Lever (1972) noted that students get confused about the number of bonds to use (multiple bonds) and the number of valence electrons to use. Others have mentioned that students’ troubles are in choosing the central atom and completing its valence shell (Ahmad & Omar, 1992; Brady et al., 1990), possibly because they “ran out” of electrons, creating an incomplete structure, or they form too many bonds (Nassiff & Czerwinski, 2015). Nassiff and Czerwinski recommend giving the students the skeletal structure to begin the process because (a) beginning students do not have the knowledge necessary to form the correct structure and (b) an incorrect skeletal process would distract from the learning objective of drawing a correct, complete Lewis structure.

Pardo (1989) summarizes the ability of students taking chemistry in their first year of college as follows:

1. Most students can draw a simple Lewis structure that has all single bonds and follows the octet rule (no expanded octet).
2. Multiple bonds present students with their first difficulties. Students will draw too few bonds, resulting in atoms surrounded by less than eight electrons.
3. Students choose the wrong central atom.

4. When presented with a cation or anion, students miscalculate the number of electrons needed to complete the structure.

5. Students neglect to calculate formal charge, resulting in structures with high formal charges that need multiple bonds to be reduced.

6. Students draw incorrect structures when the octet is expanded on the central atom.

**Why Lewis Structures Are Difficult**

A. H. Johnstone (1993) states that the world of chemistry consists of three levels: the macroscopic (oxygen in the air that we breathe), submicroscopic or particulate (two identical particles attached) and representational or symbolic (O₂). These areas can be represented by the triangle in Figure 1 (A. H. Johnstone, 1991). Experts can move from one area of the triangle to another easily (A. H. Johnstone, 1991, 1993), whereas students tend to work better from the macroscopic, what they can feel and touch (Nicoll, 2003). Experts can easily draw a Lewis structure, which is a representation or symbol of our current understanding of how atoms bond to form a molecule, but students struggle to move from the macroscopic to the symbolic or

![Figure 1. Johnstone's triangle (A. H. Johnstone, 1991)](attachment:image)
from the particulate to the symbolic. Symbols like Lewis structures are like a foreign language to students. For students to learn chemistry, they must learn to move among the three domains; this is difficult for students and takes time (A. H. Johnstone, 2000).

**Purpose of Study**

In the Model of Educational Reconstruction, Duit (2007) discusses four major domains of science education research: (a) Analysis of Content Structure, (b) Research on Teaching and Learning, (c) Development and Evaluation of Instruction/Instructional Design and (d) Research on Curricular Issues and Science Education Policies. Our research fits into the development and evaluation of instruction. Duit suggests that the research methods and studies used should be closely related to the instructional practice in order for it to improve (Duit). Two methods of teaching Lewis structures, the Direct Octet Rule Method (DORM) of instruction was compared with the Currently Accepted Method (CAM) to see which instructional design is the most effective method to use when teaching Lewis structures to students. The DOR method, a method adapted from the literature (Pardo, 1989), is compared to the CA method, which is a widely accepted and used method. Thus, the development of the model and research to evaluate its effectiveness are closely related.

The focus of this project will be on improving both the researcher’s practice and the practice of other chemistry teachers. Duit (2007) mentions that a major emphasis in science education research is on improving teacher’s instructional practices, which this research seeks to do by evaluating the accepted method of teaching Lewis structures to high school students against an alternative method.
Chapter 2

Literature Review

History of Lewis Structures

The octet rule. Dimitri Mendeleev was the first person to devise “rules” for elements and their maximum “valence” in which the number eight appeared (Jensen, 1984). “Valence” was considered to be the element’s “combining power.” For example, hydrogen had a valence of one, while oxygen had a valence of two, resulting in H₂O. In 1871, his rule implicated that an element’s valence could never be more than eight, while his second rule stated that the sum of an element’s maximum valence first relative to hydrogen and its maximum valence relative to oxygen could never be higher than eight (Jensen).

In 1902, Richard Abegg proposed that all elements could show both a minimum oxidation state and a maximum oxidation state, the sum of which always equaled eight (Jensen, 1984). Abegg’s (1904) rule is as follows:

The sum 8 of our normal and contravalences possesses therefore simple significance as the number for which all atoms represents the points of attack of electrons, and the group-number or positive valence indicates how many of these 8 points of attack must hold electrons in order to make the element electrically neutral (p. 330).

Abegg did not propose an atomic model, but in 1907, J. J. Thompson proposed four concepts that contribute to our modern electronic theory of valence: (a) The atom has an electronic shell, (b) Valence electrons are in the outermost shell, (c) The outer shell structure is repeated to explain periodic properties of the elements, (d) The rare gases are stable due to a completed shell, and other atoms attempt to duplicate this shell structure (Thompson, 1907). In 1916,
Walter Kossel attempted to develop and extend Abegg’s views on valence. He developed a plot of maximum positive and negative oxidation states that proved Abegg’s rule and Thomson’s idea that electron transfer was due to element’s attempt to gain the same outer shell structure as the rare gases (Jensen, 1984).

Also in 1916, Gilbert N. Lewis published his theory of the cubical atom (Figure 2), to account for Abegg’s (1904) law. His cubical atom had spaces for up to eight electrons, which represented the electrons in the outer shell of the neutral atom. He called this the “rule of eight.” Langmuir (1919) introduced the term “octet” rule to replace the “rule of eight.”

*Figure 2. Lewis’ (1916) cubical atoms. The circles represent the valence electrons of elements lithium through fluorine.*
**Lewis structures.** Lewis (1916) stated that a chemical bond is simply a pair of shared electrons. He realized that electrons could be shared evenly, but they could also be shared unevenly, progressing all the way to an electron transfer model, which was the result of the most unequal of electronegativities. Lewis’ theory was workable because he restricted both the number of electrons in a bond (two) and also the number of atoms bonded (two) (Jensen, 1984). shows an example of two iodine atoms bonded together.

---

*Figure 3. Atomic structure of iodine, according to Lewis’ model. Structure A shows iodine completely ionized, as it would be in liquid iodine; structure B shows iodine without ionization, with one electron shared between the two atoms; and structure C shows the predominant structure of iodine, with two electrons shared (Lewis, 1916).*
Lewis (1916) went on to suggest using a colon to show that two atoms were chemically bonded, such as Cl : Cl for Cl₂. He also suggested using different spacing to illustrate different degrees of polarity: Na : I and I : Cl. He noted that for the first row of the periodic table, the “rule of two” was in place, rather than the “rule of eight,” and the hydrogen atom’s cube may be completed by inserting just one electron into the outer shell. He then suggested that a complete formula for compounds may be given by writing the atomic symbol, surrounded by the same number of dots as are electrons in the outer shell (Figure 4 and Figure 5). These were the first “Lewis structures.”

![Lewis structures](1916)

**Figure 4.** Lewis structures (1916)

H : O : H  H : I  : I : I : 

**Figure 5.** Lewis (1916) structure of ethylene. It shows two shared electron pairs – a double bond.

H : C : : C : H

Problems with Lewis’ theory. Lewis’ (1916) cubical theory of the atom could not represent a triple bond. Also, much evidence indicated that carbon’s valences were in a tetrahedral shape, which was not represented by his cubical model. He presented a possible solution by showing how the pairs of electrons could be placed symmetrically around the center of the atom (Figure 6), which gave a tetrahedral arrangement. The solid dots are the
eight electrons shared by carbon and other atoms not in the figure. The open circles illustrate how the electrons would be attracted to one another in sets of two, by some magnetic force.

![Diagram of carbon atom](image)

*Figure 6. Lewis’ (1916) diagram of the carbon atom. The symmetrically placed pairs of electrons demonstrate the tetrahedral direction of the valence.*

By 1923, Lewis decided that instead of a static atom as he had proposed earlier (Lewis, 1917), the atom was more dynamic, “suggesting a model in which the electrons of the static atom corresponded to the average positions of electrons moving in small directional orbits” (Jensen, 1984). Eventually, he abandoned the cubical atom concept due to these issues, and elaborated on the “rule of two,” which he perceived as being more fundamental than the “rule of eight,” or the octet rule. He said that the “rule of two,” where electrons form pairs, led to the octet rule (Lewis, 1923).

**Langmuir’s contribution.** Irving Langmuir published more than 12 articles and gave numerous lectures which extended, refined and popularized Lewis’ model (Jensen, 1984). For a time, the model was known as the Lewis-Langmuir Theory, although the two men did not collaborate on the theory (Lewis, 1923). In 1920, the chemical community still used the ionic electron-transfer bond and saw no reason to adopt Lewis’ electron-pair bond (Kohler, 1974). The reason that Lewis’ model received widespread acceptance was because of Langmuir:

What made the difference was, of course, Langmuir himself and his personal reputation.

The new theory was well received because it was “Langmuir’s theory” and not because
of its intrinsic intellectual worth. Once received, of course, its worth became evident.

What I wish to stress is that the advantages of the new theory were not immediately obvious and that had it not been “Langmuir’s theory,” the rediscovery and adoption of Lewis’ theory might well have awaited a real crisis in the theory of bonding. (Kohler, p. 66-67).

Methods for Drawing Lewis Structures

Many methods for drawing Lewis structures exist. An overview of the methods found in literature, beginning with the most common method presented in textbooks, along with its variations. Then less common methods will be discussed.

**Common method presented in textbooks.** In 1991, Packer and Woodgate published an approach to drawing Lewis structures. They described the method as being more “user-friendly” than methods found in textbooks at the time of publication:

1. Determine the total number of valence electrons in the species by adding together the numbers of valence electrons of each atom and, if an anion, by adding the overall charge of the ion and, if a cation, by subtracting the overall charge of the ion.

2. Place the atoms in their relative positions.

3. Draw a line representing a single bond containing two electrons between joined atoms.

4. Distribute the remaining electrons evenly in pairs on the outer atoms so these have up to eight electrons (except for hydrogen). Any still not used after this should be placed on the central atom.

5. If the central atom is now surrounded by fewer than eight electrons, move sufficient nonbonding pairs from outer atoms other than halogens to between joined atoms, thus
making them bonding, to bring the number on the central atom up to a maximum of eight.

6. Count the number of electrons "owned" by each atom pretending bonding electrons are evenly shared. To evaluate the formal charge at that atom, compare the result with the number of valence electrons of the neutral atom. Show only nonzero charges.

7. For central atoms from the second or later rows of the periodic table, move further nonbonding pairs to bonding positions to lower the positive formal charge on the central atom to one or zero (Packer & Woodgate, 1991, p. 456)

These rules do not require any chemical knowledge other than how to count the number of valence electrons in an atom. They also allow for multiple bonds to be placed (rule 5) and for expanded octets (rule 7).

Packer and Woodgate’s (1991) article states that they followed the approach used by Snadden (1987) and Gillespie (1986) to develop their method, which is commonly used in textbooks (Bettelheim, Brown, Campbell, & Farrell, 2010; Brown et al., 2015; Buthelezi, Dingrando, Hainen, Wistrom, & Zike, 2008; Chang, 2010; Ebbing & Gammon, 2013; Hein, Pattison, Arena, & Best, 2009; Tro, 2014; Zumdahl, 1996; Zumdahl & Zumdahl, 2012). Like the method proposed in Snadden’s article and the similar method proposed in Gillespie’s textbook, some textbooks told students to connect each atom with a single bond and then calculate the net number of electrons needed to complete the structure, which was a slight variation of Packer and Woodgate’s method (Buthelezi et al., 2008; Hein et al., 2009; Zumdahl & Zumdahl, 2012).
Buthelezi et al.’s (2008) first-year high school textbook gives the additional instruction to determine the number of bonding pairs by dividing the valence electrons by two. This is a confusing instruction because the student is calculating the bonding pairs plus the nonbonding pairs. The authors state that the bonding pairs leftover after connecting each atom to the central atom with a single bond will become lone pairs.

The methods above involve drawing a temporary skeleton structure, with atoms connected by single bonds, and then converting the remaining nonbonding pairs to bonding pairs, if necessary. Aside from Buthelezi et al. ‘s (2008) confusing terminology instructing the student to determine the number of “bonding” pairs, none of the common methods in textbooks determine the exact number of bonding pairs and nonbonding pairs prior to drawing the structure.

**Less common methods.**

**Direct pairing.** A direct pairing approach involves imagining valence electrons approaching each other and fusing together to form a bond (Ahmad & Zakaria, 2000; Miburo, 1998; Snadden, 1987). Students begin by selecting the central atom; it is (a) any single atom in a compound, (b) the atom with a higher covalence, or (c) the atom from the higher period. Exceptions to these guidelines exist, in which the student would just need to know the central atom or be told (Ahmad & Zakaria). Then, to draw the Lewis structures, the directions are as follows:

1. Arrange Lewis symbols with the unpaired electrons of the peripheral atoms facing the unpaired electrons of the central atom;
2. Add or remove electrons to equal the charge of an ion. For a polyatomic anion surrounded by monovalent atoms, like hydrogen or halogens, add an electron to the central atom. If at least one of the peripheral atoms is polyvalent, add an electron(s) to the peripheral polyvalent atoms. For a cation, remove an electron(s) from the central atom.

3. Pair the unpaired electrons from step 1. Remaining unpaired electrons will form lone pairs. A structure with more than an octet on the central atom should try to reduce the structure to an octet or convert the structure to all single bonds.

4. Draw resonance forms (Ahmad & Zakaria).

6n + 2. Lever (1972) proposed a procedure for drawing Lewis structures that give the ability to rapidly draw a correct structure for an element in the first short period. He states that in a single-bonded structure, \(8n\) electrons are necessary to produce an octet around \(n\) atoms. When sigma electrons are shared, \(8n - 2(n - 1)\) or \(6n + 2\) electrons are needed. If that number of electrons equals the number of valence electrons (\(V\)) in the molecule, only single bonds are needed – no multiple bonds.

If that number \((6n + 2)\) is greater than the number of valence electrons, pi bonds are necessary to create additional sharing. The number of electrons that need to be shared through pi bonds (\(P\)) is \(P = 8n - 2(n - 1) - V\) or \(P = 6n + 2 - V\). Pi electrons are added to the skeleton structure; then electrons are added as needed to additional atoms to complete the octets. After all electrons are added, the number should equal the number of valence electrons (\(V\)). Elements in the third period are not restricted to the octet rule. Therefore, after formal charge
is calculated, charges can be equalized by adding additional pi bonds to the structure (Lever, 1972).

If \(6n + 2\) number of electrons is less than the valence electrons, the structure has an expanded octet (Clark, 1984). Clark changed Lever’s (1972) method by adding the electrons to the structure before any hydrogen atoms were placed. Doing the procedure this way allowed the hydrogen atoms to be placed in such a way that minimizes the quantity and magnitude of formal charge on atoms.

Zandler and Talaty (1984) proposed the “6n+2 Rule” for drawing Lewis structures, based on Lever’s (1972) idea of \(6n + 2\) electrons. This rule is based on the premise that a single-bonded structure, without rings always needs six valence electrons for each major atom that is bonded, with two additional electrons to fill in the structure. (See Figure 7).

Figure 7. Example of the 6n+2 rule. (Zandler and Talaty, 1984)
An extra bond needed to create multiple bonds would reduce the valence electrons needed by two. Therefore, if the total number of valence electrons is fewer than $6n + 2$, an extra bond must be introduced for every two electrons that are missing. Add all hydrogen atoms, starting first with carbon, then add lone pairs until all heavy atoms have an octet (four pairs). It is possible that this method may benefit students because it is more visual.

**Other methods.** Carroll (1986) thought that some methods relied too much on the octet rule and allowed expanded octets when required (Clark, 1984; Lever, 1972; Zandler & Talaty, 1984), which was confusing to students first learning to draw structures. Carroll proposed this method that focuses on lowering formal charge at the expense of the octet rule: (a) after a skeleton structure is obtained, valence electrons are calculated, (b) atoms are joined with a single bond, (c) then, electrons are added in pairs around each atom until each atom has a formal charge of zero, (d) and lastly, resonance forms are drawn.

This method requires a skeleton structure to start the process, rather than the student determining the skeleton structure, which is what Nassif and Czerwinski (2015) recommended. McGoran (1991) believes that “the problems of constructing correct atomic frameworks from molecular formulas often adds a dimension of complexity to an already difficult task”; therefore, the skeletal structure should be given to the student.

Ahmad and Omar (1992) noted that since textbooks had not yet provided a simple guide to drawing the structure, many students use the “trial and error” method. Ahmad and Omar give a method that requires students to know only the location of the elements on the periodic table and their electronegativities. The central atom is the lowest in electronegativity and/or lowest in number. After each atom is connected with a sigma bond, three unshared electron
pairs are added to the peripheral atoms (except H) to complete the octet. Any remaining pairs of valence electrons are added to the central atom. Then, the central atom’s octet is completed by moving pairs of electrons to form a pi bond(s). The last step involves trying to minimize formal charge by converting nonbonding pairs to bonding pairs.

The method proposed by Nassiff and Czerwinski (2015) is similar to that of Ahmad and Omar (1992) because atoms are given eight valence electrons after the skeletal structure is established, rather than placing the valence electrons and then trying to complete the octet. However, they state that in most cases, too many electrons are drawn and a pair of valence electrons must be removed, an instruction that does not appear in the method from Ahmad and Omar.

**Direct octet rule methods (DORM).** Pardo (1989) suggested that the “6N+2” rule created unnecessary difficulties for beginning students and may seem arbitrary. He also believed that Carroll’s (1986) method would lead to teaching difficulties with beginning students. He stated that the octet rule should be used when teaching Lewis structures to beginning students. Later, more advanced students might be able to learn a different technique.

To correct these problems, Pardo (1989) proposed the following method based on the octet rule:

1. Calculate the number of valence electrons in the molecule.
   a. For an anion, add the number of electrons equal to the charge of the ion.
   b. For a cation, subtract the number of electrons equal to the charge of the ion.
2. Determine the number of electrons needed to complete the octet of all atoms.
   
   (Every atom needs eight electrons except hydrogen, which needs two.)

3. Calculate the number of shared electrons by subtracting the valence electrons from
   the octet electrons.

4. Place the least electronegative atom in the center, as the central atom, and place
   the remaining atoms around it.

5. Calculate the number of bonding regions by counting the areas where two atoms
   connect.

6. Calculate the number of sigma electrons by multiplying the number of bonding
   regions by two.

7. Draw single bonds to connect the atoms.

8. Determine the number of pi electrons by subtracting the total number of shared
   electrons (from step 3) and the number of sigma electrons.

9. Calculate the number of nonshared electrons by subtracting the shared electrons
   (step 3) from the valence electrons (step 1).

10. Distribute the nonshared electrons so that the octet rule is satisfied for each atom.

11. Calculate formal charge and try to reduce any high formal charge by forming
    multiple bonds.

Malerich (1987) gives a method for recognizing a compound with an expanded octet
when given only the molecular formula, such as PF₅, SF₄, SF₆, BrCl₃, or I₃⁻. This method requires
a procedure for counting the number of bonds predicted by the octet rule. When the number
of bonds is less than the number of atoms available, the molecule exhibits an expanded octet,
which is the same as the DOR method proposed in this paper. Malerich used Miller’s (1976) procedure for counting the number of bonds, which is similar to Pardo’s (1989). While Miller’s (Miller) procedure is similar to the proposed DORM, it would seem that it does not give a procedure for counting the number of electrons each atom must share to complete its octet. An explicit procedure would be advantageous to beginning students.

**Problems with Other Methods**

The direct pairing methods (Ahmad & Zakaria, 2000; Miburo, 1998; Snadden, 1987), used to form a covalent bond, are reasonable for very simple molecules. However, step 3 of the method given by Ahmad and Zakaria seems too complicated for high school students. They would be required to convert lone pairs (nonbonding pairs) to bonding pairs or convert the entire structure to single bonds. They would not understand when to do which procedure.

In 6n + 2 methods (Clark, 1984; Lever, 1972; Zandler & Talaty, 1984), the number of extra bonds are calculated, so that a student always knows how many bonds are needed without guessing, like the proposed Direct Octet Rule Method (DORM). However, the skeleton structure has to be drawn correctly in order to calculate the number of valence electrons required if the structure had all single bonds. That step is necessary to calculate the number of valence electrons needed for extra bonds. An incorrect skeleton structure would make the number of extra bonds impossible to calculate, whereas the DORM gives the number of bonds needed without drawing a structure. Furthermore, I believe that his method of using “6n + 2” to determine whether or not a structure needs multiple bonds would be confusing for beginning students, as well. The formula seems arbitrary and does not seem to correspond with a physical feature of the molecule.
Carroll’s (1986) method uses formal charge to complete the structures rather than the octet rule. While this method may have merit for students who already know the basics of how to draw a Lewis structure, it seems as if it would be difficult to teach this method to beginning students. They would be exhausted from calculating the formal charge for each atom, when they really do not even know what that means. Methods involving the octet rule give a convenient way for a student to check this structure – make sure that all of the atoms, except hydrogen, have eight electrons.

The methods proposed by Ahmad and Omar (1992) and Nassiff and Czerwinski (2015) involve filling the octet and then comparing the number filled in with the number of valence electrons. Students may have to erase electrons if they initially add too many and then erase electrons to form multiple bonds. Students may just erase the electrons to match the valence electrons, missing the point of trying to reach an octet.

**Rationale**

I chose to base my study on the method that I named the Direct Octet Rule Method (DORM), from Pardo (1989) because it is an approach to drawing the structures that gives students the specific number of bonds and non-bonding electrons. It clarifies the symbols that students need to use, instead of changing a nonbonding pair of electrons to a bonding pair. This is important because students need to know what the symbols mean in order to complete the process, and this method tells students which electrons are bonding and which are nonbonding without it being necessary to change one type of electrons to another. This method is simple enough for beginning students, but it works on even the most complicated atoms. It is also easy to teach.
In contrast, the CA method (Packer & Woodgate, 1991) involves creating a temporary skeleton structure held by single bonds, and students change nonbonding electrons to bonding electrons if necessary. Students have to understand that there are not enough electrons to complete an octet for each element in the structure, which leads to more decision-making.

**Theoretical Framework**

In educational research, the theoretical framework helps guide the research by providing assumptions, helps the researcher choose research questions, and suggests appropriate data collection methods (Bodner, 2007). The theoretical framework chosen for this study is ethnomethodology, defined by Bodner as “The study of people making sense of their experiences to behave in socially acceptable ways.” Bhattacharyya (2007) states that “…ethnomethodology seeks to understand how individuals make sense of their routine activities as members of a culture.” Ethnomethodology was developed by Garfinkle (1967) for studies in sociology. It asks, “How do people make sense of their everyday activities so as to behave in socially acceptable ways?” (Patton, 2015) It gets at the norms, understandings and assumptions that are so deeply understood by people in a setting that they do not think about what they are doing or why they are doing it; they just do it (Patton, 2015). A major goal is to “make the implicit explicit” (Bhattacharyya, 2007).

In chemistry, the people in the culture would be expert chemists. In a chemistry classroom, the expert chemist is the teacher. Then, the student needs to make sense of routine activities that the teacher performs, maybe even without thinking, in order to interact in an acceptable way. Data collection in ethnomethodology involves finding out how an outsider to a culture makes sense of the daily activities in the new culture (Bhattacharyya, 2007). For a
chemistry classroom, the “outsider to a culture” is a student trying to figure out how to make sense of what the teacher, the member of the culture, is teaching. When drawing Lewis structures, a student should be asked about his or her actions and asked to justify each of those actions while drawing a structure. Focusing on chronology is important because *when* the student performs an action or makes a decision is as important as *what* that action or decision is (Bhattacharyya). Student interviews will satisfy this data collection.

**Strengths and weakness of ethnomethodology.** Since ethnomethodology focuses on the individual’s learning as a member of a group, it has the ability to “reconcile the dilemma of individual versus social learning,” which is a strength of the framework (Bhattacharyya, 2007). A second strength is that it is compatible with many post-positivist frameworks, like constructivism. Both constructivism (Bodner, 1986) and ethnomethodology do not try to reveal an absolute reality; instead, reality is defined by the experiences of the students (Bhattacharyya).

Ethnomethodology is concerned with the individual’s experience within the group setting, or the student’s experience within the classroom. Because of this, it cannot be used to make judgments about the group as a whole. It can only explain how the individual learns within the group.

**Hypothesis**

We hypothesize that the DORM will be able to help students draw more correct structures than the CAM because it immediately gives the number of bonding and nonbonding electrons that are needed, rather than placing electrons and then moving them to achieve an
octet. Using this approach will allow students to achieve a correct structure with less trial and error.

Research Questions

This research project aims to determine which method works better for a particular group of students. With that in mind, the following research question will be proposed: Will high school chemistry students draw more accurate Lewis structures using the DORM or the CAM? Sub-questions are as follows:

1. Do students in Honors Chemistry 1 classes perform better using the DORM or the CAM, as compared to students in Regular Chemistry 1?
2. Does a student’s GPA predict his or her posttest score?

Direct Octet Rule Method. The Direct Octet Rule Method (DORM) is very similar to Pardo’s method (1989), but it has been edited for simplicity (Figure 13 in Chapter 3).

Commonly Accepted Method. The CAM is essentially the same method proposed by Packer and Woodgate (1991), but it has been edited for high school students: (a) the total number of valence electrons is found, (b) elements are arranged with the single element in the center and connected by a single bond, (c) the remaining electrons are placed around the elements until they reach eight electrons, and finally (d) make double or triple bonds as necessary to fill the octet.
Chapter 3

Methods

Design

The design of the research in teaching Lewis structures was a mixed methods, quasi-experimental project. Data were collected from high school students enrolled in Regular Chemistry 1 (Reg Chem 1), Honors Chemistry 1 (Hon Chem 1) or Honors Chemistry 2 (Chem 2) during the Spring 2015 and Spring 2016 semesters. Since students were already assigned to classes and assigned to a teacher by a school counselor, the classes are the groups for the study. This convenience sample makes the study quasi-experimental rather than experimental, since the students were not randomly assigned to groups or to a teacher (McMillen, 1996). This study was cross-sectional because data was only collected from the students during the time that they were in chemistry class (Anderman, 2006).

Sampling

A convenience sample of chemistry students at Marion High School (MHS), in Marion, Indiana was used as the subject for this study. The Reg Chem 1 and Hon Chem 1 classes can be freshman, sophomores or juniors in high school. The Chem 2 students can be sophomores, juniors or seniors.

It is important to note that beginning with the 2014-2015 school year, Reg Chem 1 and Hon Chem 1 students using the Chemistry Modeling curriculum, provided by the American Modeling Teachers Association (2016). This curriculum focuses on the particulate domain of chemistry, as in Johnstone’s (1991) triangle (Figure 1). Students began the year by learning that everything in the world is made of particles. As the year progressed, students learned to build a
mental model of the particulate nature of chemistry, understanding that particles combine and react with one another, eventually learning the terms “atoms” and “molecules.” Lewis structures are not in the modeling curriculum, but we taught Lewis structures after the bonding unit in the modeling curriculum. Chem 2 had traditional instruction for their first year of chemistry.

MHS is a multiracial urban high school, of low socio-economic status. For the 2015-2016 school year, 1018 students were enrolled: 50.2% white, 23.9% black, 15.5% multiracial, 9.1% Hispanic, and 1.1% Asian (See Figure 8) (Indiana Department of Education, 2016a). More than half of the students receive free/reduced lunch (61.0%), indicating low socio-economic status (Indiana Department of Education, 2016a).

Consent. Before data were collected, the project was submitted to the IRB at Ball State University. The IRB determined that this research was not human subjects research (See Appendix A). The principal from Marion High School submitted a letter to allow research to take place at the high school (See Appendix B). In order to participate in the study the first year, students signed a Child Assent Form (See Appendix C), and their parents signed a Parental Consent Form (See Appendix D) if the student was under the age of 18. If the student was over the age of 18, that student signed an Adult Consent Form (See Appendix E) in order to participate. A teacher in the building who was not teaching any of the courses involved in the study explained the study to each class. He handed out the Child Assent Forms, Parental Consent Forms, and Adult Consent Forms, and explained to the students that they were not
required to participate in the study, but if they wanted to participate, they needed to have their parents fill out the forms and return them to school. That same teacher collected all of the forms in his room and did not disclose to the researcher which students had turned in the forms to participate and which had not until grades had been posted for the semester. The second year, parents were given the opportunity to sign an opt-out form, rather than a consent form (See Appendix F). One opt-out form was turned in for this study, and that student’s data was excluded.

**Research Data**

The research data collected were both quantitative and qualitative – mixed methods (Anderman, 2006). The quantitative data was collected through an identical pretest and

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Ethnicity</th>
<th>Number of Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.20%</td>
<td>Caucasian</td>
<td>511 students</td>
</tr>
<tr>
<td>23.90%</td>
<td>African-American</td>
<td>243 students</td>
</tr>
<tr>
<td>15.50%</td>
<td>Multiracial</td>
<td>158 students</td>
</tr>
<tr>
<td>9.10%</td>
<td>Hispanic</td>
<td>93 students</td>
</tr>
<tr>
<td>1.10%</td>
<td>Asian</td>
<td>11 students</td>
</tr>
<tr>
<td>0.20%</td>
<td>American Indian</td>
<td>2 students</td>
</tr>
</tbody>
</table>

*Figure 8. MHS 2015-2016 enrollment by ethnicity. (Indiana Department of Education, 2016a)*
posttest over the Lewis structures (See for Reg Chem 1 and Hon Chem 1 pretest), consisting of 23 numerical response questions and constructed free response questions (drawings) - two for Reg Chem 1 and Hon Chem 1 and six for Chem 2. After the numerical response section was scored, students were selected to be interviewed, based on their numerical response score from the posttest. Qualitative information was gathered in the interviews, aimed at understanding how students make sense of their world

**Pretest and posttest.**

**Numerical response.** The numerical response questions for Reg Chem 1, Hon Chem 1 and Chem 2 were the same (Figure 9). The numerical response questions required students to draw three different structures – NH$_3$, HCN, and CH$_2$O. The same six questions were asked about each of the structures, in order to try to determine where students made errors. Those questions involved the identity of the atoms in the formula, number of valence electrons, number of bonding and nonbonding electrons, placement of nonbonding pairs and bond order. The last five questions were similar, but they were asked about a larger organic molecule that the students would not have seen before. They were given the structure and asked if they could identify the features of the molecule that was already drawn for them. The students entered their responses from the numerical portion of the test into a classroom response system, or “clicker.” The information from the clickers was transmitted to the teacher’s computer, where the numerical response portion of the test was graded immediately by AccelTest, a computer program from Renaissance Learning (2016).
Lewis Structures Pre-Test (Chemistry 1)

For one molecule of ammonia, NH₃,

1. How many hydrogen atoms are present?
2. How many valence electrons are in the molecule?
3. How many electrons are considered bonding electrons?
4. How many electrons are considered nonbonding electrons?
5. How many nonbonding electrons are on the central atom?
6. What is the bond order of the nitrogen – hydrogen bond?

For one molecule of HCN,

7. How many hydrogen atoms are present?
8. How many valence electrons are in the molecule?
9. How many electrons are considered bonding electrons?
10. How many electrons are considered nonbonding electrons?
11. How many nonbonding electrons are on the central atom?
12. What is the bond order of the carbon – nitrogen bond?

For one molecule of CH₂O,

13. How many hydrogen atoms are present?
14. How many valence electrons are in the molecule?
15. How many electrons are considered bonding electrons?
16. How many electrons are considered nonbonding electrons?
17. How many nonbonding electrons are on the central atom?
18. What is the bond order of the carbon – oxygen bond?

Answer the following questions, using the molecule above.

19. What is the total number of valence electrons in this molecule?
20. What is the total number of bonding electrons?
21. What is the number of nonbonding electrons?
22. What is the number of single bonds?
23. What is the number of double bonds?

Draw the following structures ON THIS PAGE.

Draw the Lewis structure of NO₃⁻
Draw the structure of CO₂.

Figure 9. Chemistry 1 pretest. This test was given as the pretest and the posttest for Reg Chem 1 and Hon Chem 1. Chem 2 had the same numerical response questions 1-23.
Free response. Although all students answered the same numerical response questions, students in Chem 2 had more difficult free response questions than Chem 1 students, since they have had previous instruction. Reg Chem 1 and Hon Chem 1 students drew the nitrate ion (NO$_3^-$) and carbon dioxide (CO$_2$), while Chem 2 students drew the following structures: CH$_4$O, C$_2$H$_6$O, CH$_3$OH, CH$_3$CH$_2$OH, N$_2$H$_4$, and CH$_3$CO$_2$H. Free response questions were graded using a rubric (See Figure 10) to produce quantitative information.

<table>
<thead>
<tr>
<th>Description</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accurate representation of bonds</td>
<td>Correct representation of atoms</td>
<td># of bonds</td>
<td>Placement of bonds</td>
<td># of lone pairs</td>
<td>Placement of lone pairs</td>
<td></td>
</tr>
<tr>
<td>2 dots or 1 line per bond, drawn between atoms (all bonds drawn, including between C and H)</td>
<td>All atoms in the formula are drawn in the structure</td>
<td>Correct total number of bonds per structure.</td>
<td>All bonds are drawn between the correct atoms (includes H with 2)</td>
<td>Correct number of lone pairs</td>
<td>All lone pairs are placed on the correct atoms.</td>
<td></td>
</tr>
<tr>
<td>1 bond incorrectly represented</td>
<td>+/- 1 atom</td>
<td>+/- 1 bond</td>
<td>+/- 1 lone pair</td>
<td>+/- 1 lone pair</td>
<td>+/- 1 lone pair</td>
<td></td>
</tr>
<tr>
<td>0 bond incorrectly represented</td>
<td>+/- 2 atoms</td>
<td>+/- 2 bonds or more</td>
<td>+/- 2 lone pairs or more</td>
<td>+/- 2 lone pairs or more</td>
<td>+/- 2 lone pairs or more</td>
<td></td>
</tr>
</tbody>
</table>

Figure 10. Grading rubric for free response questions on pretest and posttest.

The rubric addresses six criteria for drawing a correct structure: (a) accurate representation of bonds (a line drawn between two atoms), (b) correct representation of atoms (H$_2$O had two hydrogen atoms and one oxygen atom), (c) number of bonds, (d) placement of bonds, (e) number of lone pairs (nonbonding electrons were counted as pairs), and (f) placement of lone pairs. Each criterion could be scored as a two, one or zero. If it was completely correct, it was scored a two. If one item was incorrect in that category, it was scored a one. If more than one item was incorrect, it was a zero. An example of a student’s drawing
using the DORM, along with how those structures were graded, is shown in Figure 11. The corresponding example using the CAM is shown in Figure 12.

The student using the DORM in Figure 11 drew the correct number of bonds for $\text{NO}_3^-$ but did not draw enough nonbonding electrons. The error in calculation was in subtracting an electron for the negative charge instead of adding it. This resulted in a calculation of 5 bonds and 12 nonbonding electrons. This student earned the following points for $\text{NO}_3^-$: $A = 2$, $B = 2$, $C = 2$, $D = 2$, $E = 0$ (missing 2 lone pairs – 4 nonbonding electrons), and $F = 1$ (one lone pair on the central atom that should be on a peripheral atom). The total score was 9 out of 12. He/she calculated four bonds for $\text{CO}_2$ but only drew 2 bonds. This structure earned the following: $A = 2$, $B = 2$, $C = 0$ (missed 2 bonds), $D = 2$ (although bonds were missing, they were placed correctly), $E = 2$, $F = 2$. The total score was 10 out of 12 because the only thing wrong was the number of bonds.

In Figure 12, the student using the CAM drew 3 bonds instead of 4 and 18 nonbonding electrons instead of 16 for $\text{NO}_3^-$. The score is as follows: $A = 2$, $B = 2$, $C = 1$ (missing one bond), $D = 2$ (bonds are placed correctly), $E = 1$ (1 extra lone pairs – 2 nonbonding electrons), and $F = 2$ (nonbonding electrons are placed correctly) for a total of 10 out of 12. For $\text{CO}_2$, the student
failed to move the nonbonding electron pairs from the O to make a bond between C and O.

Scoring is as follows: A = 2, B = 2, C = 0, D = 2, E = 0 (2 extra lone pairs), and F = 2 for a total of 8 out of 12.

Figure 12. Example of a student (M1H702) using the CAM to draw the structures on the posttest.

Interviews. After the posttest numerical response portion was scored by the computer, two to three students in each group who scored low and high were interviewed by the video instructor. These selected students were asked questions in a semi-structured interview to investigate their thought processes as they completed their task, which would give qualitative data (Anderman, 2006).

The interviewer recorded the interviews using a Livescribe Sky wifi smartpen and Livescribe notebook (Livescribe, 2016). Students’ voices were able to be recorded, as well as any drawings or notes the students made during the interviews. The interviewer asked a main question and then asked probing questions to encourage students to elaborate:

1. What did you learn?
   a. Tell me about your learning about Lewis structures. What is a Lewis structure?
b. (For second year students) Did you learn the same method to draw the structures this year or was it a different method than last year?

c. What is the process in drawing a Lewis structure? Walk me through it.

2. What was confusing or difficult about the process?

a. Where did you get confused in the process? What is the hardest part? Do you skip steps?

b. What makes a particular structure easier than another?

c. Do you do something to help you draw a more difficult structure?

3. What would you like your teacher to know about the process?

a. Were you interested and engaged in this activity? How so? How not?

b. How does your teacher test you on Lewis structures?

c. Do you feel that drawing Lewis structures was important to learn? Why?

d. If you were going to make any recommendations to your teacher about helping you to learn how to draw Lewis structures what would you suggest?

Students were asked to draw one or two structures and explain what they were thinking as they drew the structures. If they reached a point that they could not go any farther, the interviewer asked a question or two to help the (B. G. Glaser & Strauss, 1967) students finish the drawing. Out of the 15 students interviewed, only one was not able to draw a structure, even with hints from the interviewer (a student in Reg Chem 1 who scored “low” on the posttest).

Interviews were transcribed by TranscribeMe (2016). The transcripts were then uploaded to Dedoose (2016) online for analysis. Dedoose allowed the interview transcripts to
be uploaded, along with the notes students drew. These qualitative data can be categorized according to descriptors, such as the method taught, group, teacher, etc. (Talanquer, 2014). Then, the data can be organized using a color-coded coding system to analyze each line of the transcripts. The researcher also used paper and a highlighter to color-code sections of the transcripts. Next, the transcripts were analyzed using open coding (Strauss & Corbin, 1998), an inductive approach to data analysis, and the constant comparative method of data analysis (B. G. Glaser & Strauss, 1967).

Strauss and Corbin (1998) described open coding in the following way: “...during open coding, data are broken down into discrete parts, closely examined, and compared for similarities and differences” (p. 102). The first step is to conceptualize each phenomenon that is significant in the data and name it. The name may be chosen because of the imagery or meaning that comes to mind when the analyst examines the data or the name may be taken from the transcripts directly, known as “in vivo codes” (B. G. Glaser & Strauss, 1967). When the analyst identifies a phenomenon that shares common characteristics, the phenomenon is given the same name, or code. Then, the beginning concepts or codes are classified by grouping into higher order concepts, or categories and subcategories. The categories are developed by defining the categories’ properties, general or specific characteristics, and dimensions, the location of the property along a continuum. Lastly, the categories are related through hypotheses or statements of relationships (Strauss & Corbin).

B. G. Glaser and Strauss’ (1967) constant comparative method involves four stages:

1. Comparing incidents applicable to each category,
2. Integrating categories and their properties
3. Delimiting the theory, and
4. Writing the theory.

While coding a particular incident or phenomenon during the first stage, the analyst compares it with the previous phenomenon that are coded the same way. This first rule of the constant comparative method begins to generate theoretical properties of the category. B. G. Glaser and Strauss describe the second rule of the process – memo-writing – in the following way:

After coding for a category perhaps three or four times, the analyst will find conflicts in the emphases of his thinking. He will be musing over theoretical notions and, at the same time, trying to concentrate on his study of the next incident, to determine the alternate ways by which it should be coded and compared. At this point, the second rule of the constant comparative method is: stop coding and record a memo on your ideas. This rule is designed to tap the initial freshness of the analyst’s theoretical notions and to relieve the conflict in his thoughts. In doing so, the analyst should take as much time as necessary to reflect and carry his thinking to its most logical conclusions (p. 107).

During the second stage, these memos are used to change the comparison from incident with incident to comparison of incident with properties of the category. The theory develops as the categories and their properties become integrated (B. G. Glaser & Strauss, 1967). The third stage of delimiting the theory allows the analyst to solidify the theory and eliminate any nonessential properties of the categories. The last stage of writing theory involves the coded data, the series of memos and the theory. The information in the memos describes the categories, which are the major themes of the theory.
Procedures

The tests were collected by the teacher in charge of each class and handed to the researcher. The posttest was given approximately two weeks after the pretest. Since the researcher was the classroom teacher for many of the students in the study, the researcher was not aware which students were participating in the study and which were not while the instruction was taking place. Only the numerical portion of the test was scored by the computer, in order that students could be chosen to participate in the interview process. The teacher who kept the Child Assent, Parental Consent and Adult Assent forms was the person who asked students to participate in the interview process because he was the only person who had access to those forms. He also conducted the interviews. All of the data and consent forms were kept sealed in an envelope until after grades were posted for the semester, so that bias toward a student’s grade based on participation in the study could not occur. After the semester was over, the researcher scored the constructed response portion using a rubric created by the researcher (Figure 10) and had interviews transcribed (TranscribeMe, 2016).

Instruction

Three teachers were involved in teaching the methods for drawing Lewis structures. The researcher taught one Hon Chem 1 course, along with two Chem 2 courses. A different teacher (other) taught a total of three Hon Chem 1 course, along with five Reg Chem 1 courses. A third teacher (video instructor and teacher who collected the consent forms and conducted the interviews) who was not teaching any of the chemistry classes involved in the project recorded teaching lessons on how to draw Lewis structures. He recorded a total of six lessons:

1. Day 1 Formal Charge for Reg Chem 1 and Hon Chem 1
2. Day 1 Octet Rule for Reg Chem 1 and Hon Chem 1
3. Day 1 Formal Charge for Chem 2
4. Day 1 Octet Rule for Chem 2
5. Day 2 Formal Charge for all classes
6. Day 2 Octet Rule for all classes

These recorded video lessons were shown to students to introduce Lewis structures and teach the appropriate method, ensuring that both methods were treated equally each time the lesson was taught. All of the classes were shown two videos for their first two lessons in drawing Lewis structures. They were also given a worksheet to use while watching the video, which included additional examples to be done in class, with the help of the classroom teacher (See Appendix H for Reg Chem 1 and Hon Chem 1, Day 1 worksheet; Appendix I for Chem 2 Day 1; and Appendix J for Day 2 for all classes). It is important to note that no differentiation was provided between the Reg Chem 1 and Hon Chem 1 classes. Those classes had the same examples and same structures to draw both days. Later, though, when the students were practicing drawing structures and doing a molecular shape lab, Hon Chem 1 proceeded through the curriculum at a faster pace. Chem 2 classes had different examples and different structures to draw on Day 1, since they had previous experience with drawing Lewis structures. However, on Day 2, Reg Chem 1, Hon Chem 1 and Chem 2 classes were all shown the same examples and asked to draw the same structures. See Table 1 for a complete list of which class were shown which video.
Table 1

*Videos shown to each class period*

<table>
<thead>
<tr>
<th>Group</th>
<th>Year/Class period/instructor</th>
<th>Method</th>
<th>Day 1 video/worksheet</th>
<th>Day 2 video/worksheet</th>
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<tr>
<td>Reg Chem 1</td>
<td>2015 / 1 / other</td>
<td>CAM</td>
<td>Day 1 CAM for Reg and Hon Chem 1</td>
<td>Day 2 CAM for all classes</td>
</tr>
<tr>
<td></td>
<td>2015 / 2 / other</td>
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<td></td>
<td>2015 / 4 / other</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Reg Chem 1</td>
<td>2015 / 5 / other</td>
<td>DORM</td>
<td>Day 1 DORM for Reg and Hon Chem 1</td>
<td>Day 2 DORM for all classes</td>
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<td>2015 / 6 / other</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Hon Chem 1</td>
<td>2015 / 7 / other</td>
<td>CAM</td>
<td>Day 1 CAM for Reg and Hon Chem 1</td>
<td>Day 2 CAM for all classes</td>
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<td></td>
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<td>Hon Chem 1</td>
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<td>Octet Rule</td>
<td>Day 1 DORM for Reg and Hon Chem 1</td>
<td>Day 2 DORM for all classes</td>
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<td></td>
<td>2016 / 3 / other</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chem 2</td>
<td>2015 / 1 / researcher</td>
<td>Formal Charge</td>
<td>Day 1 CAM for Chem 2</td>
<td>Day 2 CAM for all classes</td>
</tr>
<tr>
<td>Chem 2</td>
<td>2015 / 6 / researcher</td>
<td>Octet Rule</td>
<td>Day 1 DORM for Chem 2</td>
<td>Day 2 DORM for all classes</td>
</tr>
</tbody>
</table>

Two Hon Chem 1 classes used the previously recorded video to learn the DORM, while a third Hon Chem 1 class, learned the CAM using the video. Of two Chem 2 classes, one class learned the CAM, while the other class learned the DORM. Of the five Reg Chem 1 classes, two learned the DORM, while the remaining three learned the CAM. The number of participants in each class ranged from 5 students to 22 students. See Table 2 for distribution of methods learned, including the classroom teacher for each class (either the researcher or other teacher).
Table 2

*Distribution of methods learned. Includes both Spring 2015 and Spring 2016*

<table>
<thead>
<tr>
<th></th>
<th>Number of Classes Learning the CAM</th>
<th>Number of Classes Learning the DORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reg Chem 1 (Other teacher)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Hon Chem 1 (Other teacher)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Hon Chem 1 (researcher)</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Chem 2 (researcher)</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Day 1 instruction for Hon Chem 1 and Reg Chem 1.** All Reg Chem 1 and Hon Chem 1 students received the same worksheet with the same problems on the first day (See Appendix H). Each student was provided with a list of rules on lime green paper, corresponding to the method they were learning (See Figure 13 for DORM handout and Figure 14 for CAM handout), and a periodic table. The objective given to students for the day’s lesson was as follows: I can draw the Lewis structure from a molecular formula. The video instructor recorded two videos – one for each method. On the worksheet, students were asked two questions: a) what are valence electrons? And b) how can you determine the number of valence electrons in an atom? These questions were designed to make the students think about what they had learned previously – valence electrons.

The videos started with this statement: a Lewis structure shows the arrangement of atoms within a particular molecule. Then the video instructor explained how to draw NH₃, H₂O, N₂, and SO₄²⁻ structures using whichever method the students were learning in that particular
**Drawing Rules for Lewis Structures (Octet Rule)**

1. Calculate the # of bonding electrons
   - Find # of octet electrons (8 for nonmetals, 2 for H and alkali metals, 4 for alkaline earth metals, 6 for B and Al)
   - Find # of valence electrons (add one for each – charge, subtract one for each + charge)
   - Bonding e⁻ = octet - valence

2. Calculate the # of bonds.
   - Bonding e⁻ / 2
   - If # of bonds is less than # of atoms available to attach to central atom, then central atom does not obey the octet rule. Skip to 7.

3. Calculate the # of nonbonding electrons.
   - Valence e⁻ - bonding e⁻

4. Identify the central atom
   - Least electronegative; never H

5. Attach atoms to central atom using the # of bonds determined in step 2.
   - Add nonbonding electrons to outer atoms first to complete octets, then to central atom

6. Add formal charges to all atoms and include resonance forms, when present
   - Count electrons on each atom (1 per bond), subtract this value from the valence electrons

7. If central atom has exceeded its octet, attach all atoms to central atom using a single bond
   - Nonbonding electrons = valence – bonding (count the number that were used to bond)
   - Add nonbonding electrons to outer atoms first to complete octets, then to central atom until all valence electrons are accounted for

---

*Figure 13. DORM rules for drawing Lewis structures. This was the handout given to all students learning the DORM, copied on lime green paper.*
Figure 14. CAM drawing rules. This was the handout for all students learning the CAM, copied on lime green paper. It was originally called the “Formal Charge Method.”

class section. After the video, students drew CO, PF₃, and Cl₂O structures on individual whiteboards while the classroom teacher circulated around the room to give guidance. Students were encouraged to talk with their classmates while going through the process of drawing the structures on their individual whiteboards. After students had been given a chance to draw one structure, the classroom teacher demonstrated the correct procedure for drawing the structure so that students could check their work. The process was repeated for the other two practice structures.

For practice on their own, students were asked to draw the Lewis structure for CO₂ and SCN⁻. Those structures were checked on Day 2 and used as an introduction to resonance.
structures and calculating formal charge. Chemistry 1 students were not taught to draw structures with expanded octets. That instruction was saved for Chemistry 2.

**Day 1 instruction for Chem 2.** Both Honors Chemistry 2 classes received the same worksheet with the same problems on the first day. They also used a periodic table and the Rules for Drawing Lewis Structures sheet, according to whichever method they were using. The objective given to students for the day was the same as for the Chemistry 1 lesson and is as follows: I can draw the Lewis structure from a molecular formula. Before the video, recorded as described previously, was shown to teach the method, students were asked what a Lewis structure is, and they were asked to draw the Lewis structure for water. This was an attempt to get the students to think about what they learned in their previous year of chemistry. It is important to note that students could have been taught either method during their first year of chemistry instruction. We do not know which method the students were originally taught, unless a student commented on it during his/her interview.

The video for each method began with the statement that a Lewis structure shows the arrangement of atoms within a particular molecule. The video instructor then demonstrated how to draw CH₄, N₂, and PCl₅, and SO₄²⁻ using the CAM for Period 1 and the Octet Rule Method for Period 6. After the video was completed, students were then asked to draw Lewis structures for the following molecules on their personal whiteboards: CO, SF₆, and Cl₂O. They were encouraged to ask a neighbor for help, and the classroom instructor circulated to offer assistance, also. After students were given time to draw the first structure, the classroom instructor demonstrated how to draw the correct Lewis structure. This process was repeated for the remaining three examples. Then, students were asked to draw the structures for CO₂
and SCN\(^{-}\) on their paper, on their own. Those structures would be used to introduce resonance structures and calculating formal charge on Day 2 of instruction.

**Day 2 instruction for all classes.** For the second day of instruction, Reg Chem 1, Hon Chem 1, and Chem 2 classes were taught the same lesson introducing resonance structures and giving instruction on how to calculate formal charge. The objectives given to students were the following: a) I can draw the Lewis structure from a molecular formula, and b) I can draw resonance structures and determine the correct structure based on formal charge. The video instructor recorded two different videos, one for each method. All classes being taught the CAM watched the same video, and all classes being taught the Octet Rule Method watched the same video.

Students were given a worksheet with two questions to answer before watching the video: a) What are resonance structures? and b) What is the Lewis structure for SCN\(^{-}\)? These questions allowed students to start thinking about what they learned the previous day. They also used a periodic table and the Rules for Drawing Lewis Structures sheet. Students had already drawn the structure for SCN\(^{-}\) and CO\(_2\) at the end of the previous lesson. The video instructor began the video with the correct drawing for SCN\(^{-}\), and students could check what they had drawn at the beginning of the class period. The video instructor then went on to demonstrate how to calculate formal charge for SCN\(^{-}\) and CO\(_2\). As was done on the first day of instruction, students were asked to draw structures while the video was paused and then check their drawings when the video instruction resumed. The structures for the second day were O\(_3\) and NO\(_3\)^{-}. Students were asked to draw all resonance structures and calculate formal charges in addition to drawing the structures. After checking these structures with the video instruction,
students were given one final structure to complete on their own to be checked the next day – SO₄²⁻.

**Additional instruction before posttest.** Students were given a chance to practice drawing Lewis structures before the posttest by learning VSEPR and doing a laboratory exercise that included drawing Lewis structures and building models of the molecules with molecule sets.

**Threats to Validity**

First, internal and external validity will be defined and threats to validity will be discussed. “Internal validity is the degree to which the experimental treatment makes a difference in (or causes change in) the specific experimental settings” (Dimitrov & Rumrill, 2003). Internal validity can be threatened by the following factors: history, maturation, pretest effects, instruments, statistical regression toward the mean, differential selection of participants, mortality, and interactions of factors (e.g., selection and maturation) (Isaac & Michael, 1981). “External validity is the degree to which the treatment effect can be generalized across populations, settings, treatment variables, and measurement instruments” (Dimitrov & Rumrill). Potential threats to external validity are as follows: interaction effects of selection biases and treatment, reactive interaction effect of pretesting, reactive effect of experimental procedures, and multiple-treatment interference (Isaac & Michael, 1981).

This study is a “nonrandomized control group pretest-posttest design” (Dimitrov & Rumrill, 2003). This design “has practical advantages... because it deals with intact groups and thus does not disrupt the existing research setting. This reduces the reactive effects of the experimental procedure and, therefore, improves the external validity of the design (Dimitrov &
Rumrill, p. 160). However, this nonrandomized design is more sensitive to problems with internal validity due to interaction of the following factors: (a) selection and maturation, (b) selection and history, and (c) selection and pretesting (Dimitrov & Rumrill). In this study, for example, the groups were not randomized; therefore differences in the posttest could be attributed to characteristic differences between the groups, rather than the tested method.

**Statistical Methods for Quantitative Analysis**

Traditionally, when analyzing data from pretests and posttests, four methods have been used: (a) analysis of variance (ANOVA) on the gain scores, (b) analysis of covariance (ANCOVA), (c) ANOVA on residual scores, and (d) repeated measures ANOVA (Dimitrov & Rumrill, 2003). Dimitrov and Rumrill define a “gain score” as the difference between the pretest scores and the posttest scores. Initially, an ANCOVA was conducted using the posttest score as the dependent variable and the pretest, group (Reg Chem 1, Hon Chem 1 and Chem 2), and method (DORM and CAM) as covariates for both the numerical response and the free response questions. The ANCOVA requires several assumptions to be met. Only the homogeneity of slopes assumption, the most difficult assumption, was satisfied. The other assumptions were not satisfied. As a result, ANCOVA could not be used.

Then, a two-way ANOVA using the gain scores was performed, as well as the repeated measures ANOVA, both of which yielded the same results. The two-way ANOVA on the gain scores was chosen as the statistical method for quantitative analysis for the numerical response portion, including all three groups, and for the free response portion, including Reg Chem 1 and Hon Chem 1. For post hoc analysis, the Bonferroni pairwise comparison was used. Since Chem 2
completed different structures on the pretest/posttest, the data was analyzed separately using nonparametric tests. This will be discussed in more detail in Chapter 4.
Chapter 4

Results/Discussion

Ethnomethodology, which studies the way people make sense of their world (Garfinkle, 1967), was the theoretical framework chosen for this study. This study tried to determine how novice chemistry students in Reg Chem 1, Hon Chem 1, and Chem 2 made sense of their high school chemistry “world” by seeking to find out how experts in chemistry (teachers) draw Lewis structures. The research data will be viewed with this theoretical framework in mind.

Pretest / Posttest Analysis

Free response.

Reg Chem 1 and Hon Chem 1. For the two groups Reg Chem 1 and Hon Chem 1, the total score on the two structures from the free response section was calculated. Then the gain score was calculated by finding the difference between the posttest score and the pretest score. A two-way ANOVA was conducted, with the gain score as the dependent variable and methods (DORM and CAM) and groups (Reg Chem 1 and Hon Chem 1) as the independent variables (See Table 3 for sample size). No significant difference was shown in the gain score.

Table 3

Sample size for method and group

<table>
<thead>
<tr>
<th>Method</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>DORM</td>
<td>35</td>
</tr>
<tr>
<td>CAM</td>
<td>39</td>
</tr>
<tr>
<td>Group</td>
<td></td>
</tr>
<tr>
<td>Reg Chem 1</td>
<td>23</td>
</tr>
<tr>
<td>Hon Chem 1</td>
<td>51</td>
</tr>
</tbody>
</table>
and either independent variable. The ANOVA showed that the interaction effect between method and group was significant, $F(1, 70) = 10.960, p = 0.001$. Post hoc comparisons using the Bonferroni pairwise comparison showed that Reg Chem 1 students demonstrated larger gain scores when they had been taught the CAM (Mean difference = 3.275, SE = 1.324, $p < 0.05$), while Hon Chem 1 students demonstrated larger gain scores after learning the DORM (Mean difference = 1.931, SE = 0.848, $p < 0.05$) (See Table 4 for means).

Table 4

*Means for the gain scores of Reg Chem 1 and Hon Chem 1 on the free response section. A significant difference was found between the means when method and group were considered together.*

<table>
<thead>
<tr>
<th>Method</th>
<th>Group</th>
<th>M</th>
<th>SD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>DORM</td>
<td>Reg Chem 1</td>
<td>4.1250</td>
<td>5.19443</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Hon Chem 1</td>
<td>6.8889</td>
<td>2.63604</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>6.2571</td>
<td>3.50078</td>
<td>35</td>
</tr>
<tr>
<td>CAM</td>
<td>Reg Chem 1</td>
<td>7.4000</td>
<td>3.18030</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Hon Chem 1</td>
<td>4.9583</td>
<td>2.36789</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>5.8974</td>
<td>2.92714</td>
<td>39</td>
</tr>
<tr>
<td>Total</td>
<td>Reg Chem 1</td>
<td>6.2609</td>
<td>4.19109</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Hon Chem 1</td>
<td>5.9804</td>
<td>2.67200</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>6.0676</td>
<td>3.19388</td>
<td>74</td>
</tr>
</tbody>
</table>

Chem 2. As was discussed in Chapter 3, Reg Chem 1 and Hon Chem 1 students drew two structures on their posttest, while Chem 2 drew six structures. Since Chem 2 drew six
completely different structures, that data was analyzed separately. A two-way ANOVA was
initially performed. Since assumptions were not met, likely due to the small sample size (See
Table 5), nonparametric tests were used. The null hypothesis stated that no difference existed
between the pretest and posttest scores. The Wilcoxon Signed Ranks Test gave evidence that
the null hypothesis could be rejected; a difference between the pretest and posttest scores
does exist (Z = -3.171, p < 0.001). However, we do not have enough evidence to reject the null
hypothesis that the gain score is the same across all categories of method.

Table 5

Chem 2 statistics for the free response portion. M is the mean gain (posttest – pretest).

<table>
<thead>
<tr>
<th>Method</th>
<th>M</th>
<th>SD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>DORM</td>
<td>4.5926</td>
<td>4.15925</td>
<td>9</td>
</tr>
<tr>
<td>CAM</td>
<td>5.6000</td>
<td>1.67332</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>5.9700</td>
<td>3.15804</td>
<td>14</td>
</tr>
</tbody>
</table>

Since Chem 2 students had learned Lewis structures previously, it is not surprising that a
difference in gain scores was not found. They could have been taught the other method the
previous year. Although their instruction during this study was for a specific method, they could
have used the method they learned the previous year to draw the structures. For example,
student T2H107 drew HCN correctly during her interview using the DORM, which she had
learned the previous year, rather than the CAM that she learned the year of the study.

**Numerical response.** For the numerical response section, a two-way ANOVA was
conducted. The dependent variable was the gain score, while the two independent variables
were the methods (DORM and CAM) and the groups (Reg Chem 1, Hon Chem 1, and Chem 2) (See Table 6 for descriptive statistics). The null hypothesis states that no difference exists between the methods and the groups, while the alternative hypothesis states that a difference does exist between methods and groups. We do not have enough evidence to accept the alternative hypothesis that a difference exists between methods and groups.

Table 6  
*Numerical response results. M is the mean of the gain score.*

<table>
<thead>
<tr>
<th>Method</th>
<th>Group</th>
<th>M</th>
<th>SD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>DORM</td>
<td>Reg Chem 1</td>
<td>12.00</td>
<td>7.690</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Hon Chem 1</td>
<td>11.00</td>
<td>4.745</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Chem 2</td>
<td>11.50</td>
<td>5.380</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>11.28</td>
<td>5.353</td>
<td>46</td>
</tr>
<tr>
<td>CAM</td>
<td>Reg Chem 1</td>
<td>9.47</td>
<td>5.693</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Hon Chem 1</td>
<td>10.86</td>
<td>6.093</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Chem 2</td>
<td>12.60</td>
<td>4.506</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>10.61</td>
<td>5.802</td>
<td>49</td>
</tr>
<tr>
<td>Total</td>
<td>Reg Chem 1</td>
<td>10.35</td>
<td>6.400</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Hon Chem 1</td>
<td>10.93</td>
<td>5.424</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Chem 2</td>
<td>11.87</td>
<td>4.969</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>10.94</td>
<td>5.569</td>
<td>95</td>
</tr>
</tbody>
</table>
**Similarities between numerical response and free response.** Some questions on the numerical response portion had corresponding items on the free response rubric. Questions 1, 7, and 13 asked how many hydrogen atoms were present, which corresponded to the “Correct representation of atoms” section of the rubric. If students answered questions 1, 7, and 13 correctly on the numerical response, I would expect them to earn all of the points available on the “Correct representation of atoms” section on the free response and vice versa. I would expect the same from the other two similar sets of questions: (a) questions 3, 9, 15 and 20, which asked for the number of bonding electrons, corresponding to the rubric segment about the number of bonds, and (b) questions 4, 10, 16 and 21, which asked for the number of nonbonding electrons, corresponding to the section on the rubric regarding the number of lone pairs.

To test to see if students did indeed answer those sets of questions in the same manner, a t-test was run. However, before running a t-test, the data needed to be transformed so that a comparison could be made between the numerical response, which was a correct or incorrect answer, and the free response, in which students could earn two points for a correct response, one point for mostly correct or zero points. First, the numerical response correct answers were assigned “1” and the incorrect answers were assigned “0”. Then, the free response scores from the rubric were adjusted to match the “correct” or “incorrect” format of the numerical response. The middle score of “1” for a mostly correct answer was removed, since students could not receive any points for “mostly correct” on the numerical response. Lastly, the score for a completely correct answer on the free response was changed from “2” to “1” in order to match the correct score of “1” on the numerical response.
After the scores were standardized, a paired-samples t-test was used to determine if a difference existed between each set of questions. For example, we compared the numerical response questions 1, 7 and 13 and segment “B” from the rubric, as mentioned above. All three sets of questions were examined, and no significant difference was found in any of the sets. That result confirms what I expected: Students who correctly answered the questions regarding the number of hydrogens in a structure could also represent atoms correctly when drawing the structures in the free response. Students who correctly calculated the number of bonding electrons in the numerical response drew the correct number of bonds in the free response. Students who correctly calculated the number of nonbonding electrons in the numerical response also drew the correct number of lone pairs in the free response.

**Correlation between posttest and grade point average (GPA).**

**Numerical response.** For all three groups (Reg Chem 1, Hon Chem 1, and Chem 2), a strong correlation was shown between the posttest score on the numerical response section and a student’s GPA (p < 0.01). It was necessary to show this correlation in order to analyze the data using linear regression. A linear regression was performed, which showed that the numerical response posttest score could be predicted by the student’s GPA (See Table 7 for results and Figure 15 for the plot.)
Table 7

Linear regression for numerical response posttest score versus GPA

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE B</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant (Intercept)</td>
<td>-3.72</td>
<td>4.27</td>
<td></td>
</tr>
<tr>
<td>GPA (slope)</td>
<td>5.83</td>
<td>1.21</td>
<td>.46*</td>
</tr>
</tbody>
</table>

Note: $R^2 = .21$, * p < .001

Free response. A correlation was demonstrated between the posttest score for CO$_2$ and a student’s GPA ($p < 0.05$) for Reg Chem 1 and Hon Chem 1. It was necessary to demonstrate this correlation in order to analyze the data using linear regression, as mentioned previously.
Then, a linear regression was performed, which showed that GPA predicted the posttest score for CO$_2$ (See Table 8 for results and Figure 16 for the plot.)

Table 8

*Linear regression for free response posttest score for CO$_2$ versus GPA*

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE B</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant (Intercept)</td>
<td>6.06</td>
<td>2.31</td>
<td></td>
</tr>
<tr>
<td>GPA (slope)</td>
<td>1.33</td>
<td>0.66</td>
<td>0.23*</td>
</tr>
</tbody>
</table>

Note: $R^2 = .053$, * p < .05

*Figure 16. A plot of the free response posttest score for CO$_2$ versus GPA.*
Do the numerical response and free response sections measure the same thing? Recall that we did not have enough evidence to accept the alternative hypothesis that the gain from numerical portion of the pretest/posttest was different for different groups or methods, but we did accept the alternative hypothesis for the free response section, with Chem 2 results excluded. With these results in mind, it seems reasonable to propose that the numerical response portion of the pretest/posttest was measuring something different than the free response was. Students were required to draw structures for both portions. One portion showed a difference in the gain scores for a particular group and method, but the other did not.

Besides requiring students to draw structures, the numerical response portion required students to answer questions about the structure (e.g. How many valence electrons? What is the bond order?). The answers on the numerical response were either right or wrong – no partial credit was given. In contrast, the free response was graded with a rubric that analyzed the structure itself, without asking questions that students had to answer. Students were also given partial credit for segments of the structure that they drew correctly (e.g. number of bonds, placement of bonds).

Students might have struggled with answering questions on the numerical response, simply because it involved reading comprehension in addition to drawing the structure. One Chem 2 student asked for practice answering the questions:

*Interviewer:* If you’re going to make any recommendations to your teacher about helping you to learn how to draw Lewis structures, what would you suggest?
Student T2H106: I don’t know. I think she did a pretty good job explaining how to do it. Maybe more about – not drawing the structure, but how to answer these questions.

Interviewer: So, actually practice answering the questions...

Student T2H106: Yes.

Interviewer: ...that are going to be on the test so you know what you’re looking for?

Student T2H106: Yeah, yeah.

Interviewer: Okay.

Student T2H106: That was my hardest part.

Interviewer: So, you felt like drawing them wasn’t bad.

Student T2H106: No, it’s just, how many hydrogen atoms are present, all those questions.

Interviewer: So, you couldn’t count how many...

Student T2H106: But I got confused, though.

The objective of this project was to teach students to draw Lewis structure, not necessarily to teach them test taking skills or reading comprehension. It seems that if students drew the structure from the numerical response correctly, they should be able to answer the questions correctly; but they did not. Perhaps the numerical response portion with the questions was actually testing their reading comprehension and/or vocabulary rather than their ability to draw Lewis structures. This could be confirmed by grading the structures drawn on the numerical response portion with the same rubric as was used on the free response portion. Unfortunately, students were not asked to show their work, and not everyone drew structures.
Does a student’s GPA predict the posttest score? The linear regression performed on the numerical response posttest score and GPA (See Table 7, above) showed that a student’s GPA was able to predict the student’s numerical response posttest score. Therefore, a student with a higher GPA would have a higher posttest score. (The free response posttest score for CO$_2$ could also be predicted by GPA (Table 8), but the correlation between GPA and posttest score in the free response was not as strong as the correlation with the numerical response.) Students with higher GPAs are most likely better readers than students with lower GPAs. It seems reasonable that better readers could perform better on an assessment with written questions, rather than just drawing the structure. That is what the linear regression above is showing.

Other interesting observations.

**Numerical Response.** A relatively large percentage of students answered a few specific numerical response questions correctly on the pretest (See *Table 9*). Over 80% could answer how many hydrogen atoms were present in the formula when given the following formulas: NH$_3$, HCN, and CH$_2$O. On the posttest, more of those questions were answered correctly, with the exception of Reg Chem 1 and Chem 2 on HCN (74%, 80% respectively) and Reg Chem 1 on CH$_2$O (78%). This is most likely due to test-taking error since so many answered correctly on the pretest and answered the other similar questions correctly.

Two-thirds (67%) of Chem 2 students were able to count the number of single bonds in a given structure, while just over half (53%) of those same students gave the correct number of double bonds in the same molecule. Since these students had learned about Lewis structures
Table 9

*Percentage of students who answered specific questions correctly on the pretest and posttest*

<table>
<thead>
<tr>
<th>Question</th>
<th>Reg Chem 1</th>
<th>Hon Chem 1</th>
<th>Chem 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 (H atoms)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>83</td>
<td>96</td>
<td>93</td>
</tr>
<tr>
<td>Post</td>
<td>91</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>7 (H atoms)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>87</td>
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The previous year, some of them may have counted a double bond as two single bonds, which would have made the answer incorrect. Almost all of the Chem 2 students answered those questions correctly on the posttest.

The first-year students (Reg Chem 1 and Hon Chem 1) were able to identify the number of double bonds (48%, 69%, respectively) better than the number of single bonds (13%, 46%, respectively). Perhaps the number of double bonds were easier to recognize for someone who had never seen a Lewis structure before or knew what a bond was because they were drawn with two lines (double). All of those percentages increased from the pretest to the posttest (See *Table 9*).
**Free Response.** Literature has shown that students struggle with choosing the central atom when drawing the skeleton structure of Lewis structures (Brady et al., 1990; Pardo, 1989) and do not have enough chemical knowledge to draw the skeleton structure correctly (Cooper et al., 2010). Some authors even suggest giving students the skeleton structure before starting the process of drawing Lewis structures because this task is considered to be too difficult (Bettelheim et al., 2010; McGoran, 1991; Nassiff & Czerwinski, 2015; Packer & Woodgate, 1991). However, in this study, when Reg Chem 1 and Hon Chem 1 students were presented with the instruction to “draw a Lewis structure,” more than half (58% for NO₃ and 54% for CO₂) of the Hon Chem I students drew correct skeleton structures for both structures with no previous instruction in how to draw a Lewis structure (See Figure 17). Of the Reg Chem 1 students, 30% drew the correct skeleton structure for the molecules.

Additionally, 22% of Reg Chem 1 students and 11% of Hon Chem 1 students drew a representation for the skeleton structure, as seen in Figure 18, Figure 19, and Figure 20.
Figure 18. Student M1R309's pretest. This student drew a skeleton structure without identifying atoms, exactly as we would do in the Chemistry Modeling Curriculum (American Modeling Teachers Association, 2016).

Figure 19. Student 16M1H310's pretest. This student drew circles for atoms, as we have done in modelling instruction. It does not show correct bond representation or identify the atoms, but it does show atoms attached to the "central atom" correctly.

Figure 20. Student 16M1H515's pretest. This student drew circles for atoms but identified the atoms in the circles. Although bonds are not represented correctly, atoms are attached to the "central atom" correctly.
Observations from interviews

Many students gave positive answers regarding drawing Lewis structures, regardless of the method they were taught or the score they received. Out of the 15 students interviewed, 10 of them thought that learning Lewis structures was important. One student was not sure, while four of the 15 were not asked that question. Five students stated that learning about Lewis structures was interesting, and two students thought it was easier than what they usually learn.

Students mentioned that they learned various things during the study. Two students thought that it helped them visualize structures. Three students knew that Lewis structures were drawn in order to determine the molecular shape. Five mentioned that they learned the rules of how to draw the structures.

Common errors. When asked to draw a Lewis structure, many students made math errors, either when adding or subtracting numbers. One mentioned that he did not have a calculator, and he usually used one. Another error was using the total number of electrons instead of calculating the valence electrons. Most of the students needed to use the “cheat sheet,” a periodic table that had the valence electrons written at the top of the groups, but even when using the sheet, some still made errors. Some used the total electrons rather than the valence electrons. The interviewer was able to help with errors made and all but one student were able to draw at least one structure correctly.

What is a Lewis structure? At the beginning of the interview, students were asked what a Lewis structure is. Several students gave vague answers:
• *Student M1R408:* If it has any, like those – if it were to have an H with a C in the middle and then draw two bonds going out with an H on each side, and then one going up....

• *Student M1R515:* I know that you had to put a dot somewhere.

• *Student M1R418:* I know that if you have two electrons at the top and then if it’s not an even number, you had to cross them out and make another bar.

• *Student M1R105:* I honestly don’t remember that much about it. That’s bad but... I remember how to get the valence electrons. That’s the main thing I remember.

• *Student M1R517:* All I know is drawing it.

  *Interviewer:* What are you drawing?

  *Student M1R517:* I don’t remember.

• *Student T2H106:* Like H₂O, you’ll draw two hydrogen.

• *Student T2H603:* Isn’t it the diagram of how you – like the compound or the whatever and the drawing. I don’t know the formal name for it.

Some students thought they knew what the structure was, even though they could not explain it:

• *Student T1H518:* It’s like a – I don’t – I know what it is. I did a hard test, and I don’t know if I failed it, but anyways, I know what it is.

• *Student T2H105:* I don’t know.... I know what it is, but I don’t know how to explain it.... It shows the form of the actual compound.

Others gave a better description of what a Lewis structure is:
• **Student M1R106**: It shows the bonds that molecules have, and how many electrons there are.

• **Student M1R601**: ...it is what the molecules look like when it’s explained on the paper.

• **Student M1H708**: It is a picture with lines and dots that represent a certain molecule, pretty much.

• **Student T1H516**: I don’t know. It shows the bonds and – I forget what it’s called.

• **Student M1R614**: It’s basically just drawing an outline of the atoms....

• **Student T2H621**: You’re showing the diagram of a molecule.

**What makes drawing Lewis structures more difficult?**

Cooper et al. (2010) noted that students have more difficulty with Lewis structures that have more atoms, specifically carbon atoms. Many students who were interviewed stated that having more atoms would make drawing the structures more difficult.

• **Student M1R408**: Having different ones of these going off of the H’s. Because of more different elements, so something like this... (pointed to the larger organic structure on the pretest).

• **Student M1R517**: Just having more. More elements.

• **Student M1R106**: It if had more atoms in it, it would probably be harder to add up.

• **Student M1R601**: The amount of – which ones you have. The amount of different things you have on the periodic table... like if you had three or four different ones.
• Student T2H106. When you have bigger ones, it’s more confusing.

While one student said that nothing makes them more difficult (M1H708), another stated, “When they’re different, like if there’s a different rule. Like I had to remember that two was H” (T1H516), which is a possible indication of overloading the student’s working memory. A Chem 2 student thought, “It’d be harder if it exceeded its octet and it’s be easier if... it’d be easier if it was like H₂O where it’s just two different elements. Because the ones with two different elements are easier, I think” (T2H621). The Chem 2 students were the only students who were taught that atoms could have an expanded octet.

What recommendations would you make to your teacher?

• Student M1R418: Give more examples.

• Student M1R408: Don’t put it all together. Work it out little by little piece.

• Student T1H516: Probably just try and make sure the students know what’s on the sheet a little bit more. Memorize, maybe having a little quiz over what was actually the steps or the order.

Interviewer: So making sure you know the order... a quiz on things. Would you say, like, how do you know how to subtract these things? Or how to find them? Or vocabulary? What would be on that quiz?

Student T1H516: The steps, like how would you find the number of bonds, or how would you find the number of non-bonding.

• Student M1R515: Go slower for the people that need longer time to understand.
Interviewer: Going slower as in like taking more time in between or practicing longer? So, you’re shaking your head yes to practice longer? What about doing more examples? Would that be part of going slower? So, spending more time with it?

Student M1R515: Yes.

- Student M1R603: Take their time and make sure the student understands every single step and know the different rules and stuff.

Levels of Understanding

Students made comments such as, "I learned how to set up a certain molecule," or "I don't know what I learned. I just know how to do it." It seems that they have trouble understanding or articulating the point of drawing the structure. Students are learning the algorithm to drawing Lewis structures, but they have not learned what a Lewis structure means. I have categorized students who were interviewed as having a “low,” “medium”, or “high” level of understanding of drawing Lewis structures.

Low. A student who still did not know what to do after instruction is in the “low” category. For example, student M1R418 was taught the CAM and scored 5/23 on the numerical response posttest. This student was categorized as a “low” achieving student for the posttest, and he demonstrated his lack of understanding with the answer to the question, “What is a Lewis structure?”

Student M1R418: I know if you have two electrons at the top and then it’s not an even number, you had to cross them out and make another bar.

Interviewer: So what it that you’re crossing out and doing – since you’re talking about the electrons, what is that overall thing, that Lewis structure? What is it showing you?
Student M1R418: Equation that is balanced.

Student M1R515 was taught the DORM and was also categorized as low-achieving, earning 4/23 on the posttest. This was her answer to the question, “So what do you know about Lewis structures, these things that we’ve been drawing?”

*Student M1R515:* I know that you had to put a dot somewhere, a dot in one H, if there is one.

*Interviewer:* ...And so what actually is this Lewis structure that you’re drawing these dots around?

*Student M1R515:* I don’t know.

**Medium.** Students who were able to draw structures on the posttest and who were able to give a relatively accurate description of what the structure is have been classified as *medium*. These students understood what to do but not why they were doing it. Student T1H516 learned the DORM and earned 20/23 on the posttest. This conversation started with the instruction to tell the interviewer what this student learned about Lewis structures in general. Although the student is not confident, he/she knew the general concept:

*Student T1H516:* Well, we learned how to make them and what the marks on them mean.

*Interviewer:* So what exactly is a Lewis structure that you’re making?

*Student T1H516:* [chuckles] I don’t know. It shows the bonds and – I forget what it’s called. I’m not a good chemistry student.

Student T2H105 earned 20/23 and learned the CAM:

*Interviewer:* What is a Lewis structure?
Student T2H105: I don’t know.

Interviewer: You don’t know?

Student T2H105: No. I know what it is, but I don’t know how to explain it.

Interviewer: Can you describe what it is or what you’d...?

Student T2H105: It shows the form of the actual compound.

Student T1H518 learned the DORM and earned 16/23 on the posttest:

Student T1H518: I learned like there's octet rule and the valence and stuff. Well I learned a lot, but it's kind of hard to explain.... If you solve it in the equation and then you get the bonding which is how many-- I don't know, it's kind of hard to explain. But I get it.

Student M1R517, who learned the DORM had very low confidence throughout the interview, but earned 23/23 points on the posttest.

Interviewer: What is a Lewis structure? Can you remember what it was or can you describe it to me?

Student M1R517: All I know is drawing it.

Interviewer: Drawing it? What are you drawing, though?

Student M1R517: I don’t remember. It’s like... I’m just good at the math.

High. A student who was interviewed and whom I consider to be in the “high” category after instruction knew how to draw the structures and understood what the structure actually was. Student M1H708 learned the CAM and scored 23/23 on the posttest. The conversation began with a question about what this student had learned.
Student M1H708: I learned how to set up certain molecules based on electrons, and then eventually found out what kind of shapes, like three dimensional shapes they make.

Interviewer: Cool. So what actually is the Lewis structure then?

Student M1H708: It is a picture with lines and dots that represent a certain molecule pretty much.

Student T2H621 learned the DORM and scored 22/23 on the posttest. She correctly drew HCN during the interview, and she was able to give an excellent oral explanation of what she was doing. She also knew what a Lewis structure was:

Interviewer: ...what is exactly a Lewis structure that you’re drawing...?

Student T2H621: You’re showing the diagram of the molecule.

Students from each method were almost equally dispersed throughout each category. Of the eight students learning DORM, two were low, four were in the medium category and two were high. Of the seven students learning CAM, two were low, three were medium and four were high. Students from both methods were able draw correct structures and demonstrate an understanding of what a Lewis structure is during the interview portion.

Research Questions

The following research question was proposed: Will high school chemistry students draw more accurate Lewis structures using the DORM or the CAM? Sub-questions were as follows:

1. Do students in Honors Chemistry 1 classes perform better using the DOR method or the CA method, as compared to students in Regular Chemistry 1?
2. Does a student’s GPA predict his or her posttest score?

The answer to the main research question is a mixed result and also answers the first subquestion. Reg Chem 1 students drew better structures using the CAM, and Hon Chem 1 students drew better structures using the DORM. While teaching both methods, the instructors felt that the DOR method was better suited to Hon Chem 1 students because Reg Chem 1 students seemed to struggle more with the DORM during instruction than they did with the CAM. The instructors’ suspicion seems to be confirmed by the results of this study, although additional research would help clarify this finding, since the sample size was small.

Assuming that the structure students are drawing does not have an expanded octet, the DORM requires five mathematical operations: (a) calculate octet electrons by addition, (b) calculate valence electrons by addition, (c) calculate bonding electrons by subtraction, (d) calculate number of bonds by division, and (e) calculate nonbonding electrons by subtraction. CAM requires only one mathematical operation, which is calculating the valence electrons by adding. Bain, Moon, Mack, and Towns (2014) reviewed many studies and concluded that the findings show a relationship between a student’s ability to perform mathematical operations and their success in solving thermodynamics problems. Thus, students who struggle with mathematics, as the Regular Chem 1 students would be more likely to do than the Hon Chem 1 students, would also struggle in chemistry. In this case, although it is simple arithmetic operations, students still seem to struggle, as was evident in the interviews when students committed several math errors. For example, here is an excerpt from a Reg Chem 1 student who was using the DORM and had trouble adding 6 + 8 and then subtracting 14 - 8:

*Student M1R601*: So then you have two times three, which is six, plus eight, which is...
Interviewer: It's 14.

Student M1R601: 14, all right.... So, nitrogen is five and hydrogen, we go one, hydrogen's one. So then you have one times three, which is three and then plus five. That equals-- [inaudible] that'd be eight. Then you have to subtract them and then what do we get from that? Five.

Interviewer: It's six.

In the free response section, though, the math errors were restricted to miscalculating the valence electrons (4 students out of 74, 3 DORM and 1 CAM, 1 Honors and 3 Regular), dividing by the wrong number (1 student, DORM, Reg Chem 1), and accounting for the extra electron in NO$_3^-$ incorrectly (3 students, 1 CAM Reg Chem 1, 2 DORM Hon Chem 1) (See Figure 21, Figure 22, and Figure 23 for examples of incorrect valence calculation).

![Draw the structure of CO$_2$.](image)

*Figure 21. Incorrect drawing of CO$_2$ by student M1R417 using CAM. This student calculated valence electrons correctly, but did not double bond the carbon atom.*
Figure 22. Incorrect drawing of NO$_3^-$ by student M1R316 using CAM. This student calculated the valence electrons correctly, but put too many bonds on nitrogen.

Figure 23. Incorrect drawing of CO$_2$ by student M1R505 using DORM. This student calculated the octet electrons correctly (24) but made a mistake when calculating the valence electrons.

Since math errors account for a very small number of errors on the free response and math errors were made with both methods, it seems that something else must be the reason for Hon Chem 1 performing better with the DORM, while Reg Chem 1 performed better with the CAM. Of the eight Reg Chem 1 students who learned DORM, two did not perform any calculations, while a third left the free response blank (although that student completed the calculations correctly for the numerical response). This lack of effort or understanding definitely affected the mean gain score for the DORM. Alternatively, none of the CAM students left the free response blank. The main error for the CAM was too few bonds or too many bonds – the students did not move the electrons around to completely fill the central atom’s octet.
Interestingly, if the DOR method is carried out correctly, the student will know the correct number of bonds and nonbonding electrons before drawing the structure.) Why did three of the eight Reg Chem 1 students learning the DORM give up on calculations? Why did Hon Chem 1 students perform better with DORM?

It is possible that some students are more conceptual thinkers than algorithmic problem solvers. They want to know why chemistry happens rather than how it happens (Nakhleh, 1993). Perhaps these students and others who did not perform well preferred concepts to algorithms and just were not interested in the process. Other ideas include overloading their working memory capacity and reduced metacognition skills.

**Working memory capacity.** Reber and Kotovsky (1997) commented that problem-solving theories assume that rules and problem-solving strategies are stored in the long-term memory, with a separate working memory that is used to evaluate strategies and plan the sequence of the operations that will be performed. Even if students are using a list of rules with the sequence of operations, some working memory space would be used in performing those operations.

Jaušovec (1998) found that gifted individuals use less mental activity than typical individuals when performing such tasks as mathematical operations and tasks using short-term memory. DORM uses more mathematical operations and has more steps to the algorithm than CAM. Conceivably, gifted students, such as those in Hon Chem 1, would not struggle with DORM because they are not using as much mental activity as a typical student, such as those in Reg Chem 1, would. (It is important to note that although gifted students are placed in Hon Chem 1, not all students in that course are gifted. Any student can take the honors course.)
It is possible that the DORM overloaded the working memory capacity of some students, especially regular students. Barrouillet and Camos (2014) define working memory as “the assembly of systems devoted to the active maintenance of information within the cognitive system.” A. H. Johnstone (2000) talks about working space, which he defines as the “conscious part of our mind.” He states the following:

... Working space is limited and we can handle only a limited amount of information in a given time. If we try to manipulate too much at once, learning can become faulty or not take place at all, because we just overload and shut down (p. 11).

Perhaps students gave up on calculations because their working memory was overloaded and they shut down. They either did not learn the method, or they were unable to use any of the method to draw the structure.

Alternatively, Hon Chem 1 students performed better with the DORM. This result could be explained by the fact that enhanced working memory has been correlated with students’ ability to solve problems in chemistry (A. H. Johnstone & El-Banna, 1986; Opdenacker et al., 1990). Gifted students, particularly those with mathematical giftedness, demonstrate an enhanced working memory (Benbow & Minor, 1990; Dark & Benbow, 1990; Opdenacker et al., 1990).

**Metacognition.** Gifted students have superior cognitive skills than typical students and may also have superior metacognitive abilities (Snyder, Nietfeld, & Linnenbrink-Garcia, 2011). Students with superior metacognition, which involves self-regulatory skills (R. Glaser, 1989), are able to apply the algorithm correctly and check to see if they are drawing the structure
correctly according to the algorithm. R. Glaser (1989) commented on metacognition and self-regulatory skills:

Superior monitoring skills reflect the domain knowledge and representational capabilities of experts, and these skills contribute to the utility of knowledge. Knowledge of a rule or procedure is enhanced by overseeing its applicability and monitoring its use. Thus, self-regulatory skills are important candidates for learning and instruction and can be significant predictors of problem-solving abilities that results in new learning (p. 274).

Flavell (1979) defines metacognition as the “knowledge and cognition about cognitive phenomena” (p. 906). It can be thought of as the ability to understand, regulate and use a person’s thought processes to help perform the task at hand (Flavell), or as thinking about one’s thinking. He found that young children do not use metacognition, but as children get older, they start using metacognition.

Flavell (1979) proposed that cognitive monitoring occurs through these four classes of phenomena: (a) metacognitive knowledge, (b) metacognitive experiences, (c) tasks, and (d) strategies. An example of metacognitive knowledge would be when a student believes he/she is better at math or better at chemistry than his/her friends. An example of metacognitive experiences would be a student’s sudden feeling that he/she did not understand what the teacher just said. Perhaps it is the sudden feeling that he/she did not understand a particular part of the algorithm for drawing Lewis structures. An example of tasks and strategies would be the task of drawing a Lewis structure using the CAM strategy or the DORM strategy.
All four of these contribute to the overall cognitive monitoring that occurs as a student is drawing a structure. Students made comments about their metacognitive knowledge, such as the following:

- **Student T1H516**: I don't know. It shows the bonds and-- I forget what it's called. I'm not a good chemistry student.

- **Student M1R418**: Kind of, I have a bad memory. I remember how to get the valance electrons, that's the main thing I remember and then... And I don't know what else to do [laughter]. I'm terrible at this.

If students have metacognitive experiences in which they do not understand what the teacher is saying at that particular time, they may combine that metacognitive experience with the metacognitive knowledge that they are not “good chemistry students,” and refuse to even try to task of drawing a Lewis structure using the strategy or method provided. Interestingly, Student M1R517 was not confident in what she was doing, but she could go through the DORM algorithm and draw a correct structure. She said repeatedly that she couldn't explain it, yet she drew a correct structure.

Many students could not explain what a Lewis structure was or explain the process of drawing a structure as they were drawing it. Explaining what they are thinking as they are drawing is a metacognitive process (Flavell, 1979). Some students gave excellent explanations, leading to the conclusion that they had better metacognitive skills. In a problem-solving task involving a puzzle, Reber and Kotovsky (1997) found that participants who solved the puzzle were not able to explain how they solved it. They also suggest that the process of solving the puzzle the first time could be thought of as “gradual acquisition of knowledge up to some
criterion” (p. 185). In this case, though, it was not the first time that students had solved the “puzzle” of drawing Lewis structures; students had drawn Lewis structures over and over again. Yet, some of them apparently were still “gradually acquiring” knowledge.

This gradual acquisition of knowledge is like students learning to read. Metacognition plays a part in memory, problem-solving and reading comprehension (Flavell, 1979). Beginning readers do not necessarily understand the meaning of the words they are learning to read, but they learn to read the words using the sounds of the letters that make up the word, a metacognitive skill. Eventually, they will learn to read more fluently by reading the same words several times, and then they will become "expert" readers. It's a process that will be discussed in the next section.

**Theoretical Framework**

How do students make sense of learning to draw Lewis structures? Teachers draw structures without thinking about how they do it, unless they are trying to teach students the process. Two processes or methods were used in this study – DORM and CAM. It appears that Reg Chem 1 students drew better structures with CAM and Hon Chem 1 students drew better structures with DORM. Both of these methods are algorithms, although DORM gives students the number of bonds and the number of nonbonding electrons right away, and CAM involves moving electron pairs around to form bonds, if necessary.

Not much is known about how a novice acquires expertise in the sciences (Stains & Talanquer, 2008). In this study, though, it seemed that no matter which method they use, high school chemistry students make sense of drawing Lewis structures by following the algorithm on the provided “rule sheet.” They acquired expertise by following the steps and practicing the
examples given, learning to organize the new knowledge in an effective manner, so they could draw correct structures. Snyder et al. (2011) commented the following:

> It is widely viewed as a critical hallmark of expert performance in that experts organize greater amounts of knowledge in a more effective manner, use more appropriate strategies, and regulate their thinking and performance more effectively than nonexperts (p. 181).

Student M1H708 in Hon Chem 1, who learned the CAM, scored a perfect 23/23 on the numerical response posttest and followed the algorithm:

> *Interviewer*: “Did you ever skip steps, like you follow the directions exactly or do you just kind of....”

> *Student M1H708*: “Yeah. I usually follow the directions pretty closely.”

Conversely, student M1R418 learned the CAM and scored 5/23 on the numerical response posttest. He did not follow the algorithm, and it showed in his low numerical response posttest score:

> *Interviewer*: “Do you ever skip any steps or...”

> *Student M1R418*: “Sometimes.”

> *Interviewer*: “Sometimes [chuckles]. All right, do you know what steps you skip or...?”

> *Student M1R418*: “No, it just depends how fast I go, but sometimes if I go fast, I miss some.”

As students gained more experience and confidence, some were able to do the process on their own without using the rule sheet, thus progressing from novice toward the expert
level. Student M1R601 in Reg Chem 1 scored 22/23 on the numerical response posttest and learn the DORM:

Interviewer: “You seem to [draw the structure] pretty well, and you didn’t really look at your [rule] sheet, either. Looks like you memorized it pretty well…. Did you skip any steps?”

Student M1R601: “No, I might have wrote it different… but no, I didn’t skip any steps.

Student M1R106 in Reg Chem 1 scored a perfect 23/23 and learned the CAM:

Interviewer: “Did you skip steps on [the rule sheet]? Do you just kind of have it memorized?”

Student M1R106: I didn’t really need to use that [rule sheet]. I already had it memorized.

Student T2H621 in Chem 2 scored 22/23 on the numerical response posttest and learned the DORM in both years of chemistry:

Interviewer: “Do you ever skip any steps in that process, or do you just follow everything to the letter?”

Student T2H621: “Sometimes I can do without [the rule sheet], like if I’ve done it enough times then I don’t really need to look at it. I can just go though it in my head.”

When learning to draw the structures, students used the provided scaffolding: the rule sheet, periodic tables with valence electrons written at the top of the page and electronegativity charts. (Lin et al. (2012) defined scaffolding as “providing assistance to help students overcome their difficulties during learning” (p. 437).) Some low and medium level students still continued to use all of the scaffolding at the interview, but others who had moved
to the high level were able to discard the provided papers and perform the process without that scaffolding, as the last three interview comments above noted. The provided scaffolding helped reduce the cognitive load by allowing students a chance to learn the method without having to remember every detail of the process.

Three students mentioned that Lewis structures help us determine the shape of the molecule, which requires more expertise than novice level. Two of the three students were answering the question of what they had learned:

Student M1R601: “I learned Lewis structures is what the molecules looks like when it's explained on the paper.”

Student M1H708: “I learned how to set up certain molecules based on electrons, and then eventually found out what kind of shapes, like three dimensional shapes they make.”

This student realized why Lewis structures were important:

Interviewer: “Do you feel that drawing these structures were actually important for your understanding?”

Student T2H105: “Yeah.”

Interviewer: “Why?”

Student T2H105: “Because it helped me understand how they actually look, and then they also helped me with - I don't remember what it's called - the actual 3-D shapes.”

No one mentioned that the shape or structure of the molecule determines its function, however. Knowing that a molecule’s function comes from its structure requires an expert-level of understanding.
Comparing learning to draw Lewis structures with learning to read. This process of learning to make sense of their world by following the algorithm and gaining expertise is very much like a student learning how to read, as was mentioned above. Students are using metacognitive processes to follow the algorithm and produce a correct structure, much the same as a beginning reader follows “rule” of phonics to pronounce a word correctly. Neither the student learning Lewis structures nor the student learning to read understand the meaning of what they are learning until they have developed some expertise. Ehri (2005) described how readers read words.

Reading words may take several forms. Readers may utilize decoding, analogizing, or predicting to read unfamiliar words. Readers read familiar words by accessing them in memory, called sight word reading. With practice, all words come to be read automatically by sight, which is the most efficient, unobtrusive way to read words in text. (p. 167)

Sight words are the most efficient way to read words because when the sight words are familiar enough, readers can recognize pronunciation and meaning without stopping to sound out the letters (LaBerge & Samuels, 1974).

Similarly, when experts draw Lewis structures, they can look at a formula and draw a structure without having to stop to do any calculations or counting of valence electrons. An expert can draw many structures by “sight,” like a reader reads “sight words.” Experts immediately know the properties of the structure they have drawn because they are familiar enough with the key parts of the structure that they can immediately draw conclusions without all of the steps that novices go through. Novices use a type of decoding, “rules” for drawing
Lewis structures, to draw a correct structure. Making meaning out of the structures only comes after the structures have become more like sight words. With practice, simple structures can be drawn easily without using the “rules,” much like a kindergarten student practices simple sight words to be able to read them without sounding out the letters. Students make sense of their world by utilizing the same strategies available to students learning to read: (a) following the provided “rules” until they become familiar and (b) eventually learning to recognize formulas (or words, for the reader) that they know by sight.

Future Research

This study concerns the specific population of high school students from an urban, multi-cultural school. Additional research could include a bigger sample of the same population or a sample of students from a different population, such as a different type of high school or a college. Due to the small sample size of this study, I would recommend repeating this study to strengthen the results even more.

If I were to conduct this study again, I would change the structures drawn by the Chem 2 students to include the same structures drawn by the other two groups. That change would allow a better comparison of Lewis structure skills. I would also have Chem 2 students draw two structures with expanded octets, since those students were taught the method for expanded octets. In addition, I would edit the handout to include the instruction that hydrogen only requires two electrons rather than eight and that each atom in the structure besides hydrogen requires eight. Students should use the octet rule as an “error check.”

Additionally, interview questions based on how students made sense of the process could be included, along with additional interviews before and during the process of learning to
draw the structures. Instruction should include more introduction as to what the structures are and why we draw them.

Recommendations for Teachers

Hon Chem 1 drew better structures with the DORM, the method that was tested during this study. To increase the effectiveness of this or any other method, I suggest the following: (a) present the steps in the method over the course of 2 - 3 days rather than one day, thus reducing cognitive load, (b) give more examples and practice than we did, increasing confidence and providing positive metacognitive experiences and (c) use strategies to enhance students’ metacognitive processes and/or working memory, such as a learning progression that teaches the function of molecules before learning to draw Lewis structures (Cooper, Underwood, Hilley, & Klymkowsky, 2012).

An alternative suggestion is to use the CAM or a more basic method like direct pairing (Snadden, 1987) for simple molecules introduced in a Chem 1 class, and use the DORM for a Chemistry 2 or AP Chemistry course, where determining an unfamiliar structure quickly is necessary. The DORM helps with speed since it gives the number of bonds and the number of nonbonding electrons immediately.

Honors students would also benefit from these recommendations. In our school, gifted students are placed in the honors classes, but not everyone in the honors classes are gifted in math/science. Strategies for regular students would work well for the honors classes, as long as gifted students or any student who understands is given more difficult structures to draw (i.e. enrichment activities) while struggling students have more time to practice. A practical suggestion is to end the class period with an “exit ticket,” or “clicker” question where students
draw a different structure every day. Then, the teacher can quickly assess the structure before class the next day and know exactly where students are struggling. We did this, along with a structure to begin the next day; however, it was only done for two days. My recommendation is to repeat the process for at least a week, although additional research regarding the number of days would be useful. Like students learning to read sight words, I believe that students learning to draw Lewis structures need daily practice.

Since counting valence electrons was a problem for students in the interviews, I recommend that teachers teach enough electron configuration so that students will understand what “valence” means and so that they understand that a “full valence shell” of eight leads to a lower energy state and chemical stability. (The octet rule concept is also the basis for the “octet electrons” found in the DORM. Understanding that concept is vital to the process of drawing structures.) Our Reg Chem 1 and Hon Chem 1 students did not learn electron configuration prior to the study. Even though counting valence electron seems like a very simple process to teachers (experts), students (novices) need to be able to attach some meaning to the process in order to remember it (Cooper et al., 2010). Students need plenty of examples and practice problems; teachers should check for understanding of valence (i.e. quiz) before teaching the entire method for drawing structures. Doing so would help reduce cognitive load and free some working memory space if students were not trying to remember what valence electrons are, along with learning the algorithm to draw a Lewis structure. Understanding the reason for the octet rule will help them remember to check for eight around each atom before they finish the structure, which is a component of metacognitive knowledge.
In summary, using the CAM or a simple direct-pairing method (Snadden, 1987) may be easier for regular students to learn Lewis structures. The direct-pairing method would allow students to see that a bond is simply two electrons shared between the atoms, as Lewis (1916) envisioned. Especially with our population of students who were taught the Chemistry Modeling Curriculum (American Modeling Teachers Association, 2016), the more visual direct-pairing method might work very well as an introductory method. Then, as the DORM would be a method that can give Lewis structures for unfamiliar compounds more quickly, it could be used in subsequent lessons or even subsequent chemistry courses. The DORM works well for honors students, and gives the number of bonds and the number of nonbonding electrons right away, so that students can draw a structure quickly and accurately. With the direct-pairing method as an introduction, students could understand what they were drawing and why they were drawing it before they were exposed to the detailed algorithm of the DORM.
References


Appendix A

Letter from IRB

Office of Research Integrity
Institutional Review Board (IRB)
2000 University Avenue
Muncie, IN 47306-0155
Phone: 765-285-5070

DATE: March 27, 2015
TO: Kari Terhune
FROM: Ball State University IRB
RE: IRB protocol # 703646-1
TITLE: Octet Rule vs Formal Charge Method of Drawing Lewis Dot Structures
SUBMISSION TYPE: New Project

ACTION: DETERMINATION OF NOT HUMAN SUBJECTS RESEARCH
DECISION DATE: March 27, 2015
REVIEW TYPE: Expedited Review

The Institutional Review Board received the above protocol. After review and consideration, the IRB concluded that this project does not meet the definition of 'research with human subjects' at this time, as specified by federal regulations at 45 CFR 46.

Research: A systematic investigation, including research development, testing and evaluation, designed to develop or contribute to generalizable knowledge.
(Activities which meet this definition constitute research for purposes of this policy, whether or not they are conducted or supported under a program which is considered research for other purposes.)

Human Subject: A living individual about whom an investigator (whether professional or student) conducting research obtains: (1) data through intervention or interaction with the individual or (2) identifiable private information.

Consequently, this project does not require IRB approval as submitted. The IRB accepts this information for our records and will retain it in our files. Thank you for providing the IRB with these materials for review. Please contact the Office of Research Integrity if any details of the study are to change so that the IRB may reconsider the protocol, if necessary.

If you have any questions regarding this decision or would like to respond in person, please contact the Office of Research Integrity.
Bryan Byers, PhD/Chair
Institutional Review Board

Christopher Mangelli, JD, MS, MEd, CIP/Director
Office of Research Integrity
Appendix B

Letter from Marion High School Principal

Marion High School
750 W. 26th Street
Marion, IN 46953

Phone # (765) 664-9051
Fax # (765) 651-4242

January 9, 2015

RE: Kari Terhune

To Whom It May Concern,

This is to inform you that Kari Terhune, has permission to use Marion High School as the site for her research dissertation. If you should have any questions, please feel free to give me a call.

Sincerely,

Keith Burke, Principal
Marion High School
Appendix C

Child Assent Form

Octet Rule versus Formal Charge Method of Drawing Lewis Structures

Assent Form

My name is Mrs. Kari Terhune. I am trying to compare methods of teaching something called “Lewis structures” because the way we teachers teach you can affect how well you learn. If you would like, you can be in my study.

If you decide you want to be in my study, you will allow me to use the information from your pre-test and post-test from the section of the bonding unit that pertains to Lewis structures.

There are no known risks for participating in the study because all students will take the same pre-test and post-test. However, you might benefit by learning about how scientific studies work.

Other people will not know if you are in my study. I will put things I learn about you together with things I learn about other students, so no one can tell what things came from you. When I tell other people about my research, I will not use your name, so no one can tell who I am talking about.

Your parents or guardian have to say it’s OK for you to be in the study. After they decide, you get to choose if you want to do it too. If you don’t want to be in the study, no one will be upset with you. If you want to be in the study now and change your mind later, that’s OK. You can stop at any time.

My telephone number is (765) 285-5561. You can call me if you have questions about the study or if you decide you don’t want to be in the study any more.

I will give you a copy of this form in case you want to ask questions later.

Agreement

I have decided to be in the study even though I know that I don’t have to do it. Mrs. Terhune has answered all my questions.

Printed name of Study Participant

Signature of Study Participant Date

Signature of Researcher Date
Appendix D

Parental Consent Form

Study Title  Octet Rule versus Formal Charge Method of Drawing Lewis Structures

Study Purpose and Rationale
The purpose of this research project is to compare two different methods of teaching the same concept – drawing Lewis structures. If one method is shown to be more effective than the other, we will teach the more effective method in the future.

Inclusion/Exclusion Criteria
To be eligible to participate in this study, your child must be enrolled in Chemistry 1, Honors Chemistry 1, or Honors Chemistry 2 at Marion High School, Marion, Indiana and must be between the ages of 14 and 17.

Participation Procedures and Duration
For this project, your child will be asked to complete a pre-test. After instruction with one of the methods, your child will be asked to complete a post-test. This is a normal part of our curriculum and will not take any additional time out of classroom activities. This part of the curriculum should take approximately one week. Select students will be asked to complete a short interview with questions about learning the method. All students will take part in the pre-test and post-test, but the data from those tests will be used in the study with parental permission and child assent only.

Audio or Video Tapes
For purposes of accuracy, with your permission, the interviews will be audio taped. Any names used on the audiotape will be changed to pseudonyms when the tapes are transcribed. The tapes will be stored in a locked filing cabinet in the researcher’s classroom for three years and then be erased.

Data Confidentiality or Anonymity
All data will be maintained as confidential and no identifying information such as names will appear in any publication or presentation of the data.

Storage of Data
Paper data will be stored in a locked filing cabinet in the researcher’s classroom for three years and then be shredded. The data will also be entered into a software program and stored on the researcher’s password-protected computer for three years and then deleted. Only members of the research team will have access to the data. The data will be stored on an external hard drive for three years and then deleted by erasing the hard drive.

Risks or Discomforts
There are no perceived risks for participating in this study.

Who to Contact Should Your Child Experience Any Negative Effects from Participating in this Study
Should your child experience any feelings of anxiety, students may contact their guidance counselor.

Benefits
A possible benefit of your child’s participation in this study is to learn how scientific studies are performed in the “real world.”

Compensation
No compensation is being offered to participate in this study.

Voluntary Participation
Your child’s participation in this study is completely voluntary and you are free to withdraw your permission at any time for any reason without penalty or prejudice from the investigator. Participation or non-participation in this study will not affect your child’s grade in this course. Please feel free to ask any questions of the investigator before signing this Parental Permission form and at any time during the study.

**IRB Contact Information**
For questions about your rights as a research subject, please contact Director, Office of Research Integrity, Ball State University, Muncie, IN 47306, (765) 285-5070, irb@bsu.edu.

**Study Title**  Octet Rule versus Formal Charge Method of Drawing Lewis Structures

*********

**Parental Consent**
I give permission for my child to participate in this research project entitled, “Octet Rule versus Formal Charge Method of Drawing Lewis Structures.” I have had the study explained to me and my questions have been answered to my satisfaction. I have read the description of this project and give my permission for my child to participate. I understand that I will receive a copy of this informed consent form to keep for future reference.

__________________________________________________________
Child’s name – please print

__________________________________________________________
Parent’s Signature  Date

**Researcher Contact Information**

Principal Investigator:  Faculty Supervisor:
Kari Terhune, Graduate Student  Dr. Patricia Lang
Chemistry Teacher  Chemistry Department
Marion High School  Ball State University
Marion, IN  46953  Muncie, IN  47306
Telephone:  (765) 285-5561  Telephone:  (765) 285-5561
Email: kterhune@marion.k12.in.us  Email: plang@bsu.edu
Appendix E

Adult Consent Form

**Study Title**  Octet Rule versus Formal Charge Method of Drawing Lewis Structures

**Study Purpose and Rationale**
The purpose of this research project is to compare two different methods of teaching the same concept – drawing Lewis structures. If one method is shown to be more effective than the other, we will teach the more effective method in the future.

**Inclusion/Exclusion Criteria**
To be eligible to participate in this study, you must be enrolled in Chemistry 1, Honors Chemistry 1, or Honors Chemistry 2 at Marion High School, Marion, Indiana and at least 18 years old.

**Participation Procedures and Duration**
For this project, you will be asked to complete a pre-test. After instruction with one of the methods, you will be asked to complete a post-test. This is a normal part of our curriculum and will not take any additional time out of classroom activities. This part of the curriculum should take approximately one week. Select students will be asked to complete a short interview with questions about learning the method. All students will take part in the pre-test and post-test, but the data from those tests will be used in the study with your permission only.

**Audio or Video Tapes**
For purposes of accuracy, with your permission, the interviews will be audio taped. Any names used on the audiotape will be changed to pseudonyms when the tapes are transcribed. The tapes will be stored in a locked filing cabinet in the researcher’s classroom for three years and then be erased.

**Data Confidentiality or Anonymity**
All data will be maintained as confidential and no identifying information such as names will appear in any publication or presentation of the data.

**Storage of Data**
Paper data will be stored in a locked filing cabinet in the researcher’s classroom for three years and then be shredded. The data will also be entered into a software program and stored on the researcher’s password-protected computer for three years and then deleted. Only members of the research team will have access to the data. The data will be stored on an external hard drive for three years and then deleted by erasing the hard drive.

**Risks or Discomforts**
There are no perceived risks for participating in this study.

**Who to Contact Should Your Child Experience Any Negative Effects from Participating in this Study**
Should you experience any feelings of anxiety, you may contact your guidance counselor.

**Benefits**
A possible benefit of your participation in this study is to learn how scientific studies are performed in the “real world.”

**Compensation**
No compensation is being offered to participate in this study.

**Voluntary Participation**
Your participation in this study is completely voluntary and you are free to withdraw your permission at anytime for any reason without penalty or prejudice from the investigator. Your participation or non-participation will not affect your grade in this class. Please feel free to ask any questions of the investigator before signing this Adult Consent form and at any time during the study.
IRB Contact Information
For questions about your rights as a research subject, please contact Director, Office of Research Integrity, Ball State University, Muncie, IN 47306, (765) 285-5070, irb@bsu.edu.

Study Title  Octet Rule versus Formal Charge Method of Drawing Lewis Structures

Adult Consent
I, _____________________, agree to participate in this research project entitled, “Octet Rule versus Formal Charge Method of Drawing Lewis Structures.” I have had the study explained to me and my questions have been answered to my satisfaction. I have read the description of this project, and I agree to participate. I understand that I will receive a copy of this informed consent form to keep for future reference.

To the best of my knowledge, I meet the inclusion/exclusion criteria for participation (described on the previous page) in this study.

________________________________
Participant’s printed name

________________________________   _____________  
Participant’s Signature                   Date

Researcher Contact Information
Principal Investigator: Faculty Supervisor:
Kari Terhune, Graduate Student       Dr. Patricia Lang
Chemistry Teacher                  Chemistry Department
Marion High School                 Ball State University
Marion, IN  46953                   Muncie, IN  47306
Telephone: (765) 285-5561            Telephone: (765) 285-5561
Email: kterhune@marion.k12.in.us     Email: plang@bsu.edu
Appendix F

Parental Opt-Out Form

Study Title  Octet Rule versus Formal Charge Method of Drawing Lewis Structures

Study Purpose and Rationale
The purpose of this research project is to compare two different methods of teaching the same concept – drawing Lewis structures. If one method is shown to be more effective than the other, we will teach the more effective method in the future.

Inclusion/Exclusion Criteria
To be eligible to participate in this study, your child must be enrolled in Chemistry 1, Honors Chemistry 1, or Honors Chemistry 2 at Marion High School, Marion, Indiana and must be between the ages of 14 and 17.

Participation Procedures and Duration
For this project, your child will be asked to complete a pre-test. After instruction with one of the methods, your child will be asked to complete a post-test. This is a normal part of our curriculum and will not take any additional time out of classroom activities. This part of the curriculum should take approximately one week. Select students will be asked to complete a short interview with questions about learning the method. All students will take part in the pre-test and post-test, but the data from those tests will be used in the study with parental permission and child assent only.

Audio or Video Tapes
For purposes of accuracy, with your permission, the interviews will be audio taped. Any names used on the audiotape will be changed to pseudonyms when the tapes are transcribed. The tapes will be stored in a locked filing cabinet in the researcher’s classroom for three years and then be erased.

Data Confidentiality or Anonymity
All data will be maintained as confidential and no identifying information such as names will appear in any publication or presentation of the data.

Storage of Data
Paper data will be stored in a locked filing cabinet in the researcher’s classroom for three years and then be shredded. The data will also be entered into a software program and stored on the researcher’s password-protected computer for three years and then deleted. Only members of the research team will have access to the data. The data will be stored on an external hard drive for three years and then deleted by erasing the hard drive.

Risks or Discomforts
There are no perceived risks for participating in this study.

Who to Contact Should Your Child Experience Any Negative Effects from Participating in this Study
Should your child experience any feelings of anxiety, students may contact their guidance counselor.

Benefits
A possible benefit of your child’s participation in this study is to learn how scientific studies are performed in the “real world.”

Compensation
No compensation is being offered to participate in this study.

Voluntary Participation
Your child’s participation in this study is completely voluntary and you are free to withdraw your permission at any time for any reason without penalty or prejudice from the investigator. Participation or non-participation in this study will not affect your child’s grade in this course. Please feel free to ask any questions of the investigator before signing this Parental Permission form and at any time during the study.
**IRB Contact Information**
For questions about your rights as a research subject, please contact Director, Office of Research Integrity, Ball State University, Muncie, IN 47306, (765) 285-5070, irb@bsu.edu.

**Study Title**  Octet Rule versus Formal Charge Method of Drawing Lewis Structures

*******

**Parental Opt-Out**
I do not want my child to participate in this research project entitled, “Octet Rule versus Formal Charge Method of Drawing Lewis Structures.” I understand that my child is expected to complete all pretests, posttests and assignments, but my child’s data will not be used in the study.

__________________________
Child’s name – please print

__________________________
Parent’s Signature  Date

**Researcher Contact Information**

Principal Investigator:  Kari Terhune, Graduate Student
Chemistry Teacher  Marion High School
Marion, IN  46953
Telephone:  (765) 285-5561
Email:  kterhune@marion.k12.in.us

Faculty Supervisor:  Dr. Patricia Lang
Chemistry Department  Ball State University
Muncie, IN  47306
Telephone:  (765) 285-5561
Email:  plang@bsu.edu
Appendix G

Lewis Structures Pre-Test (Chemistry 2)

For one molecule of ammonia, NH₃,
1. How many hydrogen atoms are present?
2. How many valence electrons are in the molecule?
3. How many electrons are considered bonding electrons?
4. How many electrons are considered nonbonding electrons?
5. How many nonbonding electrons are on the central atom?
6. What is the bond order of the nitrogen – hydrogen bond?

For one molecule of HCN,
7. How many hydrogen atoms are present?
8. How many valence electrons are in the molecule?
9. How many electrons are considered bonding electrons?
10. How many electrons are considered nonbonding electrons?
11. How many nonbonding electrons are on the central atom?
12. What is the bond order of the carbon – nitrogen bond?

For one molecule of CH₂O,
13. How many hydrogen atoms are present?
14. How many valence electrons are in the molecule?
15. How many electrons are considered bonding electrons?
16. How many electrons are considered nonbonding electrons?
17. How many nonbonding electrons are on the central atom?
18. What is the bond order of the carbon – oxygen bond?

Answer the following questions, using the molecule above.
19. What is the total number of valence electrons in this molecule?
20. What is the total number of bonding electrons?
21. What is the number of nonbonding electrons?
22. What is the number of single bonds?
23. What is the number of double bonds?
Answer the Lewis structures for the following molecules ON THIS PAGE.
1. CH₄O

2. C₂H₆O

3. CH₃OH

4. CH₃CH₂OH

5. N₂H₄

6. CH₃CO₂H
### Lewis Structures Lesson 1 – Chemistry 1

<table>
<thead>
<tr>
<th>Identify</th>
<th>Objective:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Think, pair share:</td>
<td>I can draw a Lewis structure from a molecular formula.</td>
</tr>
<tr>
<td>What are valence electrons?</td>
<td>Standard: C.3.1 Describe, compare and contrast the characteristics of the interactions between atoms in ionic and covalent compounds.</td>
</tr>
<tr>
<td>How can you determine the number of valence electrons in an atom?</td>
<td></td>
</tr>
</tbody>
</table>

#### I Do

| NH₃ |
| H₂O |
| N₂ |
| SO₄²⁻ |

#### We Do

Grab a white board and marker. Do the following structures on your white board for me to check. Feel free to check with a neighbor for help.

| CO |
| PF₃ |
| Cl₂O |

#### You Do

| CO₂ |
| SCN⁻ |
Appendix I

Worksheet for Chemistry 2, Day 1

<table>
<thead>
<tr>
<th>Identify</th>
<th>Objective:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Think, pair share: I can draw a Lewis structure from a molecular formula.</td>
<td></td>
</tr>
<tr>
<td>What is a Lewis structure? Standard: C.3.1 Describe, compare and contrast the characteristics of the interactions between atoms in ionic and covalent compounds.</td>
<td></td>
</tr>
<tr>
<td>Draw the Lewis structure for water.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I Do</th>
<th>You Do</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>CO₂</td>
</tr>
<tr>
<td>N₂</td>
<td></td>
</tr>
<tr>
<td>PCl₅</td>
<td></td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>SCN⁻</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>We Do</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grab a white board and marker. Do the following structures on your white board for me to check. Feel free to check with a neighbor for help.</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td></td>
</tr>
<tr>
<td>SF₆</td>
<td></td>
</tr>
<tr>
<td>Cl₂O</td>
<td></td>
</tr>
</tbody>
</table>
Appendix J

Worksheet for Reg Chem 1, Hon Chem 1 and Chem 2, Day 2

Lewis Structures Lesson 2 – Chemistry 1 and 2

<table>
<thead>
<tr>
<th>Identify</th>
<th>Objective:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Think, pair share:</td>
<td>I can draw a Lewis structure from a molecular formula.</td>
</tr>
<tr>
<td>What are resonance structures?</td>
<td>I can draw resonance structures and determine the correct structure based on formal charge.</td>
</tr>
<tr>
<td>What is the Lewis structure for SCN⁻?</td>
<td>Standard: C.3.1 Describe, compare and contrast the characteristics of the interactions between atoms in ionic and covalent compounds.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I Do</th>
<th>You Do</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculating formal charge for SCN⁻:</td>
<td>Draw a Lewis structure including resonance structures and calculate the formal charge on each atom in SO₄³⁻.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>We Do</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Draw Lewis structures including resonance structures and calculate the formal charge on each atom in the following molecules:</td>
<td></td>
</tr>
<tr>
<td>O₃</td>
<td></td>
</tr>
<tr>
<td>NO₃⁻</td>
<td></td>
</tr>
</tbody>
</table>