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ASSESSING ORGANIC CHEMISTRY STUDENTS' UNDERSTANDING OF CHEMICAL
BONDING CONCEPTS AND THEIR PERCEPTIONS OF A PROJECT-BASED LAB

by

NIKITA LAUREN BURROWS

Under the Direction of Suazette Reid Mooring (Ph.D.)

ABSTRACT

Organic Chemistry students' understanding of Organic Chemistry is shaped by their prior experiences, in-class experiences, and laboratory experiences. One essential prior General Chemistry experience that affects Organic Chemistry students is the understanding of chemical structures and bonding. This fundamental topic is the basis of the structure-function relationship and it highlights the numerous conceptual interconnections present in chemistry. However, many students possess incoherent knowledge structures regarding this topic. Therefore, more effective assessments are needed to identify these interconnected misconceptions. The use of concept-mapping and think-aloud interviews were used to investigate the knowledge structures of undergraduate Organic Chemistry students' understanding of bonding concepts, resonance and Lewis structures for the first chapter of this dissertation. The study found that understanding of

electronegativity was weak among students with low concept map scores (LS students) in comparison to students with high concept map scores (HS students). Additionally, several common misconceptions over the three topics were revealed through student interviews. An examination of LS student interviews further revealed that a lack of understanding of electronegativity led to a misunderstanding of polar covalent bonding. The think-aloud interviews reflected the connections students made with the concepts of electronegativity and polar covalent bonding in their concept maps.

Chemistry labs are also considered a critical component of Organic Chemistry education. Laboratory instruction is presented in a variety of styles such as traditional or “cookbook”, project-based, open inquiry, and guided inquiry. Students can experience these laboratory environments in a variety of ways which directly affects how they learn or what they take away from the laboratory experience. The second half of this dissertation characterizes undergraduate students’ perspectives of a project-based Organic Chemistry laboratory and their perceptions of success and purpose in that laboratory using the theoretical framework of phenomenography. Eighteen participants were interviewed in a semi-structured interview format to collect their perspectives. A situated cognition framework was also used to design an outcome space that describes students’ engagement in the laboratory environment and its relationship to learning.

INDEX WORDS: Meaningful learning, Situated cognition, Phenomenography, Concept mapping, Chemical bonding, Lewis structures, Resonance, Project-based laboratory

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NIKITA LAUREN BURROWS

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

in the College of Arts and Sciences

Georgia State University

2017

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May 2017

DEDICATION

This dissertation is dedicated to my loving parents, Nigel and Monique Burrows, who have supported me through primary school, high school, undergraduate school, graduate school, and my entire life. You supported me when I wanted to be a doctor, you supported me when I started my Youtube channel, you supported me when I didn't know where my life's direction was. You have always pushed for me to follow my passion and you have continually been my biggest cheerleaders. Who could fail with parents like you! You taught me to do my best and to work my hardest and this has been no exception. This would have been a long, rough, lonely road without your love and guidance. Thank you so much, I love you.

Also, I would like to dedicate this dissertation to my brothers Nigel and Neko Burrows, who have provided me with countless video game and anime stress relief sessions during this journey. I certainly would not be the person I am today if not for them. They have always supported my pursuits, academic wise, YouTube wise or otherwise, and have provided love and teasing for the best and worst of times. This is for my ride or die cheerleaders!

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1 ORGANIZATION

At the time of submission of this dissertation, four manuscripts have been or will be submitted for publication based off the data in this dissertation. One manuscript has been published, one has been revised after peer review and resubmitted, one is currently in review and one is in preparation to be submitted.. Chapter 2 discusses the uncovering of student's misconceptions on bonding and structure. It also evaluates concept maps as a formative assessment tool to uncover student misconceptions. Chapter 3 consists of two manuscripts – one focusing on students' perceptions of goals and success in a project-based Organic Chemistry lab and one on student's perception and experiences in that same lab. The concluding chapter, Chapter 4, is the conclusions and future directions for research.

2 CHEMICAL STRUCTURE AND BONDING

2.1 Introduction

This chapter has been adapted from the following publication in Chemistry Education Research and Practice (Burrows and Mooring 2015).

A large part of chemistry is dedicated to abstract concepts—that is, concepts that are not directly observable to the naked eye such as the structure of molecules. Understanding the structure of a molecule plays a powerful role in chemistry because structure has a direct effect on the observable features of a compound (Cooper et al. 2010; Cooper et al. 2012a). The structure and bonding of molecules are key concepts for various STEM (science, technology, engineering, and mathematics) disciplines; however, its importance is most observable in the Organic Chemistry course. These concepts learned in introductory chemistry courses in high school and college serve as prior knowledge for students in Organic Chemistry courses. Specifically, chemical bonding and the molecular structure of molecules directly influences phenomena

discussed in Organic Chemistry courses (Bergqvist et al. 2013; Birk and Kurtz 1999; Burrows and Mooring 2015; Coll and Taylor 2001; Coll and Treagust 2001; Coll and Treagust 2002; Levy Nahum et al. 2010; Logan 2001; Nicoll 2001; Othman et al. 2008; Özmen 2004; Peterson et al. 1986; Peterson and Treagust 1989; Peterson et al. 1989; Rabinovich 2003; Robinson 1998; Taber et al. 2012; Tan and Treagust 1999; Teichert and Stacy 2002).

Previous research has shown that students struggle to make connections between chemistry concepts such as the molecular structure of a substance and its resulting properties (Nakiboglu 2003; Nicoll 2001; Özmen 2004; Schmidt 1997). Understanding this relationship requires thorough knowledge of a variety of interconnected topics and rules that build off prior knowledge gained in General Chemistry courses. Thus, learning and the ability to make connections is dependent on prior knowledge. There are four instances that can arise concerning prior knowledge students have:

1. The student has no prior knowledge to which new information can be linked
2. The student has incorrect prior knowledge that contradicts the new information that is being presented to the student
3. The student has correct but incomplete prior knowledge
4. The student has correct and complete prior knowledge

Students come to formal education with a range of prior knowledge, skills, beliefs, and concepts that significantly influence what they notice about the environment and how they organize and interpret it. This, in turn, affects their abilities to remember, reason, solve problems and acquire new knowledge (National research Council, 1999, p.10). Of these four instances of prior knowledge, the first three can lead to the creation of poor connections.

Students prior knowledge greatly affects certain skills needed to understand and receive information in a coherent and understandable manner. Thus, it is important to look at the prior knowledge that students enter into a course with, any misconceptions students possess and the depth at which those misconceptions exists.

2.1.1 *Background of misconceptions*

Previously, students were viewed as blank slates waiting to absorb the information teachers imparted to them (Grove and Bretz 2012; Kostrubiec et al. 2012; Pinker 2003; Ver Beek and Louters 1991). However, it is becoming increasingly known that this once universally accepted concept is flawed (Grove and Bretz 2012; Kostrubiec et al. 2012). Students enter classrooms with vast amounts of knowledge on topics (Beskeni et al. 2011) and they synthesize new information with their own previous understanding of the world around them (Bernal 2006; Bretz 2001; Gunstone et al. 2013). This understanding can agree with scientifically accepted knowledge or disagree with scientifically accepted knowledge to varying degrees. It is this disagreement with scientifically accepted knowledge that births student misconceptions (Garnett et al. 1995).

A misconception describes when the understanding of a concept is different from the generally accepted scientific explanation. Taber's (2001) definition of a misconception describes a simple conception that is different from the domain accepted conception or from the desired outcome of teaching. In recent literature, the term misconception has been used to describe students naive or incomplete explanations of scientific concepts which persistently remains despite instructional interventions (Erman 2017; Tümay 2016). Several papers have been published on student misconceptions in chemistry (Birk and Kurtz 1999; Chi 2005; Duis 2011; Erman 2017; Nakiboglu 2003; Nicoll 2001; Othman et al. 2008; Özmen 2004; Peterson et al.

1986; Peterson and Treagust 1989; Schmidt 1997; Singer et al. 2012; Stefani and Tsaparlis 2009; Tümay 2016)

Vosniadou and Skopeliti (2014) also looked at misconceptions in terms of prior knowledge. They describe misconceptions as prior knowledge that is incomplete or differs from accepted scientific explanations. Misconceptions can also arise from previous instruction (Bhattacharyya 2006; Cooper and Klymkowsky 2013b; Sandi-Urena et al. 2011) and this is termed didaskalogenic misconceptions. Didaskalogenic misconceptions are frequently generated by using short cuts and analogies (for examples, lock and key / ball and stick models) that overgeneralize core ideas to save on time in content heavy courses such as General Chemistry (Cooper and Klymkowsky 2013b). Regardless of the definition used, misconceptions are often difficult to recognize and they are sometimes resistant to change if not directly addressed (Birk and Kurtz 1999; Chi 2005; Duis 2011; Erman 2017; Nakiboglu 2003; Nicoll 2001; Othman et al. 2008; Özmen 2004; Peterson et al. 1986; Peterson and Treagust 1989; Schmidt 1997; Stefani and Tsaparlis 2009; Tümay 2016). Misconceptions can be grouped in two types of incorrectness and further classified into four types of conflicting knowledge (Figure 1) (Chi 2013).

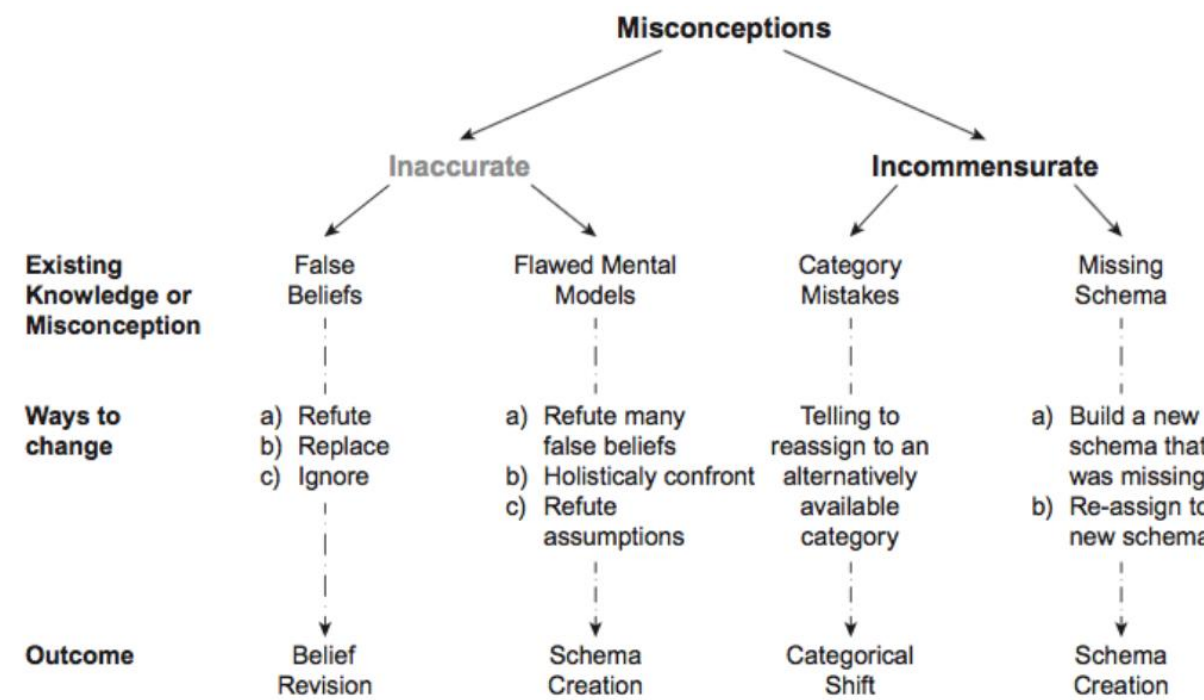


Figure 1. Four types of conflicting knowledge, ways to change and outcomes (from Chi 2013)

Thus, students can arrive into a class such as Organic Chemistry with a vast amount of General Chemistry knowledge that is correct, partially correct or incorrect on vital topics such as chemical bonding (Ayas and Demirbas 1997; Beskeni et al. 2011; Duis 2011; Garnett et al. 1995). Several studies have revealed prevalent and consistent misconceptions across a range of ages and cultural settings on vital topics such as chemical bonding (Ayas and Demirbas 1997; Duis 2011; Nicoll 2001; Özmen 2004; Peterson and Treagust 1989). A common theme emitting from these studies are the misconceptions students possess of chemical bonding and the peripheral topics relating to chemical bonding such as intermolecular forces, bonding polarity, and the octet rule.

Another layer which adds to the varying misinterpretations of a topic is the poor manner in which a particular concept is presented. Bonding, an essential concept to chemists, is often presented in a problematic way which leaves students open to multiple misinterpretations

(Teichert and Stacy 2002). Despite the widely understood notion that covalent and ionic bonds are on a continuum of electronegativity, teachers still present this information as either covalent or ionic, which leaves students to loosely interpret the association of electronegativity to bonding and the concept of a polar covalent bond (Levy Nahum et al. 2010; Taber et al. 2012). Several studies have looked at these misconceptions of polar covalent bonds and electronegativity (Birk and Kurtz 1999; Nicoll 2001; Taber and Watts 1997) and found that, in general, students do not fully understand the concept of electronegativity and its relation to bonding (Cooper et al. 2013; Cooper et al. 2012a).

Here we can see that this combination of poor content administration by teachers along with incorrect prior conceptions can both contribute to the varying misconceptions that are present in students understanding of chemical bonding. Understanding of the concept of bonding is fundamental to subsequent learning of other topics in chemistry, including chemical equilibrium, thermodynamics, molecular structure, and chemical reactions. Thus, an understanding of chemical bonding is crucial to subsequent understanding of chemical reactions, which is one of the fundamental areas of focus in Organic Chemistry. And, although students at different levels have begun to learn this concept from earlier stages of their schooling, there are many studies that report students' difficulties in understanding chemical bonding and that they hold several misconceptions at later stages of their schooling. These misconceptions appear to be resistant to attempts to change them over time, despite increased chemistry education.

2.1.2 Background on Concept Mapping

Assessments of what students already know is a critical component of curriculum change, design and addressing misconceptions (Holme et al. 2010; Singer et al. 2012). Chemistry education researchers use a variety of tools to uncover students' conceptual understanding. These

methods include think-aloud interviews (Bowen 1994; Ericsson and Simon 1998), concept inventories (Barbera 2013; Krause et al. 2004; Libarkin 2008; McClary and Bretz 2012; Pavelich et al. 2004), and concept mapping (Francisco et al. 2002; Greene et al. ; Hay et al. 2008; Lopez et al. 2011; Markow and Lonning 1998; Nakhleh and Krajcik 1994; Nicoll et al. 2001; Plotnick 1997; Ross and Munby 1991; Ruiz-Primo et al. 2001a; Ruiz-Primo et al. 2001b; Yin et al. 2005).

Concept mapping is an ideal tool to assess the depth and breadth of students' knowledge structures; that is, concept maps can indicate how students organize information into their knowledge structure (Novak and Gowin 1984). In addition, concept maps allow us to visualize how students relate various concepts to each other (Plotnick 1997; Wheeldon and Faubert 2009). Several studies have established the validity and utility of concept maps as an evaluation tool (Francisco et al. 2002; Lopez et al. 2011; Markham et al. 1994; Markow and Lonning 1998; Nicoll et al. 2001; Pendley et al. 1994; Ross and Munby 1991; Shavelson 1993; Shavelson et al. 2005; Van Zele et al. 2004). Concept maps are graphical tools used to organize and represent an individual's knowledge by creating relationships between concepts in the form of propositions (Novak and Cañas 2006; Novak and Gowin 1984). Concept maps consist of three components - concept terms, linking arrows, and linking phrases. The linking arrows provide a directional relationship between two concepts while the linking phrases (words linking concepts) represent the specific relationships between a pair of concepts (Novak and Cañas 2006) (Figure 2).

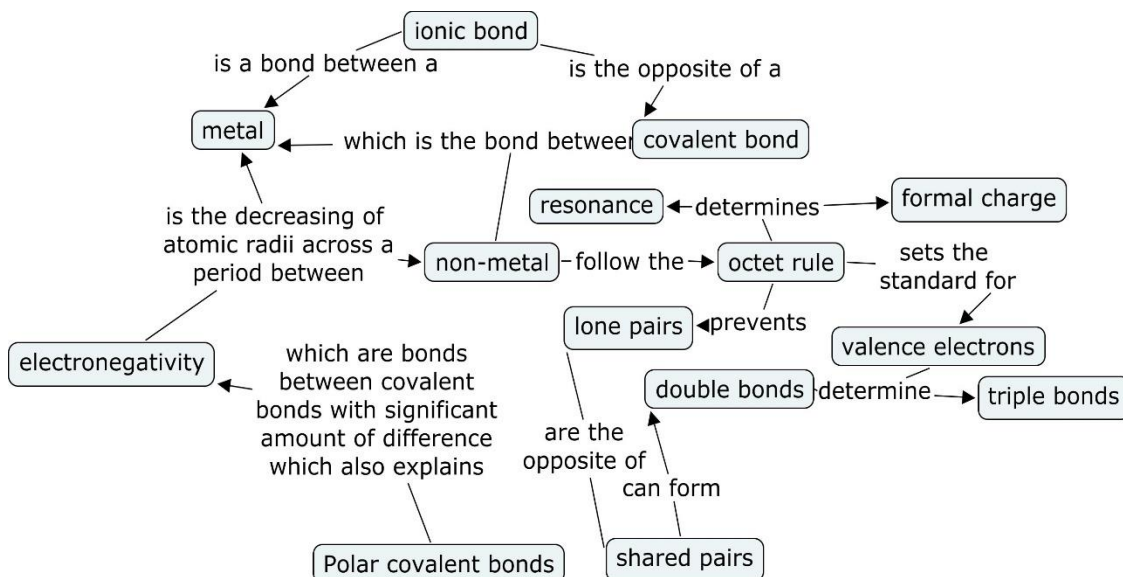


Figure 2. An example of a student-constructed concept map (Burrows and Mooring 2015)

The research literature has given several examples of the use of concept maps in chemistry. For example, Nakhleh and Nicoll (Nakhleh and Krajcik 1994; Nicoll et al. 2001) have used concept maps, generated by the researchers after open-ended interviews, to evaluate students' understandings of acid/base chemistry and bonding. However, our research study focuses on student-constructed concept maps in conjunction with interviews as a way of further probing students' responses on their concept maps. Assessment of student-generated concept maps has been extensively researched. For example, the Shavelson group has produced an extensive body of work establishing multiple ways of scoring concept maps and has validated their use in General Chemistry and Organic Chemistry as assessment and research tools (Lopez et al. 2011; Ruiz-Primo et al. 2001a; Ruiz-Primo et al. 2001b; Szu et al. 2011; Yin et al. 2005). One of their recent studies has demonstrated that concept maps can be used to represent students' knowledge structures in Organic Chemistry. Specifically, their study showed that concept map scores were correlated with scores on problem sets and final course grade (Lopez et al. 2011). There is still a need for additional studies, particularly in chemistry, that examine concept maps as an assessment tool. That is, to determine if concept maps can measure students' knowledge structures of a particular topic.

2.1.3 Purpose of the Study

In this study, we investigate students' knowledge structures regarding the bonding concepts of electronegativity, bond polarity, resonance and Lewis Structures. These topics are built upon in more advanced chemistry and biochemistry courses, considered fundamental knowledge for students in the course, and have interrelated concepts. We focused our study on students enrolled in the first-semester Organic Chemistry course, because we were interested in how their prior understanding of these topics has transferred from General Chemistry.

2.1.4 Guiding Research Questions

We employed a mixed-method primarily qualitative research design (Cope and Elwood 2009) to answer the following research questions:

- RQ1. How well can concept maps uncover students' knowledge structures regarding chemical bonding concepts?
- RQ2. Are there differences in the knowledge structures between students with high scoring concept maps (HS) and students with low scoring concept maps (LS) regarding chemical bonding concepts?
- RQ3. What drawing strategies lead to successful or unsuccessful construction of a Lewis structures?

2.1.5 Significance of Study

Examining students' prior knowledge in terms of their overall knowledge structures will help chemical educators design more meaningful curriculum materials. Concept maps can be used as a pre-assessment and formative assessment tool to analyze students' knowledge

structures regarding a group of related concepts. Chemical educators can determine which concepts and connections need to be more explicitly taught and can address common misconceptions and knowledge gaps.

2.1.6 *Assumptions and Limitations*

This research was conducted with a small number of students (N=16) at a large urban research university. Therefore, the research results and conclusions may have limited generalizability. The use of concept mapping has limitations, in that; it may not reflect every connection that a student can make. Think-aloud interviews also have limitations because we may be unable to uncover the students' thoughts regarding particular concepts despite additional probing. However, in this study concept mapping was used in conjunction with think-aloud interviews to reduce some of the limitations that each method may have when used alone. Despite these limitations, this study provides general trends among students' conceptual understanding of the bonding concepts of electronegativity, polar bonding, resonance and Lewis Structures and opens the door for similar studies in other settings.

2.2 Review of the Literature

Chemistry courses are required for many students across STEM fields. Many topics covered in General Chemistry are fundamental to chemical understanding and are built upon as students advance to Organic Chemistry and Biochemistry. However, the research literature is clear that many students complete General Chemistry but still lack conceptual understanding of several fundamental topics (Cracolice et al. 2008; Mason et al. 1997; Nakhleh 1993; Nakhleh and Mitchell 1993; Pickering 1990; Sawrey 1990). Conceptual difficulties have been uncovered in fundamental topics such as: 1) chemical bonding (Birk and Kurtz 1999; Boo and Watson

2001; Coll and Taylor 2001; Coll and Treagust 2001; Coll and Treagust 2002; Harrison and Treagust 2000; Nahum et al. 2007; Niaz 2001; Nicoll 2001; Othman et al. 2008; Peterson and Treagust 1989; Peterson et al. 1989; Robinson 1998; Tan and Treagust 1999), 2) Resonance (Bhattacharyya 2006; Duis 2011; Nicoll 2001; Zoller 1990) and 3) Lewis structures (Cooper et al. 2010; Nicoll 2003). Currently, chemical educators are giving more thought about what to teach, how to teach, and the appropriate order of topics in General Chemistry (Cooper 2010; Cooper and Klymkowsky 2013b; Gillespie 1997; Lloyd and Spencer 1994). However, despite significant advances in science education research, and more specifically chemistry education research (Singer et al. 2012), the General Chemistry curriculum remains largely unchanged

2.2.1 *Chemical bonding*

Multiple studies have agreed that bonding, an essential concept to chemists, is often presented in a problematic way leaving students open to interpret chemical bonding concepts in a multitude of ways (Birk and Kurtz 1999; Coll and Taylor 2001; Coll and Treagust 2001; Coll and Treagust 2002; Cooper and Klymkowsky 2013b; Erman 2017; Harrison and Treagust 2000; Levy Nahum et al. 2010; Niaz 2001; Nicoll 2001; Othman et al. 2008; Özmen 2004; Peterson et al. 1986; Peterson and Treagust 1989; Peterson et al. 1989; Robinson 1998; Taber et al. 2012; Tan and Treagust 1999; Teichert and Stacy 2002). Several studies have looked at misconceptions of polar covalent bonds and electronegativity (Birk and Kurtz 1999; Nicoll 2001; Nicoll et al. 2001; Taber and Watts 1997) and found that generally students do not fully understand the concept of electronegativity and its relation to bonding.

We recognize that the bonding concept is a continuum rather than a dichotomy (ionic versus covalent) (Bergqvist et al. 2013). However, students in a traditional chemistry curriculum are usually taught these concepts separately as ionic bonding and covalent bonding. Hence, it is

through these lenses that we are analyzing the data in this study as we explore students' understanding of polar covalent bonding. Essentially the study's questions on chemical bonding questioned student's misconceptions in chemical bonding in a concept format that is familiar to the students.

Chemical bonding is one of the most important topics in undergraduate chemistry and the topic involves the use of a variety of models varying from simple analogical models to sophisticated abstract models possessing considerable mathematical complexity (Walsh 2015). It is also a topic that students' commonly find problematic and develop a wide range of misconceptions. The concepts of electron, ionization energy, electronegativity, bonding, geometry, molecular structure, and stability are central to much of chemistry, from reactivity in Organic Chemistry to spectroscopy in analytical chemistry (Luxford and Bretz 2014; Weinhold and Klein 2014). And also, it is important for students to grasp these concepts in understanding why and how chemical bonds occur. Chemical bonding has been classified into a series of three target systems; metallic, ionic, and covalent bonding. However, it is specifically covalent bonding that is greatly utilized in Organic Chemistry. Butts and Smith reported that students were confused about covalent and ionic bonds (Butts and Smith 1987). Peterson et al. investigated Grade-11 and Grade-12 students' misconceptions of covalent bonding and structure. They found that these students did not acquire a satisfactory understanding of covalent bonding. Specifically, 33% of Grade-11 and 23% of Grade-12 held misconceptions regarding the unequal sharing and position of an electron pair in a covalent bond. These students seem to relate electron sharing to covalent bonding, yet did not consider the influence of electronegativity and the resultant unequal electron sharing. As a result of the analysis of the students' responses, some misconceptions were identified. One case study conducted by Taber has investigated students'

understanding of some very basic bonding concepts and found misconceptions dealing with covalent bonding, metallic bonding, resonance structure, coordinate bonding, hydrogen bonding, and van der Waals force (Taber et al. 2012) . In a study reported by Nicoll (2003), it was described the types of misconceptions related to electronegativity, bonding, geometry, and microscopic representations that undergraduate chemistry students hold. According to these results, while students may have appeared to know about the concept of polarity, they did not associate it at all with electronegativity.

Bonding is the key to molecular structure, and structure is intimately related to the physical and chemical properties of a compound. An understanding of the concept of bonding is fundamental to subsequent learning of various topics in chemistry, including chemical equilibrium, thermodynamics, molecular structure, and chemical reactions. Therefore, an understanding of molecular structure based on atomic structure and bonding is crucial to subsequent understanding of chemical reactions. But, although the students at each level have begun to learn this concept from earlier stages of their schooling, as mentioned above, there are a lot of studies reported that students have some difficulties in understanding chemical bonding and hold several misconceptions about it. These misconceptions appear to be resistant to attempts to change them over time, despite increased chemistry education. Chemical bonding misconceptions then appear to fall under the third category of misconceptions in which students possess flawed mental models regarding an interrelated set of concepts. Often the structures of molecules are represented via a Lewis Structure diagram and this represents the core categorical unit in which molecular structure is taught.

2.2.2 Resonance

One study on Organic Chemistry educators' perspectives on fundamental concepts and misconceptions found that of all the participants, more than one of the faculty in the study listed resonance as one of the difficult topics that often brings up misconceptions in students. Specifically, they stated that students often believe that resonance is a fast exchange of electrons, resonance is an equilibrium or resonance states are compounds that exist in real time. (Duis 2011). Some have suggested that the disconnect and production of misconceptions has origins in instruction (Betancourt-Perez et al. 2010). Kerber believed that instructors persist in using a terminology that is clear to experts, but confuses novice students (Kerber 2006). Others even further suggest that even if the concepts of resonance stabilization/aromaticity have been conceptualized by the students, it does not necessarily guarantee their capability to make the connections and apply these relevant gained concept(s) in new situations, even within the same domain (Zoller 1996) .

Bhattacharyya (2006) interviewed ten Organic Chemistry doctoral students about Brønsted acids. It was found that, although students referred to resonance and inductive effects in their explanations, they had incomplete understandings of these ideas. This study is one of the very few studies that has explored the topic of resonance, students understanding on the topic and their ability to connect it to chemical phenomena.

2.2.3 Lewis Structures

Chemistry involves a vast amount of molecular visualization. For Organic Chemistry, key concepts important for student success involve some aspect of molecular representations (Kozma and Russell 2005; Zoller 1996). Moreover, chemists use molecular representations to explain chemical phenomena and to predict the behavior of molecule (Kozma and Russell 2005).

Studies have shown that students have difficulties in correctly interpreting and using various chemical representations (Kozma and Russell 1997). A study by Bodner and Domin (2000) also revealed that the main difference between successful and unsuccessful problem solvers was their ability to accurately understand and translate between various organic structures. Additionally, this study also revealed that unsuccessful students either did not use chemical representations at all or incorrectly used representations when engaged in a problem-solving task (Bodner and Domin 2000). For these unsuccessful students, the representations did not have any real meaning.

Students that complete undergraduate chemistry courses are expected to both reproduce these molecular representations and ascribe appropriate meaning to them. In particular, LS serve as one of the primary starting point for representations that chemists use to explain the physical characteristics of a molecule and to describe chemical reactions (Cooper et al. 2010). Therefore, students' ability to construct Lewis structures is of critical importance to their understanding of chemistry.

As such, many publications have described how LS should be taught, and many of these publications include step-by-step instructions for students to follow (Ahmad and Omar 1992; Ahmad and Zakaria 2000; Brady et al. 1990; Carroll 1986; Clark 1984; DeKock 1987; Eberlin and Monroe 1982; Imkampe 1975; Lever 1972; Logan 2001; McGoran 1991; Miburo 1998; Packer and Woodgate 1991; Pardo 1989; Purser 1999; Purser 2001; Reed 1994; Suidan et al. 1995; Zandler and Talaty 1984). Additionally, instructors have also relied on textbooks as a student resource for Lewis structure drawing methods (Ahmad and Omar 1992; Rabinovich 2003; Suidan et al. 1995). Similar to these various publications, many textbooks also display the LS construction process as a step-wise set of instructions.

Ealy and Hermanson (2006) explained that students' ability to recall rules, and their interpretation of rules learned in General Chemistry, directly influences their ability to correctly interpret chemical representations. Additionally, Taber alluded to the idea that students use 'bootstrapping' to understand particular concepts (Taber 2001).

Although several articles have been published on Lewis structure teaching methods, few detailed studies have been conducted on students' construction of Lewis Structures (Cooper et al. 2010; Nicoll 2001).

A study by Cooper et. al. was the first in-depth investigation of student constructed Lewis Structures (Cooper et al. 2010). The main outcome of this study was that most students saw structural information in Lewis structures, but only about half of the students were able to decipher if Lewis structures provided chemical information. This study also identified five main themes that arose from participants Lewis Structures. First, study participants had a decreased ability to draw feasible structures once molecular complexity increased. Specifically, Cooper et al found that after the critical number of six atoms in a molecule, the participants' ability to draw a correct structure decreased from an 80% correct rate to a 30% correct rate. Second, they discovered that students were less likely to construct a feasible molecule without structural cues. For example, one formula had a structural cue (CH_3OH) and another had a non-structural cue (CH_4O). Upon presenting those two visually different formulae, students correct construction rate dropped from greater than 90% correct for CH_3OH to 60% correct for CH_4O . Third, they discussed the role of symmetry in Lewis Structures construction. Two students drew their structures based on the idea that Lewis structures need to be symmetrical. Fourth, this work found that many students gave expanded or deficient octets to nitrogen or oxygen. It was reported that students added and removed electrons to account for the charges seen in the

structural formulas, which resulted in expanded or deficient N and O molecules or even the formation of radicals. And fifth, as discovered in other studies, (Coll and Taylor 2001; Nicoll 2001) they also observed that students' over emphasized the "octet rule."

This study on students' understanding of Lewis structures has been important to the chemistry education community. Therefore, similar studies on the topic of Lewis structures conducted at various institutions will help chemistry educators gain further insight into the chemistry curriculum in the United States and the reforms that must take place to improve student learning.

2.3 Theoretical Framework

The development of learning theories and interest in understanding how people learn can be found as far back as the days of Aristotle. More recently, this area of research has been influenced by pioneers such as Jean Piaget, B. F. Skinner, and David Ausubel.

2.3.1 *Meaningful Learning*

Students do not arrive in the classroom with a clean slate to which new knowledge is added. Current research has moved towards a constructivist point of view that purports that knowledge is actively constructed by the learner (Ausubel et al. 1968; Bodner 1986). In order for students' knowledge construction to be meaningful, three components are necessary: 1) the student must have some relevant prior knowledge to anchor to new knowledge, 2) the material to be learned must be meaningful in and of itself, and 3) the student must "consciously choose to non-arbitrarily incorporate this meaningful material into her existing knowledge" (Novak 2010). If meaningful learning does not occur, rote learning takes precedence. As a result of rote learning, students are unable to effectively connect new information to their prior knowledge. Another consequence of rote learning is that new material is merely memorized, easily forgotten

and not transferred (Bretz 2001; Novak and Gowin 1984b). The theories of constructivism and meaningful learning highlight the importance of General Chemistry for upper level chemistry courses. Fundamentally, General Chemistry provides crucial prior knowledge for the completion of other chemistry courses. One reason that students struggle with Organic Chemistry and biochemistry is because their knowledge structures of fundamental chemistry concepts are lacking and incoherent.

2.3.2 Knowledge Structures

Chemistry is a complex subject that explores a number of abstract topics and concepts. The understanding of these topics necessitates that students make sense of a number of interrelated concepts and ideas; that is, that they develop coherent knowledge structures. In this study, we define 'knowledge structure' as the schema in which students organize and relate various concepts in order to make sense of a particular topic (Novak 2010; Novak and Cañas 2006). Studies that compare novices and experts agree that experts have a more complex knowledge structure, with many interconnections that are focused around fundamental concepts (Bransford et al. 2000). In contrast, novices then have limited knowledge structures with few connections and fewer cross connections. It follows that if there are gaps in students' understanding or missing conceptual links, learning new material or incorporation of new concepts into a disjointed knowledge structure will be difficult. While appropriate conceptions provide a stepping-stone to a new understanding, incorrect, low quality, missing, or fragmented knowledge can act as barriers (Taber, 2003b). A misconception describes when the understanding of a particular concept is different from the generally accepted scientific explanation (Taber 2002).

There are several theories that attempt to describe the origin of misconceptions and how to elicit conceptual change. For example, Chi proposes that students' misconceptions can be put into three levels (Chi 2008). These three levels are: 1) incorrect beliefs at the level of a single idea, 2) assigning concepts to incorrect categories, and 3) flawed mental models that apply to interrelated concepts. How these misconceptions are addressed depends on which level they reside. Misconceptions assigned to the third level are highly robust, resistant to change, and require the correction of several incorrect beliefs (Chi 2005). Another perspective on misconceptions suggests that students' concepts are coherent, interrelated, and can be described as a naïve "theory" (Vosniadou 1994). In contrast, diSessa proposed that students' concepts are not theory-like, but are fragments or pieces that are not put together in a coherent manner (diSessa 2008; diSessa and Sherin 1998). Regardless of which theory one ascribes to, they all suggest that an essential part of conceptual understanding is the relationship students make between concepts.; that is, their knowledge structures.

Essentially, the knowledge structure of a student gives insight into the organization and connections that student has between various concepts (Novak 2010; Novak and Cañas 2006). Through these connections, the conceptual understanding a student possesses on a particular topic can be observed as well as their misconceptions. Therefore, tools that can correctly show a student's knowledge structure are beneficial to uncovering their misconceptions

2.4 Methodology

This study was conducted in three parts. First, Organic Chemistry the study participants were taught how to construct a concept map. A subset of words relating to chemical bonding concepts were chosen to develop a list of concepts for students to connect while constructing their concept maps. Second, the Organic Chemistry participants were give the list of chemical

bonding concepts to construct their own map. Lastly, they were given a set of problems to complete in a think aloud interview. Data from these interviews informed, validated and provided additional insight into the claims made during the student constructed concept maps.

2.4.1 *Participants and Settings*

The study presented here represents one interview of a three-interview study conducted at a large, urban, research-intensive university in the southeast United States. Participants completed one interview on each of three topics – Lewis structure and bonding, molecular geometry and acids and bases. A total of sixteen undergraduate students (N=16), participated in the first interview. Herein, we will only focus on the first interview regarding bonding concepts.

Homogenous sampling was used to recruit participants for this study. This sampling technique was used to specifically describe the group of first-semester Organic Chemistry student's in-depth (Teddlie and Yu 2007). To this end, only students enrolled in the Organic Chemistry course for the first time were selected for the interview. To recruit these participants, an announcement was made during the first day of the course by a graduate student researcher (see Appendix), which was then coupled with a follow-up email (see Appendix). In attempts to assess prior knowledge, student interviews were scheduled within the first two weeks of the course. At the time of the interview, a review of General Chemistry topics was just beginning.

Students selected for this study were all enrolled in a first-semester Organic Chemistry course that carried a load of four credit hours. Of the 16 participants, nine were biology majors, three were chemistry majors, three were psychology majors, and one student was a nursing major. Students in the study identified as Asian (6 students) or African-American (10 students). Student grades in General Chemistry varied from 'A' to 'C'. Student participation in the study was voluntary and informed consent was obtained. Each student received a \$10 gift card for

participating in the interview. To protect their identity, their names were replaced with pseudonyms. The Institutional Review Board of the University approved the study in August 2012 (see Appendix).

2.4.2 Research Design

The interview took place during the first two weeks of the Spring 2013 semester. The interviews were conducted in the following format: 1) Concept map tutorial 2) Concept mapping and 3) Think-aloud problem solving.

2.4.2.1 Concept Map Tutorial

Most students in the study had little to no exposure to concept maps. Thus, to eliminate the probability of receiving poorly constructed concept maps due to unfamiliarity with the concept map software, students were given an in-depth tutorial describing a concept map and informing on how-to construct a concept map. Each tutorial (Appendix C-1) provided a number of examples of varying complexity degrees of concept maps. Participants also received a one-on-one concept map construction demonstration.

2.4.2.2 Concept Mapping

After a hands-on tutorial on how to construct concept maps, the participants were asked to construct their own concept map using only the 14 terms (Figure 3) given to them (Ruiz-Primo et al. 2001b). The terms for the development of their concept maps were derived from end-of-chapter key terms from two textbooks (McMurry 2007; Tro 2010). Two course instructors reviewed the terms and adjustments were made based on their suggestions. Research participants

utilized the *CMap Tools* software (IHMC 2013) to construct their concept maps. This software allowed participants to move concept terms around and easily add arrows and linking phrases.

Octet Rule	Resonance
Formal Charge	Valance Electrons
Double Bond	Ionic Bond
Triple Bond	Electronegativity
Lone Pair	Metal
Polar Covalent Bond	Non-metals
Covalent Bond	Shared Pair

Figure 3. The 14 Concept terms used by students for constructing concept maps

2.4.2.3 *Think-aloud Problem Solving*

In the think-aloud portion of the interview, students were asked to say what they are thinking and doing as they solved various problems. Think-aloud protocol is a popular strategy used to explore students' conceptual understanding (Bowen 1994; Ericsson and Simon 1998) and has also been used to investigate problem solving in chemistry education. The problems used for the "think-aloud" section were taken from the Peterson and Treagust bonding concept inventory, (Peterson and Treagust 1989; Peterson et al. 1989) and a General Chemistry text book (Tro 2010). Students also completed the Implicit Information from Lewis Structures Instrument (ILLSI) (Figure 4) (Cooper et al. 2012a). The ILLSI was used at the beginning of the interview to get students thinking about Lewis structures and bonding concepts before they began working on the problems.

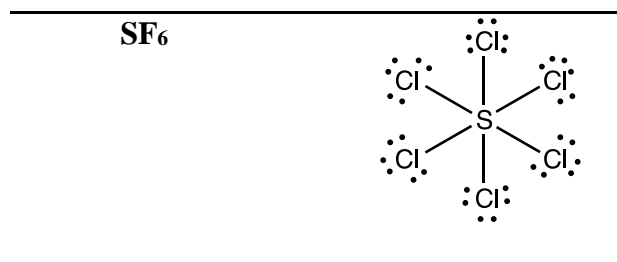
What information could you determine using a Lewis structure and any other chemistry knowledge you may have? (Mark all that may apply)

<input type="checkbox"/> Hybridization	<input type="checkbox"/> Intermolecular forces
<input type="checkbox"/> Polarity	<input type="checkbox"/> Formal charges
<input type="checkbox"/> Element(s) present	<input type="checkbox"/> Relative melting point
<input type="checkbox"/> Reactivity	<input type="checkbox"/> Geometry/shape
<input type="checkbox"/> Type of bond(s)	<input type="checkbox"/> Physical properties
<input type="checkbox"/> Relative boiling point	<input type="checkbox"/> Number of valence electrons
<input type="checkbox"/> Number of bonds between particular atoms	<input type="checkbox"/> Potential for resonance
<input type="checkbox"/> Bond angle	<input type="checkbox"/> Acidity/basicity
<input type="checkbox"/> No information	

Figure 4. Implicit Information from Lewis Structures Instrument (ILLSI) (Cooper et al. 2012a)

Students were then given problems to solve via a think-aloud protocol. The problems given were used to probe for some of the concepts represented in the concepts maps. Lewis Structure questions were also given to assess their Lewis Structure construction abilities.

Students were requested to construct five Lewis Structures from the given molecular formulas (Figure 5). Before the interview, students were asked: “In general, how do you go about drawing a Lewis structure?” Participants were also asked whether they were familiar with or have seen each of the Lewis Structures before to indicate whether that information may play a role in their Lewis Structure construction. Students then proceeded to draw each Lewis Structure and explain their drawing process. Follow up questions regarding their drawings were also asked.



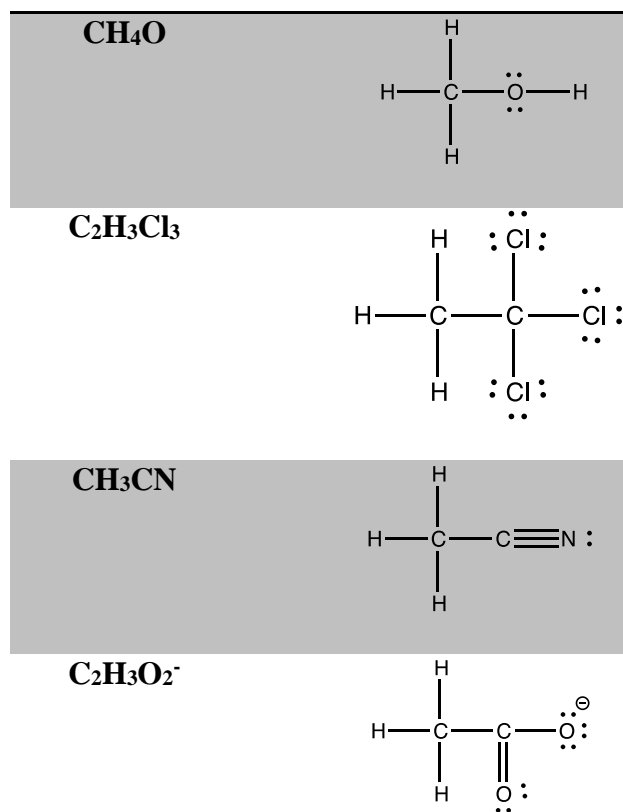


Figure 5. Lewis structure construction molecule list

The five structures of varying difficulty were chosen to both reflect Lewis Structures that students may have already seen in a General Chemistry course and Lewis Structures they may have encountered in their current Organic Chemistry course. The list included (Figure 5): a structure that did not conform to the octet rule (SF_6); a structure in which the molecular formula had no structural cues for the Lewis Structure (CH_4O); a structure containing multiple bonds (CH_3CN), and a structure with a negative charge ($\text{C}_2\text{H}_3\text{O}_2^-$). Throughout the interview, students had access to a periodic table. The goal of this portion of the study was not solely to determine if students could correctly draw these Lewis Structures, but rather to further investigate the misconceptions, strategies and rules students used to construct Lewis Structures. The think-aloud portion of the interview was video and audio recorded.

2.4.3 *Data Collection/Analysis*

Participants were assigned unique identification numbers and pseudonyms. All identifiable information, including the participants' consent forms, pseudonym code sheet, and surveys were stored in a locked filing cabinet. Audio recordings and notes related to these recordings were stored on a secured, password-protected computer. Documents were kept up to three years following the completion of the study. If at any time, a participant chose to cease participation in the study, his/her information was destroyed.

2.4.3.1 *Concept maps*

Concept maps were scored by two senior chemistry doctoral students using the following four-level scale (Lopez et al. 2011; Szu et al. 2011): 0 - incorrect or scientifically irrelevant, 1 - partially incorrect, 2 - correct but scientifically 'thin' (i.e. technically correct but answers are too general and/or vague), and 3 - scientifically correct and precisely stated. Each proposition in the concept map was assigned the average of the scores given by the two doctoral students. Each proposition in the concept maps was given a score between 0 and 3 according the grading scale, and then the total score for all the propositions in the map was given to each student. An example of the grading of one students' concept map is shown in Table 1. We used the sum score because: 1) there is literature precedence that provides evidence that using a sum total for each concept map is a good indicator of a students' conceptual understanding (Ruiz-Primo, 2001) and 2) to account for the variety of links that can be made by students. We also determined the *saliency score* for each concept map. The *saliency score* is defined by the proportion of valid propositions (scoring ≥ 2) out of all the propositions in the student's map.

Table 1. Example of complete scoring chart for one students' concept map

Concept 1	Linking Phrase	Concept 2	Grader 1	Grader 2	Average
Valence Electrons	can also be	Lone Pair	2	2	2
Valence Electrons	can also be used to create a	Double Bond	2	2	2
Valence Electrons	can also be used to create a	Triple Bond	2	2	2
Valence Electrons	uses the extra electrons of a molecule called	Ionic Bond	0	0	0
Lone Pair	is the opposite of a	Shared Pair	2	2	2
Ionic Bond	deals with a	Metal	2	2	2
Ionic Bond	is the opposite of a	Covalent Bond	0	2	1
Resonance	structures use different types of bonds such as	Covalent Bond	2	1	1.5
Covalent Bond	is related to	Polar Covalent Bond	2	2	2
Covalent Bond	deals with	Non-metal	2	2	2
Metal	can be	Electronegativity	0	0	0
Metal	have a positive	Formal Charge	1	0	0.5
Electronegativity	determines an atom's	Formal Charge	1	1	1
Total Score					18

2.4.3.2 Coding of Bonding Data

The audio and video recording from the think-aloud portion of the interviews were transcribed. The interview transcripts were analyzed for emergent themes using an open coding strategy (Corbin and Strauss 2008). Codes were then refined through revision of the original codes and the constant comparison method (Glaser and Strauss 1967). The first researcher (NLB) initially coded the transcripts of the interviews. Then, the codes were discussed and refined by

collaborative coding with the second researcher (SRM). After that process, the first researcher (NLB) completed the final coding. Then to establish reliability, the other researcher analyzed two interviews using the final codes and greater than 90 percent agreement between the two researchers was reached.

2.4.3.3 Coding of the Lewis Structure Data

The transcripts for the Lewis Structure portion of the interviews were paired with their respective Lewis Structure drawing and coded for misconceptions, strategies or reasoning used to construct each structure. In addition, each student's Lewis Structure was also examined and designated as correct or incorrect. All of the participants' drawings, strategies and use of rules were compared to uncover the general themes for students who drew the structure incorrectly and those who drew it correctly. An example codebook is shown in the appendix (Appendix D).

2.5 Research Findings

2.5.1 Chemical Bonding

Since only 16 students participated in the study, only the descriptive statistics are presented (Table 2). The average concept-map score and the salience score were obtained for each student.

Table 2. Descriptive statistics for N=16 students in the study

Map Components	Mean	SD	Minimum Score	Maximum Score
# of Propositions	14	3.0	10	21
# of accurate Prop (≥ 2)	7	3.4	2	12
Sum Score	23.6	7.0	12	35.5
Salience Score	0.5	0.2	0.17	0.92

Students made an average of 14 propositions of which half were accurate. The average sum score on participants' concept maps was 24. Concept maps scores ranged from 12 to 35. The

sum concept map scores were used to partition the students into high, medium and low scorers. These divisions gave us a way of comparing students with low scoring concept map scores (LS) to students with high scoring concept map scores (HS) (Figure 6).

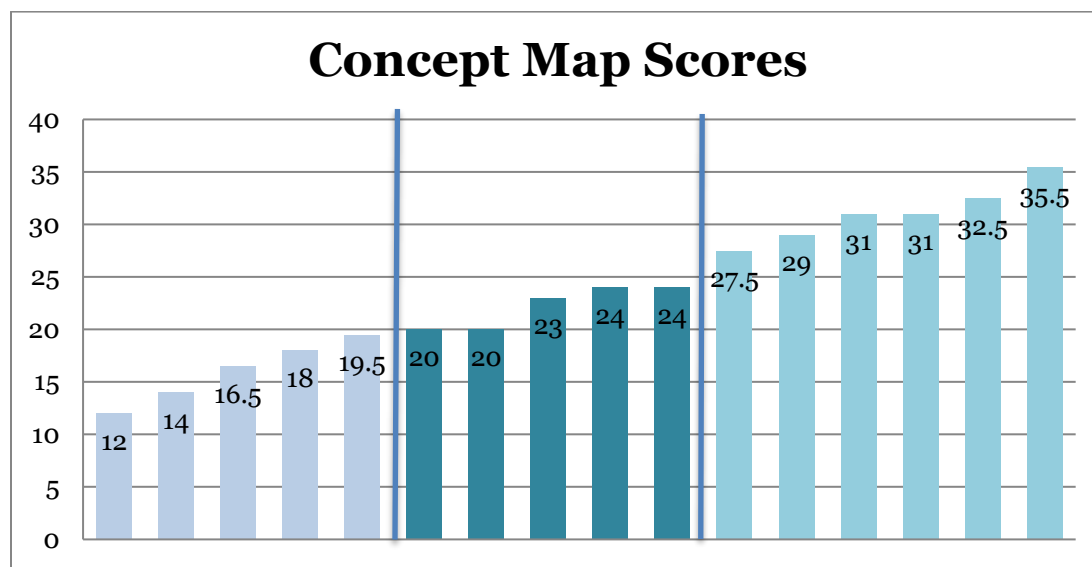


Figure 6. Graph showing the distribution of concept map scores for the 16 participants into low, medium and high scoring concept maps.

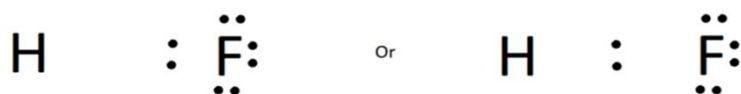
A number of recurring themes emerged regarding the topics of electronegativity and polar covalent bonds. The concept maps for all participants were evaluated for the connections they made with these concepts. Additionally, each student's interview was evaluated to determine which interviews from the LS and HS groups had the richest data.

Electronegativity and Polar Covalent Bond

During the interview, each participant was presented with a question from the Peterson and Treagust bonding concept inventory (Peterson and Treagust 1989; Peterson et al. 1989) to probe their understanding of electronegativity and polar bonding (Figure 7). They were initially presented with the main question without the four distractors and asked to predict the position of

a shared electron pair between the HF molecule. After their initial explanation, students were shown the distractors and asked to choose an answer.

Which of the following best represents the position of the shared electron pair in the HF molecule?



- Non-bonding electrons influence the position of the bonding or shared electron pair.
- As hydrogen and fluorine form a covalent bond the electron pair must be centrally located
- Fluorine has a stronger attraction for the shared electron pair.
- Fluorine is the larger of the two atoms and hence exerts greater control over the shared electron pair.

Figure 7. Electronegativity probing question

Table 3. Shows each participant's pseudonym, their sum concept map score, and whether or not they correctly answered the electronegativity question (before and after seeing the distractors).

Student	Concept Map Score	Correct answer before distractors shown?	Correct answer after distractors shown?
Lori	12	No	No
London	14	No	No
Linda	16.5	No	Yes
Liza	18	No	No
Luanne	19.5	Yes	No
Alexa	20	Yes	Yes
Angel	20	Yes	No
Ashley	23	Yes	Yes
Ana-Marie	24	No	No
Abby	24	Yes	Yes
Hayden	27.5	Yes	No
Harper	29	Yes	Yes
Haley	31	Yes	Yes
Helen	31	Yes	Yes
Hilda	32.5	Yes	Yes
Holly	35.5	Yes	Yes

Understanding of electronegativity was weak among LS students compared to HS students. Several common misconceptions of electronegativity were revealed through student interviews. The most prevalent misconception was that “*electronegativity is determined by the number of electrons around an atom.*” One example of this misconception comes from a senior undergraduate student, Luanne. Luanne had a concept map score of 19.5 and circled the first answer. This indicated that she believed the shared electron pair in the HF molecule would gravitate more towards the fluorine atom. Further probing revealed that despite her correct response, she possessed flawed ideas. After seeing the distractors, she responded:

I chose D because it says, ‘Fluorine is the larger of the two atoms and hence exerts greater control of the shared electron pair.’ I chose that because according to the number of valence electrons, it has seven and hydrogen has one, so therefore, when you're thinking of electronegativity, it pulls more [directs hands in a pulling motion] -- it pretty much, like, since they are non-metal, it wants more electrons than hydrogen does. The hydrogen always gives away and the fluorine always gets because they're trying to fulfill the octet rule.

Here we see that Luanne views electronegativity as a property that has to do with the number of valence electrons. Closer inspection of her concept map regarding electronegativity also indicated that Luanne had this misconception of electronegativity that involves valence electrons. Her concept map proposition states: ‘Valence Electrons are involved in Electronegativity’ (Figure 8).

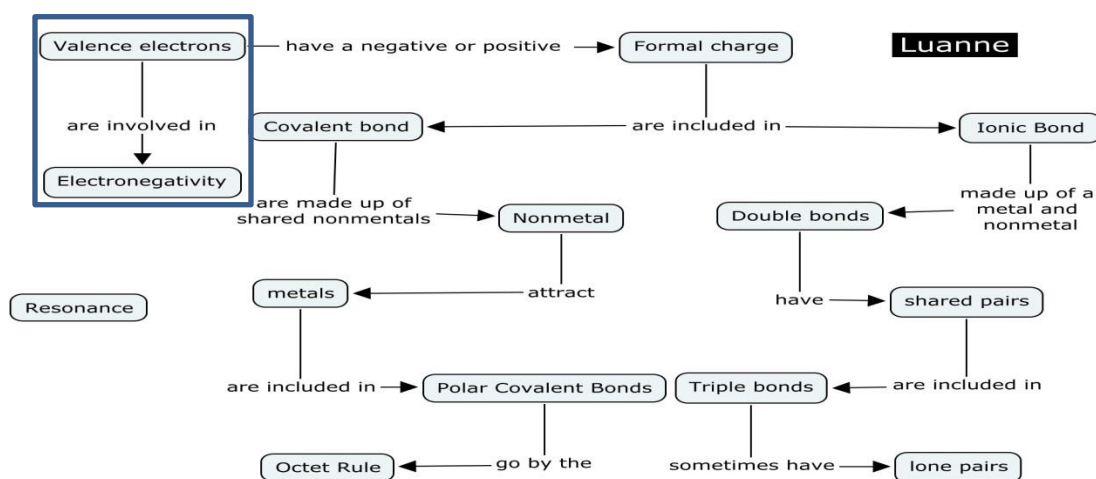


Figure 8. Concept map for Luanne highlighting electronegativity concept map link

Further examination of Luanne's interview reveals a lack of understanding of electronegativity, which in turn leads to a misunderstanding of polar and ionic bonding. In her interview she stated, "The hydrogen always gives away and the fluorine always gets because they're trying to fulfill the octet rule." Here Luanne seems to be categorizing HF as an ionic bond rather than a polar covalent bond. Her concept map also highlights her confusion between ionic and polar covalent bonds. Her concept map proposition linking formal charge was: "Formal charge[s] are included in ionic bond". This proposition received a score of 0.5 and seems to imply that she associates formal charge with ionic bonding.

Another common misconception revealed during the interviews was the belief that *shared electron pairs should be centrally located*. As observed in previous studies (Nicoll 2001; Peterson et al. 1986), the position of the shared electron pair was often stated as centrally located by LS students. A good example of this comes from London, a senior pre-med student with a low-scoring concept map score of 14. During the interview, London circled the HF molecule with the shared pair centrally located and defended his answer by saying:

London: [points to picture with electron equally between fluorine and hydrogen] I'm thinking it's this one because it just like -- because there's nothing over here at all [points to picture that has electrons closer to fluorine]. But yeah, I mean I've never seen anything like quite like this before though. Like I've never seen this before or like that. Because like I think H is just there, and like I don't know.

Interviewer: What do you mean by the H is just there [referencing first drawing]?

London: Like it's [H molecule] over by itself. That's why I would think it's this [points to centrally located pair drawing] because like over here in this thing [referencing first drawing], you kind of don't even see this. It's supposed to be HF, but this is -- I don't know, I'll say that. I don't know.

Interviewer: [Turn over paper to show distractors] So similarly you can choose the best reason or fill in your own.

London: Yeah, this sound about right [circles B – As hydrogen and fluorine form a covalent bond the electron pair must be centrally located].

Interviewer: Why did you choose B?

London: Because B looks like -- B like bread just like this sounds the same [as my reasoning] like because it said that the electron must be centrally located for him to form a covalent bond and that's what exactly what this looks like. Because the electron pair is centrally located, so I guess they're about to form a covalent bond.

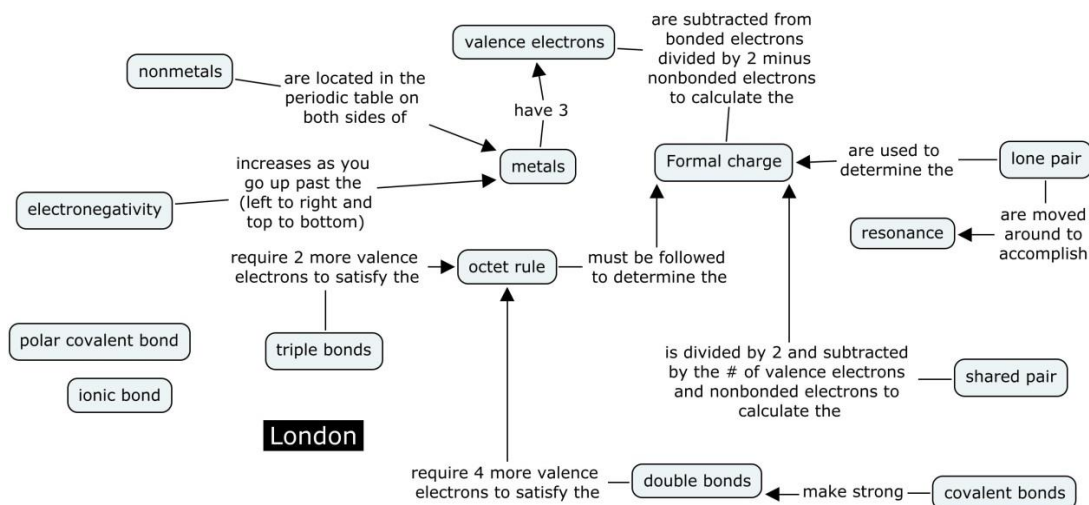


Figure 9. London's Concept Map

Part II

What information could you determine using a Lewis structure and any other chemistry knowledge you may have? (Mark all that may apply)

- | | | |
|--|--|---|
| <input checked="" type="checkbox"/> Hybridization | | <input type="checkbox"/> Intermolecular forces |
| <input type="checkbox"/> Polarity | | <input checked="" type="checkbox"/> Formal charges |
| <input checked="" type="checkbox"/> Element(s) present | | <input type="checkbox"/> Relative melting point |
| <input type="checkbox"/> Reactivity | | <input checked="" type="checkbox"/> Geometry/shape |
| <input checked="" type="checkbox"/> Type of bond(s) | | <input checked="" type="checkbox"/> Physical properties |
| <input type="checkbox"/> Relative boiling point | | <input checked="" type="checkbox"/> Number of valence electrons |
| <input checked="" type="checkbox"/> Number of bonds between particular atoms | | <input type="checkbox"/> Potential for resonance |
| <input checked="" type="checkbox"/> Bond angle | | <input type="checkbox"/> Acidity/basicity |
| <input type="checkbox"/> No information | | |

Figure 10. IILSI from London's Interview

Throughout the entire interview, London never made any mention of electronegativity despite being questioned about polarity. London made no connections with the term ‘polarity’ on his concept map (Figure 9). In addition, London did not tick the word ‘polarity’ on the IILSI (Figure 10). When probed as to why ‘polarity’ was not checked on the IILSI London responded:

London: Because like on the last thing [referencing the concept map construction], I'm not like really familiar with that.

Interviewer: So in regards to, what do you know about polarity?

London: Like with water, like --

Interviewer: You can elaborate?

London: Like hydrophobic, hydrophilic and stuff like that. And polar like -- because if something is polar that means it likes water. Yeah, so.

Interviewer: So polarity you don't associate with Lewis structure?

London: I don't, no. But I'm pretty sure that it's somewhere in there but I don't know.

Overall, London's interview confirms a limited understanding of electronegativity and polarity. The combination of interviews, problem sets and concept mapping highlighted students' inability to make meaningful connections among and between those concepts. London, like other LS students, did not have a clear understanding of the concept of electronegativity, which in turn connects to their limited understanding of polar covalent bonds and polarity.

In contrast, HS students displayed a good understanding of the concept of electronegativity and polar bonding. Unlike the LS students, the HS students all checked the term polarity on their ILSI indicating that they understood that polarity was an implicit concept relating to Lewis structures. Table 4 shows a list of all the links made with polar covalent bond by the HS students. The majority of their propositions received a scored 2 or greater.

Table 4. List of Polar Covalent bond links made by HS students

Concept 1	Linking Phrase	Concept 2	Link Score
Polar covalent bonds	is electronegatively different from	Covalent bond	2
Polar covalent bonds	involves	Electronegativity	2
Electronegativity	determines polarity	Polar covalent bond	3
Polar covalent bond	are between two polar	nonmetals	1
Covalent bond	has a sub group called	Polar covalent bond	2
Polar covalent bonds	have	Lone pair	1.5
Covalent bond	with a net dipole moment is considered a	Polar Covalent Bond	3
Electronegativity	determines whether or not a bond is a	Polar Covalent Bond	2.5
Polar covalent bond	has between 0.4 and 2.0 in	Electronegativity	2

Holly is an HS student with a concept map score of 35.5. During the interview, Holly correctly chose the HF molecule with the shared electron pair closest to the fluorine atom (Figure 7). When asked about her reason for choosing that answer she responded:

Holly: [points to HF molecule with the shared electron pair closest to the fluorine] This one. Well, oh yeah [fluorine] is more electronegative, so fluorine would be more electronegative than hydrogen, therefore the electrons are pulled towards the fluorine atom, therefore this would be closer, meaning it's this one [circles HF molecule with the shared electron pair closest to the fluorine].

Interviewer: Okay. So why did you choose that?

Holly: Because the -- in this one the electrons look like they're equally distributed between these two atoms, when it's -- because this [Fluorine] is more electronegative, it's [points to electron pair] more toward the more electronegative atom.

Interviewer: Okay. Based on this question can you choose an answer?

Holly: Okay [circles C - fluorine has a stronger attraction for the shared electron pair].

Interviewer: Okay, why didn't you choose D [Fluorine is the greater of the two atoms and hence exerts more control over the electron pair]?

Holly: Oh, actually I didn't even read it yet. So, maybe I should read it. Can I just read it? Okay, I don't think size has to do with any effects the electrical pull between two atoms. I think it's just really more of how polar the different atoms are.

Holly, unlike the LS students, has a clear understanding of the role electronegativity plays in directing the position of the shared electron pair in the HF molecule. Her understanding of electronegativity is further magnified by her ability to sort through why the distractor D (Fluorine is the larger of the two atoms and thus exerts greater control over the shared electron pair) is incorrect.

Additionally, many LS students were confused between the periodic trend of size and electronegativity. For example, Lacy could not distinguish between size and electronegativity when looking at answers C (Fluorine has a stronger attraction for the electron pair) and D (Fluorine is the larger of the two atoms and hence exerts a great control over the shared electron pairs). Specifically, Lacy stated:

C and D is similar to me just kind of based on the fluorine. Not only is it larger, I mean, it is stronger. It has a stronger attraction...Fluorine would be -- it does have a stronger attraction and a higher electronegativity. So, I think that it would take -- I was going to say it would take the H. But these answers are similar, I mean to me, just kind of -- it's the larger of the two and it's exerts greater control. So, I would change D and I'll use C instead because it does have a stronger attraction, which will bring the electron to the F.

The clarity to which HS students understand electronegativity is further exemplified in their recognition of the concepts examined in the study. In the probing HF question, Helen was able to recognize the concepts being assessed despite her initial misinterpretation of the problem. She initially chose the incorrect answer and was further questioned about her response:

Interviewer: So, on to the next question. Which of the following best represents the position of the shared electron pair in the HF molecule?

Helen: The position of it? Okay. This one [points HF molecule with the shared pair centrally located].

Interviewer: Okay. Now why did you choose that one?

Helen: Because it's [referencing shared electron pair] in the middle, and you can see that they're sharing it.

Interviewer: Okay. So what do you mean by that?

Helen: Honestly, I'm just going off of the word sharing. So well shared, and for me, I would write it in the middle to show that they're sharing it. And over

here, it looks like this one, the F, has it more. Like it's just hogging it. And it's just for that and that this is on its own like they're two separate things.

Interviewer: Okay. Okay. So, what is your reasoning [Turn over page and shows distractor answers]?

When Helen saw the distractors, the meaning of the question became clearer:

*Helen: Okay, now that I see what you want [looks at the options and points to the word electronegativity] -- well, I don't know. I'm going to put my own reasoning, but it's because how I took the question literally. Like, yeah. Not based off of how much one pulls electrons toward it. So, I'm going to say because. But that's because -- oh, because I said the first image doesn't seem like they are sharing the electrons. And that's because when I read the sentence, or you read the sentence, I thought you just meant literally does the image look like they share the electrons. **But reading these, I think what you wanted more is to see if the F pulls the electrons more towards itself, or does the hydrogen pull them? Or do they share them equally?***

Interviewer: So, what do you think, based on that interpretation?

Helen: Based on that, then I think it would be the first one [first picture in the problem] because F is more electronegative than the H. And then hydrogen only has one electron, and it's usually more positive.

A number of misconceptions were revealed during this interview and Table 5 below shows a summary of the three major electronegativity misconceptions revealed during the interviews along with an example of that code.

Table 5. Major codes revealed through the interview

Code Name	Code Description	Example
Valence electron determines electronegativity	The amount of valence electrons surrounding an atom determines how electronegative an atom will be	<i>Angel: Well, the one single electron is taken from the hydrogen and shared with the F molecule. Since it's stronger... I mean, more electrons making it stronger than the hydrogen.</i>
Larger equal more electronegative	The larger the atom the more electronegative	<i>Harper: Fluorine? Fluorine is bigger, right? I think it's from physics: the greater a mass, the greater the attraction. So, it does make sense too.</i>
electronegativity has no effect on bonding	When molecules form a covalent bond, despite the presence of electronegativity, there is no effect on the position of the shared electron pair	<i>Ana-Marie: Well, I know fluorine has a higher electronegativity than hydrogen, but I don't think that affects like the position...when you draw the Lewis structure, if one's stronger, you don't draw like a longer line because that one's stronger...I still feel like it would be this one because they're sharing it</i>

Resonance

Another emerging theme was resonance and the various degrees of understanding students possessed of resonance. Resonance is often a topic many students are exposed to in General Chemistry; however, many students have poor understanding of resonance. It was found that three of the five students in the lower third made no connections with the term “resonance” on their concept map; however, understanding of resonance was generally poor overall. Table 6 highlights this lack of connection that participants in the lower third made with resonance on their concepts map as well as their overall C-Map scores.

Table 6: Students' pseudonyms, C-Map score and concept links that arose during the interview

Student	Concept Map Links (score in parenthesis)	Sum concept map score
Lori	Electronegativity shows a compounds resonance (0) Resonance structures have a double bond (1.5)	12
Lamar	No link made	14
Linda	No link made	16.5
Liza	Resonance structures use different types of bonds such as covalent bond (1.5)	18
Luanne	No link made	19.5
Alexa	Resonance structure can be drawn multiple ways and still have the same meaning much like a triple bond (0.5)	20
Angel	Resonance involves carbons with alternating double bond (2)	20
Ashley	Octet rule determines resonance (1.5)	23
Ana-Marie	Nonmetals can form resonance structures (2.5)	24
Abby	Resonance structures can have different elements with lone pairs (1) Resonance structures can be used in a formula to find the formal charge (1)	24
Hayden	Double bonds move across the structures of resonance (1.5) Non-metals have resonance (1.5)	27.5
Harper	Lone pair can be moved in order to make structured that are resonance (2)	29

Haley	Resonance is a way to ensure stability in the compound without completely filling the outer electron shell an element, which is known as octet rule . (2)	31
Helen	Double bond might have to do with resonance . (2)	31
Hilda	Resonance structures will show any lone pair (2.5) Double bonds can be drawn differently as a lewis dot structure to determine resonance (3)	32.5
Holly	Resonance can change an atom's formal charge (2.5) Resonance structures can alter the geometric form of a molecule using valence electrons (1.5) Resonance are not limited to ionic bond (1) Resonance are not limited to covalent bond (1)	35.5

Linda, an aspiring pediatrician with a C-map score of 16.5, made no connection with the term resonance along with formal charge, octet rule and valence electrons (Figure 11). This lack of connection on her concept map gave a good indication of her limited knowledge on resonance.

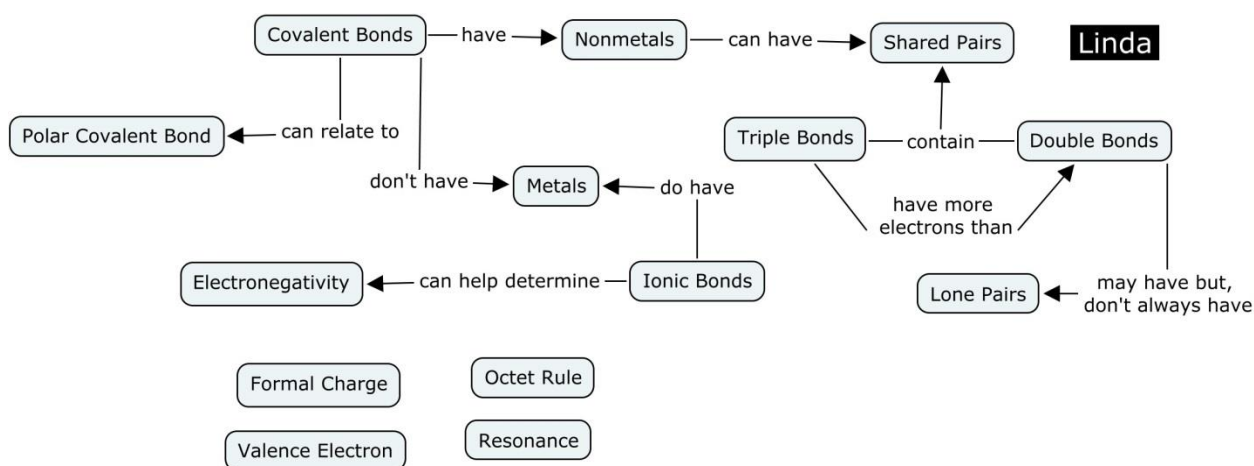


Figure 11. Concept map of Linda (C-map Score 16.5)

During her interview, Linda ticked most of the items on the IILSI with the exception of geometry and potential for resonance (Figure 12). This further magnified her lack of knowledge on the topic of resonance and her inability to see a connection between Lewis Structures and resonance. When questioned about her inability to select potential for resonance on the IILSI Linda responded:

Linda: And this one? I don't remember that word. So that's why I didn't pick that one.

Interviewer: Resonance?

Linda: Yes. Because I didn't do it for the other one [refencing C-map] we just did.

Interviewer: So, you don't remember resonance at all inside of chemistry?

Linda: No.

What information could you determine using a Lewis structure and any other chemistry knowledge you may have? (Mark all that may apply)	
<input checked="" type="checkbox"/> Hybridization	<input checked="" type="checkbox"/> Intermolecular forces
<input checked="" type="checkbox"/> Polarity	<input checked="" type="checkbox"/> Formal charges
<input checked="" type="checkbox"/> Element(s) present	<input checked="" type="checkbox"/> Relative melting point
<input checked="" type="checkbox"/> Reactivity	<input type="checkbox"/> Geometry/shape
<input checked="" type="checkbox"/> Type of bond(s)	<input checked="" type="checkbox"/> Physical properties
<input checked="" type="checkbox"/> Relative boiling point	<input checked="" type="checkbox"/> Number of valence electrons
<input checked="" type="checkbox"/> Number of bonds between particular atoms	<input type="checkbox"/> Potential for resonance
<input type="checkbox"/> Bond angle	<input checked="" type="checkbox"/> Acidity/basicity
<input type="checkbox"/> No information	

Figure 12. Linda's IILSI depicting her lack of connection between resonance and Lewis Structures

This inability to recall resonance translates to either Linda's unexposed General Chemistry background or the lack of connection inside her chemistry background. This

deficiency of knowledge also transcended into her problem-solving ability. During the interview, Linda was asked to provide an appropriate resonance structure for the molecule below:

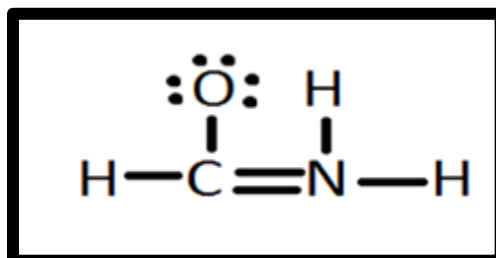


Figure 13. Structure of formamide given during interview

In her response, Linda was unable to correctly determine the resonance structure despite her reliance on other information to determine the correct resonance structure. During her interview, Linda relied on her knowledge of Lewis Structures to determine a correct resonance structure.

Linda: I'm counting the electrons, and then trying to match them up...

Interviewer: So, what are you thinking about that one [see below]?

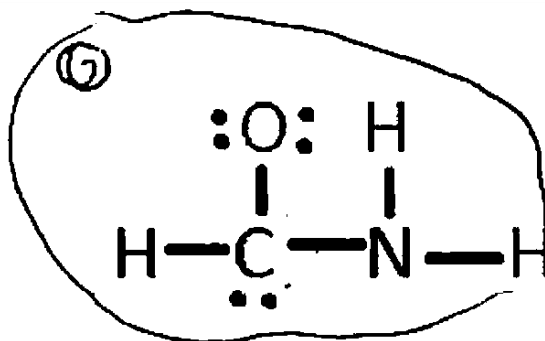


Figure 14. Linda's resonance structure choice for formamide

Linda: I'm trying to count them all. I'm trying to.

Interviewer: And when you're counting these, what are you doing?

Linda: I'm trying to see if it matches with this [original structure, see figure 13], or if it just matches in general, with how many electrons they have, or what they're sharing. But I don't know what resonance means, so that's what's going to mess me up with this one.

Linda eventually ended up selecting Figure 14 above despite its electron deficient number. Although Linda's basis for her answer selection was the Lewis Structure, she failed to realize that her selected answer was not an appropriate Lewis Structure. This inability to recognize appropriate resonance structures may connect to her inability to decipher appropriate Lewis Structures. This fact is further magnified by her concept map score and her inability to link resonance to any item associated with Lewis Structure.

Lamar also struggled with selection of his resonance structure and failed to consider appropriate Lewis structures. When selecting his answer Lamar had a vague understanding that resonance involved a flow of electron. In Figure 15 below, Lamar drew what he thought was occurring inside of the molecule to produce the resonance structure.

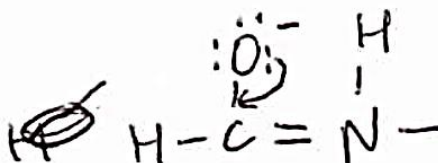


Figure 15. Lamar's representation of resonance occurrence in formamide

Through his drawing, Lamar determined that the correct answer involve a new double bond between carbon and oxygen. However, he failed to realize the incorrect Lewis Structure he would be creating by solely moving oxygen's lone pair of electrons. Ultimately, Lamar determined the Lewis Structure below as the resonance structure for the original molecule (Figure 16).

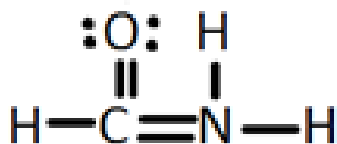


Figure 16. Lamar's resonance choice option for formamide

This disregard of Lewis Structures is explained by his understanding of resonance. When question during the interview about his understanding of resonance, Lamar responded by saying:

Lamar: Because like when I see resonance, I always think of like an actual line structure and not a Lewis structure.

Interviewer: What do you mean by a line structure?

Lamar: You know, like when it's like this [draws Figure 17]. Like that, I think of that.



Figure 17. Lamar's visual representation of resonance

Interviewer: Skeletal structures, that's what you mean?

Lamar: Yeah, I think of that.

Interviewer: And that's what you think about for resonance?

Lamar: Mm-hmm.

Interviewer: Why?

Lamar: Because that's what we were taught. Like you just move that [points to the double bond line], like say if that was right there [points to double bond line on the right of a propene carbocation], just move that right there [to

the left] ... I think it's like that. I'm not sure. I haven't done this in a minute, but it's something like that.

The illustration of resonance in Lamar's carbocation drawing was indeed a correct representation of resonance. This attests to the Lamar's partially correct understanding of resonance. Nonetheless, Lamar limited knowledge of resonance and Lewis Structures was prominent when looking at the resonance structure Lamar chose for formamide (Figure 16) and how he relates his carbocation drawing to it. This choice highlights a missing component high score students were able to recognize, which is that carbon atoms cannot have more than 4 bonds. Lamar's choice also highlights his inability to discern between different characteristics of molecules, specifically ions and molecules. Lamar's understand of resonance relative to Lewis structure is clearly seen in his concept map. His inability to make any connection with common terms found when discussion Lewis Structures verifies to his limited knowledge on resonance in relation to Lewis Structures.

Although most high score students conveyed that resonance was a concept they didn't fully understand, HS students generally had a better understanding of resonance compared to the LS students. When looking at all the C-Map connections students made with resonance, the best link (score 1.5) LS students made was "Resonance structures use different types of bonds such as covalent bond". In contrast, the best link (score 3) made by the HS students stated that "Double bonds can be drawn differently as a Lewis dot structure to determine resonance". Here we see that inside of the high score student's statements there is a less generalizability and a more concrete understanding of different specific aspects of resonance.

Interviews with the high score students also mirrored their greater specific understanding of resonance aspects. During Holly's interview, she was able to see a connection between charges and resonance which was mirrored in her concept map connections. When trying to determine a resonance structure for formamide, Holly pointed to the original structure and said:

Well, because this, I believe, should have a charge. I'm still learning chemistry so I don't know if it's negative or positive, but I think it could be a positive charge here.

This ability to recognize charge was also mirrored in her C-Map in her connection which state that "Resonance can change an atom's formal charge". Other specific aspects about resonance were also seen inside of the concept maps of high score students. Haley, a biology major, stated inside of her C-map that "Resonance is a way to ensure stability in the compound without completely filling the outer electron shell an element, which is known as octet rule". When further questioned during her interview on Figure 15, one of the resonance options, she stated:

Haley: So, always move the double bond...

Interviewer: What do you mean when you say, "Always move the double bond"?

Haley: Like that's one of the rules they told us usually in resonance structures if you have a double bond, to move it. Like that's usually the first thing you're going to do rather than messing with other stuff. Or for instance you would make a double bond so you might take away these two, this -- one of the lone pairs of oxygen and make a double bond between C and O.

However, Haley's understanding of resonance in relation to her C-map is resonated when she explained why Figure 13 cannot be correct. Haley continues on answering to the question:

Interviewer: One of these lone pairs you mean?

Haley: Mm-hmm, but I think that would be more of like a last step because you would want this one -- you can't have two double bonds right there.

Here we see that Haley has a proper understanding of the octet rule in relation to Lewis structures and resonance. Haley understands that Figure 10 cannot be a correct resonance structure because it is an incorrect resonance structure that does not obey the octet rule.

Generally, there were various levels of understanding for resonance among all students in the study; however, all students cited resonance as their weakest understood concept. For students that lacked knowledge of resonance structures, alternative strategies were often used to decipher the correct resonance structure. For students that had a general understanding of resonance, Lewis Structure strategies were employed to confirm whether or not their prediction was correct.

2.5.2 Lewis Structures

Five molecular formulas were given to participants with the instruction to construct a feasible Lewis structure for each molecule (Figure 5). During the construction process students described various strategies and rules that they used to draw their Lewis Structure. As such, these strategies led them to either the correct or incorrect Lewis structure. Hence, the results pertaining to each structure is discussed below.



The SF_6 formula was chosen as a familiar exception to the octet rule. This structure is often seen in the General Chemistry course. The SF_6 molecule was confirmed as an "expanded

octet” molecule in the General Chemistry textbook used by this institution (Tro 2011). In addition to the textbook, instructors for the General Chemistry course at this institution confirmed that the SF₆ molecule was used as an example of an expanded octet in class. Therefore, we expected that students would have seen this molecule and would be able to reproduce the Lewis Structure from memory. When students were asked about this molecular formula, 14 out of 16 students remembered something about the SF₆ molecule. For example, when Ana-Marie, a Biology major that achieved A’s in both Gen Chem I and II, was asked whether or not she was exposed to this SF₆ molecule she responded: “*Kind of... I mean, I've seen it before, but I don't remember much*”. Other students also gave similar responses:

Hilda – “*Kind of, not really, but I'm going to check, double check*”

Helen – “*I probably have seen it.*”

Many students were able to correctly arrange the six fluorine atoms around the sulfur atom in the expanded octet configuration. However, students that did not come up with an appropriate LS had the same structural flaw. The Fluorine atom typically forms one bond; however, this rule was ignored by all of the participants that incorrectly drew the SF₆ Lewis structure (Figure 17).

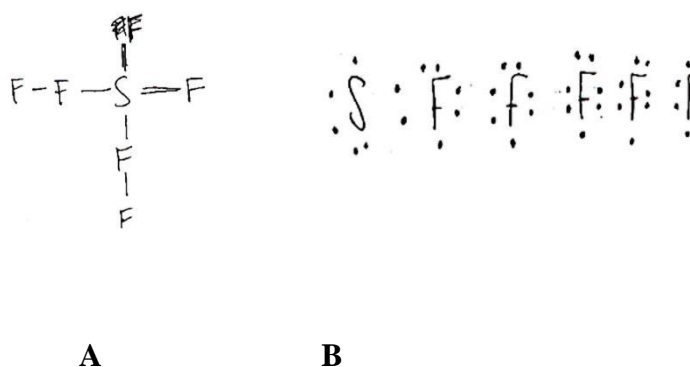


Figure 18. Typical incorrect Lewis Structure drawing of SF₆

The five students that incorrectly drew the Lewis structure for SF₆ either had no idea how to draw this molecule or vaguely recalled some special property about sulfur, which did not translate to their drawing. This was emphasized in Angel's explanation. Angel, a sophomore Biology major who received B's in both General Chemistry courses, and drew structure A (Figure 18) described that:

"I always know like something about I think it's sulfur or thallium or maybe both, they can have like ten like electrons that could -- it's like that special one to just like four bonds and like the set of lone pairs or something."

Angel clearly remembered that something special was to occur with this molecule's Lewis Structure but could not recall exactly what that was. She also did not pay attention to the valency of fluorine when constructing her Lewis structure. Such students failed to see the multiple bonds they were adding to fluorine. This is one of many examples in which students displayed problems with arrangement of atoms in their Lewis structure. Another example of the problems students have with molecular arrangement was described by Haley, a senior pre-med student who drew structure B (Figure 18). When asked about her Lewis Structure drawing Haley described:

"[I] definitely put down both the elements. That's important. Like however many are in there and then I'll just think about like -- well like for instance, I'll have to look at weird subscript so it's like oh okay, you have six Fs so I would put down the S and all of my Fs and then fill in the valence electrons after. That's usually how I do it. So S [sulfur] and

then I have one, two, three, four, five, six because that's usually the first thing that you'll mess up is like if you leave off an F, that's not right. It's completely wrong. Sulfur and fluorine.”

Clearly, Haley drew the SF₆ molecule based on the number of atoms and how it was arranged in the formula. She was mainly concerned about leaving out an element and ignored other rules such as the total number of valence electrons and how many valence electrons fluorine and sulfur can have.

Additionally, many students did not include any lone pairs on their LS of SF₆. A typical incorrect LS, without valence electrons is shown in Figure 18-B. Many of these students tried to give sulfur an octet by putting only four fluorine atoms around the sulfur atom. However, at the same time they gave fluorine two bonds (Figure 18-A).

CH₄O

Methanol, which is sometimes presented to students as CH₃OH, proved to be one of the more difficult molecules students had to construct. Out of the sixteen student participants, ten students incorrectly drew this structure and out of those ten students' two major types of incorrect construction strategies emerged.

The first major incorrect construction group consisted of five students that drew a Lewis structure in the order in which the atoms appeared in the molecular formula. Figure 19 represents the typical arrangement seen in this first group. When Luanne (Figure 19) was questioned on her reasoning for connecting the atoms in that manner, she responded by explaining a common rule:

“Because the way I was taught, like, I know most times hydrogens always are around [the Lewis structure] because they only have one valence. So, I put the oxygen on the outside because according to the formula, that's how they state it. Even though it can be, like, on the opposite end, but I just do mine like that.”

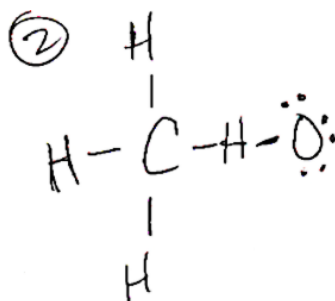


Figure 19. Typical incorrect Lewis Structure for CH₄O in group 1

Luanne’s reasoning is in agreement with previous research, which found that students construct Lewis structures in the order, which the atoms appear in the given formula (Cooper et al. 2010; Nicoll 2001). What is particularly noteworthy in this case is that despite the fact that the student remembered a rule that hydrogen atoms should be on the outside of the Lewis structure, Luanne still decide to go with the order in the formula. Moreover, even though the student could recall a particular rule about hydrogen, she did not connect the rule that “hydrogen should be on the outside of the Lewis structure” to the correct reasoning. That is, hydrogen atoms only have one valence electron, can have one bond and that is why they on the outside of the Lewis structure.

The other major incorrect construction group consisted of four students that drew a Lewis structure with the oxygen doubly bonded to the carbon atom (Figure 20).

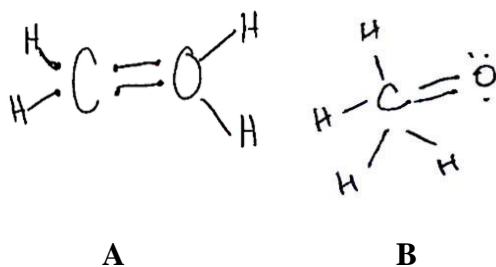
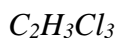


Figure 20. Typical incorrect Lewis Structures for CH₄O in group 2

This method, similar to the one above, seemed to have originated as a student-developed rule. This rule was explicitly stated as Haley drew her Lewis structure (Figure 20-A) for CH₄O asserting that *“I believe when you have between carbon and oxygen is usually a double bond so I’ll probably do it like here”*

This *“carbon should be doubly bonded to oxygen”* is a student-generated rule that led to a structure with an inappropriate number of valence electrons and an oxygen with too many bonds. This student-generated rule also ignored the valency of individual atoms and total number of valence electrons in the Lewis structure.



For the C₂H₃Cl₃ formula, 14 out of the 16 students were able to correctly draw the Lewis structure. Most students drew the structure as written in the formula (Figure 21). The majority of students began drawing the LS by trying to create a carbon chain. When asked to reason out the arrangement of C₂H₃Cl₃, Alexandria who drew structure B (Figure 21), stated that:

“I lay out the carbons. And then in Organic Chemistry, it’s all about the carbon chains, so I would make the skeleton for it first, which is the carbon skeleton. And then I would

attach the other elements onto it, and then I guess just adjust the placement of these other elements based on just really the valence electrons, what makes it more stable”

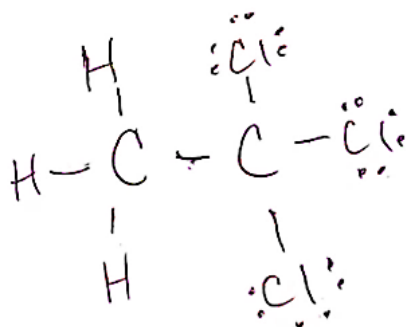


Figure 21. Typical arrangement of $C_2H_3Cl_3$ molecule

Essentially, the recent exposure to molecules similar to $C_2H_3Cl_3$ in the first-semester Organic Chemistry course influenced how the students’ drew this Lewis Structure.

CH_3CN

The CH_3CN formula with the cyanide group proved to be a challenge to the student participants (Figure 22). Ten of the 16 students drew this Lewis structure incorrectly. Despite this variety, all of the incorrect structures exhibited one common flaw of having an electron deficient carbon atom.

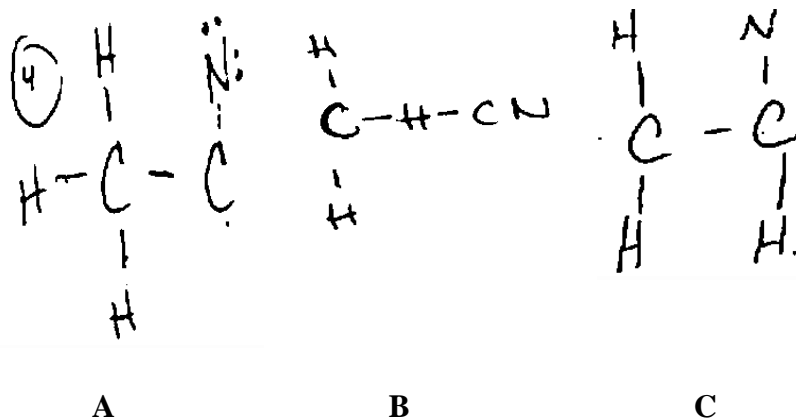


Figure 22. Incorrect Lewis structure drawings for CH_3CN

During the interview, some students were generally able to identify that the structure they drew was incorrect. However, many of them seemed stuck and unable to rectify the problem. Luanne, who drew structure A, (Figure 22) described this point when she said: *“I don't know, but I know the carbon should have four, but for some reason, when I draw it, it's hard for me to do four for this carbon.”*

As such, Luanne knew that something was wrong with her Lewis structure and that carbon should have four bonds. Despite this, she had a difficult time figuring out what to do next to correct her Lewis structure. Many of the students seemed to have trouble when the Lewis Structure involved multiple bonds were involved. Also noteworthy is that some students also drew Lewis Structure with missing lone pairs.



The ethanoate ion served as a common molecule encountered in Organic Chemistry whose structure required additional manipulations of the total valence electrons. That is, students had to add an electron to the total number of valence electrons. Ten out of sixteen students incorrectly drew this structure. Six out of those ten all made the same mistake – they drew a LS with too many additional electrons. Figure 23 shows the typical arrangement of this incorrect structure drawn by students for $C_2H_3O_2^-$.

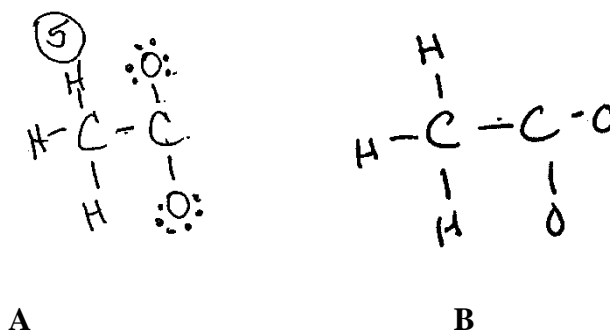


Figure 23. Typical arrangement of $C_2H_3O_2^-$ molecule

In her interview, Helen, who drew structure B in Figure 23, also explained what she thought when looking at the negative sign on the molecular formula of ethanoate. She stated that:

“This one right here [referring to $C_2H_3CO_2^-$], I know that that means that an electron is added, right. They made it more negative? I don’t know. That’s tripping me up. I know something happens with that, and it affects the -- its need of electrons, right.”

Clearly, Helen was confused as to what to do with the negative charge in this formula. One difference was noted between students that drew it correctly and students that drew this structure incorrectly. Essentially, students that drew a feasible structure added one extra electron while some students who drew incorrect structures added two. This ‘two additional electrons’ reasoning was described in Helen’s interview when she stated:

“Like it if it has a negative formal charge I would think it would have a lone pair. That’s just what I think because how else would it have been extra negative unless it had extra electrons or electron but usually it comes in the shape of a lone pair.”

The study on Lewis structure by Cooper also noted that students were unsure about what to do with positive and negative charges. (Cooper et al. 2010). It is also apparent that for this structure students also had problems dealing with multiple bonds in the Lewis structure, as was the case for the CH_3CN formula. Other general themes that emerged from our data is discussed below:

1. Lack or overuse of lone pairs

Some of the students did not include lone pair on the LS. These students were enrolled in Organic Chemistry and they often learn to draw bond-line structures in which lone pairs are only implied. Also, students did not consider the octet rule when they were drawing some of their Lewis Structures. In other cases, some students overused lone pairs in order to satisfy the octet for particular atoms without considering if the total number of electrons the structure was also correct.

2. General Student Construction Strategies

In general, 14 out of the 16 participants were able to construct acceptable structures for $C_2H_3Cl_3$ and 11 students out of the total 16 were able to construct feasible structures for the expanded octet molecule SF_6 . The remaining molecules CH_4O , CH_3CN , and $C_2H_3O_2^-$ all seemed to challenge students equally. A total of 6 out of the 16 participants correctly drew feasible structures for these three molecules. Although there was no structure that all students got correct, there were three students that constructed feasible structures for all five molecules. Two students drew all five Lewis structures incorrectly.

During construction of the various Lewis Structures, a few common drawing strategies and rules used by the students emerged. These categories are shown in Table 1 below. They include; rules and strategies related to the central atoms, arrangement of atoms and absolute rules.

Table 7. General strategies and rules used by students

Central Atom	Arrangement of atoms	Absolute rules
Carbon is always central atom	Always put hydrogen on the outside of the Lewis structure	No more than 4 bonds for carbon
First atom in formula is the central atom	Order of atoms in the formula dictate the order of connection in the Lewis structure	A formal charge indicates addition of an electron or a pair of electrons

There should be a double bond
between oxygen and carbon
Build a carbon chain first

Many students did even seem aware that their final structures did not have the correct number of valence electrons. Many of the students who drew incorrect Lewis Structures did not even mention that this was a factor when deciding if the Lewis Structures were correct or not. Students who identified that total number of valence electrons in their strategies and rules made fewer incorrect Lewis Structures. Also, many of the structures lacked lone pairs, which may account for the fact that they did not have the correct number of valence electrons in their Lewis structures.

Many students either applied their own made-up rules or tried to recall instruction-influenced rules when approaching the Lewis Structures. Some students who recalled the rules either did so vaguely or did not apply the rule appropriately or made connections to what the rule really meant.

We observed that students who had the majority of the Lewis Structures correct were more reflective than other students. These students only accepted their structures as correct once it agreed with information about the atoms in the Lewis structure. Ana-Marie (who constructed four out of five Lewis structures correctly) provides a good example of this type of student. She explained her drawing method below:

“Well, first I just look at how many valence electrons each one has, and then that way I try to figure out like how much I can fill up each one. Or like if one has like six valence electrons, then I can use like -- I can like double bond there and have two single bonds. I see how many bonds I can form with that.”

In this example, Ana-Marie's construction strategy, as well as her specific talk through for each molecule (Figure 5) consisted of reflections to ensure that each atom fulfilled the octet rule, had the proper amount of valence electron and contained an acceptable amount of bonds for a particular atom. In summary, students like Ana-Marie were able to produce correct Lewis structures were not based on a particular method of drawing Lewis Structures only, but rather on the reflective steps were taken after their initial drawing.

2.6 Discussions and Findings

This study contributes to previous research on bonding misconceptions and on the use of concept mapping as an assessment and research tool. Some of the misconceptions presented have been documented in the literature; however, this study is focused on how these misconceptions are the result of missing links and ideas in students' knowledge structures. This factor is of particular importance in chemistry since individual concepts are inextricably connected. This work provides additional evidence that students can continue with flawed understanding and misconceptions beyond the General Chemistry course, since all students interviewed were enrolled in Organic Chemistry. This study has allowed us to answer our research questions.

RQ1. How well can concept maps uncover students' knowledge structures regarding chemical bonding concepts?

In this study students' sum concept map scores were an indication of how well they understood bonding concepts overall. The concept maps gave us insight into their overall knowledge structures and allowed us to pinpoint specific gaps in students' knowledge. For

example, students who had low concept maps scores overall also had specific problems understanding the concept of electronegativity itself, how electronegativity was linked to the polarity of a bond, and resonance. Students understanding or lack thereof as indicated in their concept maps was corroborated by the explanations they gave when solving problems relating to these concepts. Therefore, we conclude that concept maps, to some extent, can uncover the students' knowledge structures regarding chemical bonding concepts.

RQ2. Are there differences in the knowledge structures between students with high scoring concept maps (HS) and students with low scoring concept maps (LS) regarding chemical bonding concepts?

The findings of the study reveal a distinction in the knowledge structures of LS students and HS students. More specifically, LS students had gaps in their understanding of the concept of electronegativity itself and also had difficulty connecting electronegativity to the concept of polar covalent bonding. These gaps were apparent in their concept map propositions and/or their inability to make any meaningful links between and among those concepts. In contrast, HS students were able to make meaningful relationship between the concepts of electronegativity and polar covalent bonding and other concepts. In addition, the concept map scores were reflected in their problem solving ability when addressing these concepts. HS students seemed to have a clearer understanding of electronegativity and polar covalent bonds, while LS students often presented flawed reasoning when trying to explain their incorrect answers. Table 9 compares HS students to LS students.

Table 8. Comparison of HS student versus LS students

Theme	High Scoring Students	Low Scoring Students
Electronegativity	Understood the periodic trend	- Confused the periodic trend

	of electronegativity	of electronegativity with size - Attributed electronegativity to the number of valance electrons
Polar covalent bond	Associated bond polarity with electronegativity differences	Confused covalent bond with ionic bond
Effect of electronegativity on bond polarity	Understood that electronegativity affects the position of the shared pair in a covalent bond	Thought that electronegativity has no effect on the position of the shared electron pair in a covalent bond
Concept map construction	Made meaningful connections with the concepts of electronegativity and polar bond	Either made no connection or incorrect connections with the concepts of electronegativity and polar bond

RQ3. What drawing strategies lead to successful or unsuccessful construction of a Lewis structures?

Participating students self-reported their grades in both General Chemistry courses. Most of the participants (14 out of 16) completed their second-semester General Chemistry course in the summer or fall semester prior to the spring research study. The other two students completed the second-semester course more than a year before taking Organic Chemistry. That being said, we did not find any correlation between the grade students received in General Chemistry courses and their ability to draw a feasible Lewis Structure (Table 9). Although the students' self-reported their grade, the fact is that students must receive at least a grade of "C" in General Chemistry before entering the first-semester Organic Chemistry result. The implications are that students can complete General Chemistry courses with a passing grade and still not have a good grasp of a fundamental topic such as construction of Lewis structures. These results indicate that

there need to be more conversations regarding curriculum reform in undergraduate chemistry courses (Cooper 2010; Cooper and Klymkowsky 2013a).

Table 9. Participants structures and final grades in General Chemistry I and II

Pseudonym	SF ₆	CH ₄ O	C ₃ H ₃ Cl ₃	CH ₃ CN	C ₂ H ₃ O ₂ ⁻	Total Correct	Gen I Grade	Gen II Grade
Total correct	11	6	14	6	5	-	-	-
Ana-Marie	Y	N	Y	Y	Y	4	A	A
Abby	Y	N	Y	N	N	2	A	A
Hollie	Y	Y	Y	N	N	3	A-	B
Lori	Y	N	Y	N	N	2	B	C
London	N	N	N	N	N	0	B	C
Liza	N	Y	Y	N	N	2	B	B
Lacy	Y	Y	Y	Y	Y	5	B	C
Alexandria	Y	N	Y	Y	N	3	B	B
Angel	N	N	Y	Y	Y	3	B	B
Luanne	Y	N	Y	N	N	2	B-	B-
Ashley	Y	N	Y	N	N	2	C	C
Haley	N	N	N	N	N	0	C	C
Helen	Y	Y	Y	N	N	3	C	C+
Linda	N	N	Y	N	N	1	C+	B-
Lilia	Y	Y	Y	Y	Y	5	C+	C+
Hilda	Y	Y	Y	Y	Y	5	C+	C

2.7 Conclusions and Implications

Chemical Bonding

The findings of this study demonstrate that many students have difficulty making meaningful relationship among the concepts of electronegativity and polar covalent bonding. This concept is fundamental to chemical understanding and has implications for future courses such as organic chemistry and biochemistry. Therefore, this study has implication for what we teach and how we teach general chemistry.

Examining students' prior knowledge in terms of their overall knowledge structures will help chemical educators design more meaningful curriculum materials. Concept maps can be used as a pre-assessment and formative assessment tool to analyze students' knowledge structures regarding a group of related concepts. Chemical educators can determine which concepts and connections need to be more explicitly taught and can address common misconceptions and knowledge gaps.

As a matter of general chemistry curriculum reform, chemistry instructors may need to consider spending more time focusing on fundamental concepts that are built upon and needs to be transferrable to other courses. It is important that students grasp these fundamental concepts and how concepts are linked together. There is certainly a need for more structured learning progressions that focus on explicit transfer of concepts across courses and disciplines. Several authors have proposed the use of learning progressions as a promising tool to design such a structured curriculum in chemistry (Boo and Watson 2001; Cooper and Klymkowsky 2013a; Cooper et al. 2012b; Johnson and Tymms 2011; Wolfson et al. 2014). Furthermore, to facilitate reform efforts increased conversation with general chemistry, organic chemistry and biochemistry instructors are essential to better coordinate and align the concepts that students need to be successful in these courses and to ensure that students can develop more coherent knowledge structures regarding fundamental topics.

We are using a similar research protocol to examine student knowledge structures regarding additional fundamental concepts such as molecular shape and acid-base chemistry. We are also expanding the sample size of our study so we can do more quantitative studies on how students' knowledge structures are related to their success in chemistry courses. We hope to use

the research results as a springboard for designing more meaningful curriculum for general chemistry.

Lewis Structures

Often, instructors equip students with necessary tools or instructions for constructing Lewis structures. Rules for the counting of total valence electrons are given to students as a guideline for proper construction of atom. However, our results have shown that these rules are often not recalled or even understood. Thus, instead of giving students rules to follow to produce proper Lewis structures students should be taught through a more metacognitive strategy approach. Metacognitive training is especially important, since in this study several students seemed to know that something was incorrect about their structures but could not come up with a solution on how to fix it. In essence, students should be taught to give justifications as to why a structure is correct as opposed to just following guideline to produce a ‘correct’ structure. Students also need to consider a variety of different structures across both semesters of general chemistry and in organic chemistry. As such, they will know when and how to apply certain rules and concepts (Graulich 2015).

In this study, it was apparent that a number of students had recalled rules, but did not connect them to the meaning of the rule. Also, it was evident that students primarily used rote memorization. Therefore, making the process of constructing and understanding Lewis structures a more meaningful process can help students recall the various rules and apply them appropriately. Meaningful learning asserts that new information must be “relevant to other knowledge (Novak 2002).” Students that can make a connection between a Lewis structure and

concepts about why bond form can better recall and rectify problems when they arise –even if it is a structure they have not seen before (Cooper et al. 2013; Cooper et al. 2010).

In addition, innovations such as PLTL and POGIL, there have been examples in the literature of chemistry curriculum that is designed to promote deeper understanding of the material and get students to think deeply about chemistry concepts for both the class and laboratory settings. One of these is the Chemistry, Life, the Universe and Everything (CLUE) curriculum (Cooper) that uses a learning progression design to allow students' to build a deeper understanding of core chemistry topics. The goal of the CLUE curriculum is that students explain and understand relationships between structure and chemical reactivity.

Additionally, the use of Predict-Observe-Explain (POE) pedagogy allows students to first make predictions about what they think will happen in a chemical scenario. Students then make observations of the actual scenario and then compare their initial predictions to the experimental results. POE is a valuable tool in developing student metacognitive skills, in that, they get to reflect on their thinking and make adjustments if necessary.

Similar to POE is the Model–Observe–Reflect–Explain (MORE) Thinking Frame. In essence, MORE focuses on student's prior knowledge for chemistry concepts, which then is proved or disproved through observations and explanations during which students are engaged in a constant reflective thought process. All in all the inquiry developed programs have all developed frameworks that facilitate classroom learning through thought engagement with heavy emphasize on metacognitive thinking.

One other factor is the structure of the general chemistry curriculum. In many curricula, Like the one at the institution in this study, Lewis structures are typically presented towards the end of the first semester and therefore students and instructors may not have sufficient time to

discuss and understand how to draw Lewis structures and relate this to other relevant concepts. In such cases, it may be better to move this topic up in the semester and continue to reiterate Lewis structures in first and second semester General Chemistry as other concepts are presented. As such, students are exposed to many various examples as new examples of chemical and physical properties of compounds are introduced.

3 PROJECT-BASED LAB

3.1 Introduction

Science has been criticized for inaccurately portraying the practice of science regarding the laboratory environment. The chemistry laboratory is considered an essential component of chemistry education of undergraduates (Dechsri et al. 1997; Elliott et al. 2008; Hofstein and Lunetta 2004; Johnstone and Al-Shuaili 2001; Johnstone 1991; Loucks-Horsley and Olson 2000; Nakhleh et al. 2003; Society 2008). The American Chemical Society (ACS) Guidelines on Undergraduate Professional Education in Chemistry (2008) recommends 400 laboratory contact hours beyond the introductory chemistry laboratory for students to receive an ACS certified undergraduate degree. However, despite these claims, the usefulness of laboratory experiences to students' education in chemistry has been challenged. For instance, one review has noted that there are few quality studies on the impact of the chemistry laboratory on student outcomes (Hofstein and Lunetta 2004). A recent report on Discipline-Based Education Research (DBER) (Singer et al. 2012) stated that: "Future DBER might compare learning outcomes associated with different types of laboratory instruction." Chemistry education researchers have called for a more comprehensive look at the laboratory environment in chemistry (Hofstein and Lunetta 2004; Nakhleh et al. 2003).

3.1.1 *Background of Current State of Labs*

A review of the literature on laboratory learning has revealed that there are numerous approaches to the design of the laboratory and multiple views on what are the best practices and goals for the chemistry laboratory (Hofstein and Lunetta 2004; Nakhleh et al. 2003; Reid and Shah 2007). For example, some researchers suggest that the purpose of the laboratory is to

improve students' understanding of chemical concepts, increase their problem solving skills, enhance their interest in science (Hofstein and Lunetta 1982; Shulman and Tamir 1973; Tamir 1990), and develop an awareness of the nature of science (Russell and Weaver 2011). However, other works support the use of the laboratory to improve students' technical skills but not necessarily their attitude or interest in science (Hodson 1993). Hofstein and Lunetta (1982; 2004) have reviewed several empirical studies on the laboratory and arrived at the conclusion that there is "sparse data from carefully designed studies to support faculty claims of the value of the laboratory." They also emphasized the need to better define the goals of laboratory work.

Reid and Shah (2007) in their review of the chemistry laboratory identified four main goals for the laboratory which include: 1) *Skills relating to learning chemistry* that are related to issues of making chemistry real, illustrating ideas and concepts, exposing theoretical ideas to empirical testing, 2) *Practical skills* that include handling of equipment and chemicals, safety procedures, mastering specific techniques, and measure accurately and observing carefully, 3) *Scientific skills* that refer to opportunities to learn the skills of observation and the skills of deduction and interpretation. These skills also include an appreciation for the empirical as a source of evidence in inquiry and to learn how to devise experiments which offer genuine insights into chemical phenomena, and 4) *General skills* are skills relating to team work, reporting, presenting and discussing, time management and problem-solving.

Furthermore, a recent mixed-methods study by Bruck and Towns (2013) investigated faculty goals for the undergraduate chemistry laboratory. This study found that faculty goals for the laboratory consisted of research experience, learning to work in groups, error analysis, and laboratory writing (Bruck and Towns 2013; Bruck et al. 2010). An extension of the Towns study by Bretz et al. looked at the faculty responses to the goals of the laboratory in terms of

meaningful learning (Bretz et al. 2013). The faculty responses were analyzed in the categories of cognitive, affective and psychomotor domains. In their study, it was noted that chemistry faculty described goals relating to affective domains to a lesser extent than for the cognitive and psychomotor domains. Some of the faculty goals that fell into the affective domain included: gaining independence, teamwork and relating students' experiences to the real world.

Chemistry laboratory instruction range from open inquiry to expository or “cookbook” styled laboratories (Domin 1999). There has been a national push towards more inquiry curriculums (Loucks-Horsley and Olson 2000) and there are numerous examples of inquiry-based laboratory in the literature in the last five years (Cacciatore 2014; Cacciatore and Sevian 2009; Cloonan et al. 2011; Eichler 2009; Everest and Vargason 2013; Fakayode 2014; Fakayode et al. 2011; Iler et al. 2012; Mandler et al. 2014; Prilliman 2012; Raydo et al. 2014; Schepmann and Mynderse 2010; Wada and Koga 2013; Walker and Sampson 2013; Zhao and Wardeska 2011).

To better characterize level of inquiry, Fay et al. (2007) developed a rubric to more clearly characterize the level of inquiry in laboratory experiments. The rubric defines the level of inquiry based on whether or not the problem, the procedure or method or the solutions of the experiment are provided to the student (Table 10).

Table 10. Rubric to describe level of inquiry across undergraduate chemistry laboratory (Fay et al. 2007)

Level	Problem/Question	Procedure/Method	Solution
	Provided to student	Provided to student	Provided to student
	Provided to student	Provided to student	Constructed by student
	Provided to student	Constructed by student	Constructed by student
	Constructed by student	Constructed by student	Constructed by student

3.1.2 *Statement of the problem*

Despite the focus on inquiry by many, the chemistry laboratory curriculum remains largely unchanged and many institutions still follow the traditional, expository-style laboratory. If chemistry departments are to truly invest in reforming the laboratory curriculum there must be convincing evidence about what kinds of laboratory experiences produce desired student outcomes and what components of the laboratory experience are necessary to produce favorable student learning outcomes.

3.1.3 *Purpose of the study*

Given the high cost of laboratory instruction, and the large amounts of time invested in laboratory education in chemistry, an examination of what kinds of laboratory experiences produce desired student outcomes, and what components of the laboratory experience are necessary to produce favorable student learning outcomes is of keen interest to the chemistry education community (Nakhleh et al. 2002; Singer et al. 2012). To this end, the purpose of this work is to investigate students' experiences in a project-based, Organic Chemistry laboratory setting. This study is different from previous studies of students' experience in the undergraduate chemistry laboratory, in that, it examines a non-traditional, project-based, Organic Chemistry laboratory, and it uses the lens of phenomenography to investigate students' experiences in the laboratory. The primary goal of our study is to contribute to data on laboratories, such that, chemical educators can design laboratories that meet the goals of instructors, promote student learning of content, and help students gain important skills.

3.1.4 *Research Questions*

To guide this study the following research questions were used:

1. What do students see as the purpose of the laboratory?
2. What do students define as success in the laboratory?
3. What are the different ways that students experience the lab environment?

3.1.5 *Significance of Study*

Although there are many examples of project-based labs in the literature, thus far, there are limited quality research studies on students' experiences in project-based labs or its effects on learning. In one study, phenomenology was used to examine students' experiences in a cooperative project-based General Chemistry laboratory (Sandi-Urena et al. 2012; Sandi-Urena et al. 2011). This work found that students initially experienced confusion since this new laboratory environment was unfamiliar to them. However, through increased metacognitive awareness, students were able to better understand this laboratory environment. One other study examined students' experiences in an open-ended, project-based Organic Chemistry course compared with students in a more conventional "cookbook" laboratory course (Cooper and Kerns 2006). In this study, students in the project-based labs viewed the laboratory as a place to make mistakes and to engage in experimentation, while those in the traditional section had a more passive view of what the lab was all about. This current study attempts to further address students' experiences in a project-based Organic Chemistry laboratory using a phenomenographical framework.

3.1.6 *Assumptions and Limitations*

The study investigated a project-based lab at a single institution. Thus, the data collected might not be a reflection of all institutions or lab types; however, the diversity of this university

lends to a wider scope that can capture a variety of experiences. The study also had a small number of participants (N=18) compared to the number of students that enroll in this course per semester (N=176). Hence, this may not be a representative sample; however, data saturation was reached for the 18 interviews conducted. Information on student learning based on each interaction was not collected. This was beyond the scope of our study and it is something we hope to address in the future.

3.2 Review of the Literature

One area of investigation of the chemistry laboratory is regarding the goals, perspectives, and experiences of students in chemistry labs. How students experience and perceive the laboratory is an important factor towards understanding the laboratory environment and in making curriculum decisions. A few researchers have made strides towards understanding students' experiences in the chemistry laboratory. One study examined students' experiences in a research-based undergraduate curriculum known as CASPiE (The Center or Authentic Science Practice in Education). The CASPiE curriculum involved students in an authentic research experience that provided them the opportunity to engage in scientific process skills, such as designing experiments and using experimental evidence to draw conclusions. In a long-term study, Szteinberg and Weaver examined students' reflections two and three years after they participated in the CASPiE research-based laboratory and traditional laboratory experiences (2013). This work showed that CASPiE students felt more confident about being able to explain what they did in the laboratory, they better understood the application of the laboratory work to their lives, and they felt a greater sense of accomplishment in their work. The CASPiE students also felt more motivated to learn and developed a better understanding of the process of doing research. The traditional lab students thought that their lab was more organized than the CASPiE

students did because they had a step-by-step structure to follow. In addition, students' views of the positive aspects of the CASPiE program persisted over time. Although students in the traditional course also had negative and positive views that persisted over time; they had forgotten much of the details and purpose of their lab experiences. This study has shown that students can have positive experiences in a non-traditional laboratory that encourages deeper thinking and learning.

Another set of quantitative studies by Galloway and Bretz used the Meaningful Learning in the Laboratory Instrument (MLLI), based on a Novak's theory of meaningful learning, to examine students' cognitive and affective perception of learning in chemistry laboratory. In one of these studies, the MLLI was administered to General and Organic Chemistry students from 15 colleges and universities in the United States (Galloway and Bretz 2015a). Using exploratory factor analysis and cluster analysis, the researchers uncovered four clusters for General Chemistry students and three clusters for Organic Chemistry students. Further analysis of this data showed that both courses had students with high cognitive and affective expectations that were fulfilled by their laboratory experience. There were also students with high cognitive expectations but low affective expectations. These students had cognitive expectations that went unfulfilled by their laboratory experience, and their negative affective expectations were fulfilled. As a result, they were hindered from experiencing true meaningful learning in the lab. Another long-term study using the MLLI also had similar results (Galloway and Bretz 2015b). In this study, 61 students were followed over two years from General Chemistry to Organic Chemistry II laboratory courses. It was found that students had reset their expectations for the Organic Chemistry laboratory. In other words, they still had high expectations for learning despite previous unfulfilled expectations in their General Chemistry laboratory. A significant

implication for both of these studies is the need to better understand and incorporate the affective domain into the design of the laboratory curriculum and the need for laboratory curricula that focus on students' decision making and sense-making skills rather than just focus on the "right" or expected outcome of an experiment.

Galloway and Bretz used additional qualitative research to further explore their findings in the quantitative studies (Galloway and Bretz 2016; Galloway et al. 2015). In one study, students were video recorded as they were performing a particular lab experiment (Galloway and Bretz 2016). These students were interviewed within 48 hours after completing the experiment. The video was shown to the students, and they were asked to describe what they were doing and why they were doing it. The students' descriptions were analyzed using the meaningful learning framework. As students discussed their experiences, their primary focus was the psychomotor aspects or the hands-on component of the lab experiments. Few students discussed chemical concepts, and only a few could explain the purpose of the experiment. Also, many of the students focused on completion of the lab rather than understanding the experiment. Students expressed many emotions, which included frustration, boredom, and enjoyment during their experiments. The authors believe that knowing how students feel can create greater awareness of students' learning experiences in the laboratory and these affective outcomes should be considered by chemistry educators as they design laboratory curriculum and assessment.

In one additional study of 13 students enrolled in General Chemistry and Organic Chemistry lab courses, they investigated students' perception of autonomy in the lab and how this autonomy influenced their laboratory experiences (Galloway et al. 2015). In general, students who perceived that they were in control or that there was a lack of control seemed to carry out the laboratory procedures without thinking about the purpose or principles behind

them. Also, it was interesting that students who described similar affective experiences responded in different ways to those feelings. For instance, students perceived the word ‘challenged’ in positive and negative ways. Some students welcomed challenges, while it was a barrier to deeper learning for other students. Again, the authors continue to point out in this study that it is possible to target the design of laboratory curricula that considers the range of affective experiences that students can have in the laboratory.

Recent work by DeKorver and Towns (2015; 2016) has offered further insight into students’ goals for the laboratory. A meaningful learning framework was used to examine students’ cognitive, affective, and psychomotor goals for the traditional General Chemistry (2015) and Organic Chemistry laboratories (2016). In both studies, DeKorver and Towns concluded that students often sought out correct answers and tried to avoid mistakes in the lab. Other major findings were that the students’ main goals for the laboratory were to finish early and just complete the necessary requirements to earn a grade. Some students also expressed the desire to learn laboratory skills as one of their goals. However, this goal conflicted with their goal of getting out of the lab quickly. The researchers proposed that if chemical educators want to elicit deeper student goals, they must design the laboratory course to do so.

3.3 Theoretical Framework

3.3.1 *Phenomenography*

This study employed phenomenography as one of its theoretical frameworks. Phenomenography is used “to define the different ways in which people experience, interpret, understand, perceive or conceptualize a certain phenomenon or aspect of reality” (Marton 1994; Orgill 2012; Orgill and Bodner 2007). The epistemology of this methodology is that human

experiences are based on the relationship between the person and the world around them (Marton 1994). As such, we consider both the person and their experiences as a whole. The basic assumption of phenomenography is that there is no right or wrong in the phenomenon being investigated. The researcher is not interested in what is 'real' but only in how the person conceptualizes the phenomenon under investigation. The participants' statements are regarded as truthful by the researcher. Marton showed that regardless of the phenomena under investigation there are a limited number of qualitatively different ways, which can be described (Marton 1981). This framework is especially suited for this research study since we are primarily interested in the experiences and perspectives of students regarding the laboratory environment.

Phenomenography has been used in several recent publications to look at student and faculty experiences in the context of chemistry (Lyle and Robinson 2002; Mack and Towns 2016; Stefani and Tsapralis 2009; Taber 2013). These studies were used to describe the perceptions of faculty and students of different learning environments, faculty perception of using analogies in the classroom (Orgill et al. 2015), faculty understanding of teaching physical chemistry (Mack and Towns 2016), students understanding of climate change (Versprille and Towns 2014), and in looking at students' perception of laboratory experiences (Russell and Weaver 2011; Weaver et al. 2008). These studies have added rich understanding of the experiences of chemistry students and faculty that can inform curriculum changes to improve chemistry learning. However, there are fewer instances of the use of phenomenography to examine the chemistry laboratory (Domin 2007; Russell and Weaver 2011). Phenomenography shaped the design of this study, the data collection, and a portion of the data analysis of this work.

3.3.2 *Situated Cognition*

Constructivism asserts that knowledge is actively built by the learner (Bodner 1986). The learner has to integrate their new knowledge with their prior knowledge to build their understanding of concepts. Social constructivism (Solomon 1987; Vygotsky 1980) incorporates the ideas that learning takes place in a social context and that the interaction of the learner with others influence the incorporation of prior knowledge and new ideas. Situated cognition (Brown et al. 1989; Hendricks 2001) builds on both personal and social constructivism. This framework focuses on how the environment in which learning occurs, and the interaction with the learner and this environment affects knowledge construction. This learning environment may include the interaction with instruments and tools of the discipline, and the learner's interaction with the instructor and other learners in the environment. The undergraduate chemistry laboratory is an ideal environment to apply situated cognition (Russell and Weaver 2011; Szteinberg and Weaver 2013) because it considers the interaction of the learners with people, with course materials and tools, and with their environment to construct an experience. As a result of using this framework, we can observe the impact of all of these interactions in relation to the students' experiences in the laboratory and their learning in the laboratory.

Cognitive apprenticeship is a critical component of situated cognition (Brown et al. 1989). The interaction of a novice learner with experts as well as other novices leads to the sharing of important skills and experiences. As a result, the novice learns from the expert (instructor) like an apprentice. The instructor scaffolds the learning for the students so that they go towards expert-like development of skills, independence, and problem-solving (Collins et al. 1988). In other words, the students' instructors and other students support the students' attempts at the task until they develop independence. Lave and Wenger (1991) has further extended and

refined the ideas about situated cognition and cognitive apprenticeship through their description of legitimate peripheral participation (LPP). According to Lave and Wenger, “A person’s intentions to learn are engaged, and the meaning of learning is configured through the process of becoming a full participant in a sociocultural practice” (1991). This so-called peripheral participation is critical for students to develop in a field. Novices gain mastery by engagement, interaction, and collaboration with experts in the field and others like themselves.

In the project-based lab described in this study, the instructor takes on the role of an expert mentor and uses scaffolding to help students gain expert-like skills and competencies in Organic Chemistry. One goal of the lab is to prepare students to enter research labs upon completion. This project-based lab introduces aspects of a research-like environment, such as problem-solving, ambiguity, and decision-making to students, which help students move towards more expert-like competencies and skills in chemistry. In other words, the instructor models chemistry practice and assists students towards becoming legitimate peripheral participants in the chemistry community. According to LPP theory, newcomers become members of a community of practice by participating in simple and low-risk tasks (like the laboratory) that are necessary for furthering the goals of the community. Through these kinds of peripheral activities, novices can become more familiar with the skills, vocabulary and ways of the community (Lave and Wenger 1991). In this work, we used situated cognition to develop and discuss the outcome space and how students’ experiences in the lab affect their learning and their role as legitimate peripheral participants.

3.3.3 *Relationship between Phenomenography and Situated Cognition*

In phenomenographic studies, the findings are described using an outcome space. The outcome space shows the various categories of description, the relationships between them and the links between them (Marton 1994). This helps the researcher and others better understand the phenomenon that is being studied (Marton and Booth 1997). In his early work, Marton seemed to indicate a link between phenomenography and constructivist approaches (Marton 1981). Even though Marton seemed to move away from these thoughts later, one author suggests that situated cognition should “in principle, be of considerable interest to phenomenographic researchers, since it suggests that thinking (both in everyday life and in educational situations) is influenced by the immediate situations and cultural contexts in which it occurs (Richardson 1999).” Although there are differences in the two perspectives, both situated cognition and phenomenography recognize that different people may experience things differently, that individuals play a role in generating knowledge, and that prior experiences play a role in the development of meaning (Cope 2006). We believe that using both phenomenography and situated learning will give us a more comprehensive view of students’ experiences and how they approach learning in the chemistry laboratory.

3.4 Overview of Project Based Lab Curriculum at Georgia State University

3.4.1 *Overview of the Laboratory Curriculum*

The institution, Georgia State University, described in this study is a large, urban, research-intensive university. Our institution has 25,314 undergraduates and 32,541 total students enrolled. We are a mix of African American (37%), White (40%), Asian (13%), Hispanic (8%), and other (2%) students; 40% of our students are men, and 60% are women.

High school students that enter college are sometimes unexposed to laboratory work in their secondary education science courses. To address this, we designed a chemistry lab curriculum that gradually moves incoming college students to a state of independence via a series of increasing inquiry levels (Lvl) from General Chemistry (G-Chem) through Organic Chemistry (O-Chem) labs (Figure 24).

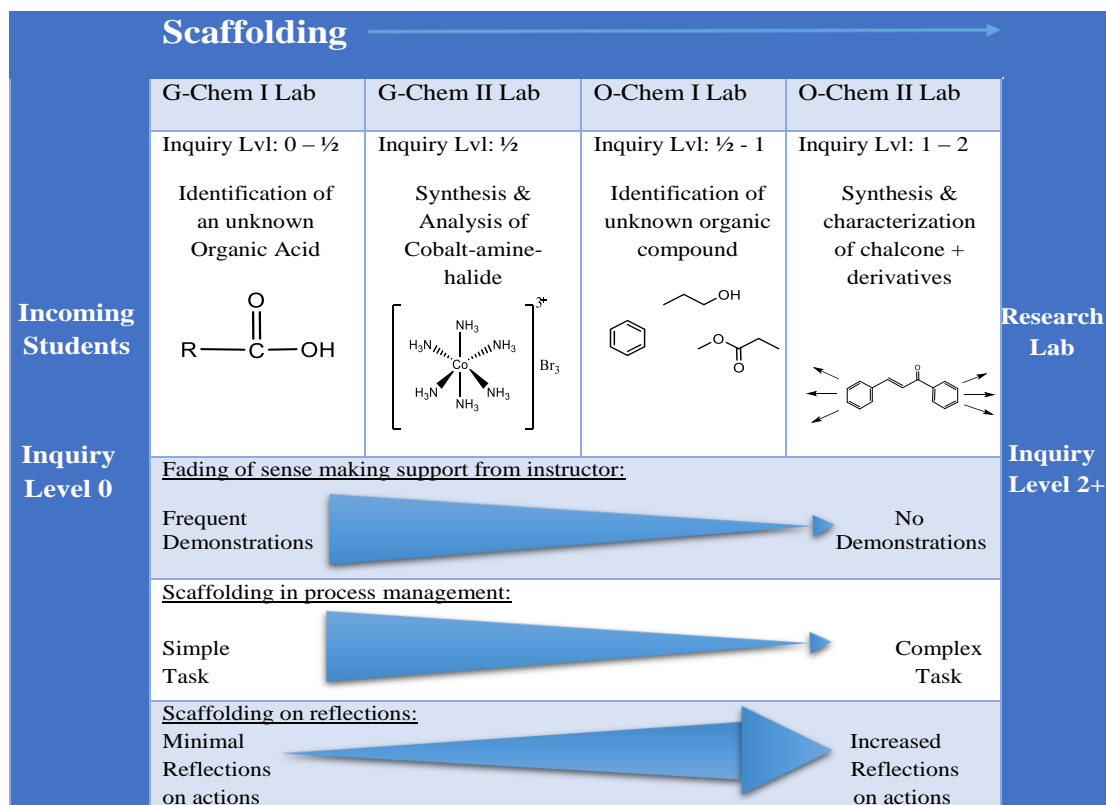


Figure 24. Design of scaffolding lab curriculum across the general and Organic Chemistry laboratory courses that incorporates sense making, process management and articulation/reflections

Our lab curriculum accounts for little to no prior lab experience for entering students and has an emphasis on moving students from dependent thinking to independent thinking. These students enter a General Chemistry I Lab that has an inquiry range 0 - ½ and leave the O-Chem II lab prepared to do research in a lab at an inquiry level of 2+. Each lab was designed to build off concepts taught in previous labs while introducing new concepts on each project.

Table 11. Characteristics of different inquiry levels in labs (Bruck et al. 2008)

Characteristic	Level 0: Confirmation	Level ½: Structured inquiry	Level 1: Guided inquiry	Level 2: Open inquiry	Level 3: Authentic inquiry
Problem /Question	Provided	Provided	Provided	Provided	Not provided
Theory /Background	Provided	Provided	Provided	Provided	Not provided
Procedures /Design	Provided	Provided	Provided	Not provided	Not provided
Results analysis	Provided	Provided	Not provided	Not provided	Not provided
Results/ communication	Provided	Not provided	Not provided	Not provided	Not provided
Conclusions	Provided	Not provided	Not provided	Not provided	Not provided

3.4.2 *Guiding Theoretical Framework for curriculum*

Developing a lab with the goal of teaching lab techniques allows for many different laboratory styles to be employed. However, designing a lab curriculum with the additional goals of teaching students how to think critically, make sound decisions and develop employable skills proves much more challenging. Scaffolding provides a framework for instructors to provide expert guidance to students while helping students acquire disciplinary ways of thinking and acting. Thus, by bringing these thought processes into the open, students can observe, enact, and

practice skills with instructor aid. Instructors can then provide support to students as they develop critical thinking and employable skills.

Scaffolding involves structuring the task, offering cues and hints, and even modeling the activity for the learner, but gradually ‘fading’ the level of support as the learner begins to master the task (Taber 2013). In the scaffolding design, a range of tasks, varying from systematic to diverse is presented to encourage students to reflect on and articulate the elements that are common across the lab project. The goal is to help students develop decision-making, problem-solving skills, and independence when faced with novel situations. To develop these skills, scaffolding theory identifies three elements: 1) sense making, 2) process management, and 3) reflection and articulation. Each scaffolding element has unique obstacles. To combat these obstacles our chemistry laboratory curriculum provides a set of scaffolding guidelines. A scaffolding guideline specifies a way in which tools modify the task to help learners overcome obstacles (Table 12) (Quintana et al. 2004).

Table 12. Table adapted from Quintana showing the different elements and obstacles to scaffolding and our chemistry laboratory curriculums solution to the obstacle.

	Challenge to Scaffold	Scaffolding Guideline
Scaffolding sense/decision making	Use representations and language that bridge learners’ understanding	Instructors provide demonstrations of experiment to give access to functionality
		Provide expert experimental tips to help learners understand use and application to science content
	Organize tools and artifacts around the semantics of the discipline	Make laboratory strategies explicit in learners’ interactions with tools (Melting temp, IR machine)
		Make problem solving strategies for generated data explicit
Scaffolding sense/decision making	Use representations that learners can inspect in different ways to reveal important properties of underlying	Provide representations that can be inspected to reveal underlying properties of data
		Enable students to inspect multiple views of the same data

	data	Give learners “malleable representations” that allow them to directly manipulate representations
		Restrict a complex task by setting useful boundaries for learners
	Provide structure for complex tasks and accessibility	Describe complex tasks by using ordered and unordered task decompositions
		Constrain the space of activities by using functional modes
Scaffolding process management	Embed expert guidance about scientific practices	Embed expert guidance to clarify characteristics of scientific practices
		Embed expert guidance to indicate the rationales for scientific practices
	Automatically handle nonsalient, routine tasks	Automate nonsalient portions of tasks to reduce cognitive demands. Eg. auto-pipette
		Provide a common use area for all chemicals needed
		Use of TA’s to facilitate navigation among tools
Scaffolding articulation and reflection	Facilitate ongoing articulation and reflection during each lab course in varying degrees	Provide reminders and guidance to facilitate productive planning (prelab write ups) of lab experiments
		Instructors probe students during experiments to guide articulation during sense-making. Assume the role of a PI
		Emphasize important points to communicate in pre-lab lecture

3.4.2.1 *Scaffolding Sense Making in the laboratory*

Sense making refers to the basic operations of science inquiry such as generating hypotheses, designing comparisons, collecting observations, analyzing data, and constructing interpretations. (Quintana et al. 2004) Sense-making must connect reasoning, assessment, and data to understand the logistics of a decision. In project-based laboratory environments, facilitators and instructors make key aspects of expertise visible to students by modeling, coaching, and eventually fading some of their support.

Experts can see meaningful patterns in problem-solving situations that may not be apparent to novices. The model that an instructor provides serves as the initial benchmark for students to observe, learn from and mimic. As part of the lab sequence across this curriculum, instructors present a laboratory project with a general overview of the goals of the lab. At the

beginning of lab, instructors give a visual demonstration of the actual equipment that will be used to carry out their projects. Reasoning for various steps in the project are provided, procedures are written in a given order and certain equipment is used. The chemistry behind the project is also explained in depth using concepts previously taught in lecture courses, thus aiding in a meaningful connection to the material as well as the project. This explanation of concepts gives students the necessary support their progression from novice to expert in the discipline.

Instructors transition from an active role of teacher to towards that of a Principal Investigator (PI) or facilitator as the students' work becomes more independent. Demonstrations are important for these novice students; however, that ability to carry out the experiment and receive feedback proves to be an essential process for students. Instructors allow students to problem solve with a significant amount of aid from the instructors themselves as well as teaching assistants. This sense-making phase allows for the instructors to evaluate technique as well as show how they would solve a problem. During this process, instructors gradually move from the role of answering questions to asking questions to students to promote decision-making.

3.4.2.2 Scaffolding Process Management

Decision making is the core process in this project-based lab; however, students need to manage this key scientific inquiry process. Students lack the strategic knowledge needed to select activities and coordinate the inquiry (Bransford et al. 2000). Therefore, when dealing with novice students the processes of scientific inquiry needs to be scaffolded to make it manageable at each level of students.

Through each of the General Chemistry and Organic Chemistry lab courses, students work individually on their project to mimic the environment of a research lab. As seen in Figure 24, across the lab curriculum there is a shift in the amount of modeling which instructors provide

for the student. In the first two lab courses, more emphasis is placed on the actions and performance of students in-lab activities. Once students grasp these techniques, more emphasis is situated on the concepts of each respective project, and demonstrating each experiment before conducting it is less emphasized. Students are then given full freedom in the Organic Chemistry II lab to select two synthesis procedures they would like to perform from their already synthesized compounds. At this point, little guidance is given to the student and the student should have developed decision-making skills to determine what steps should be taken during their synthesis.

Instructors of all labs are required to "shadow" a more experienced instructor before commencing their lab. This shadowing experience consists of an inexperienced instructor observing how the concepts and learning objectives for the laboratory course are conveyed while learning process management and troubleshooting portion that occurs during the in-lab part of the course.

3.4.2.3 Scaffolding Articulation & Reflection

A critical aspect of inquiry involves articulating an argument. In lab, students must review, reflecting on, and evaluate the results from their data. They must then explain the weaknesses and strengths of their data and how they arrive at their conclusions. As stated previously, throughout the lab curriculum, instructors assume the role of a PI and use strategic questioning of students on their respective projects. Students then share their knowledge and understanding of the process of working in lab by the close one-on-one interaction that takes place between the students and their teachers during in-lab time. During the semester, students' decision making is also assessed with in-class quizzes and homework. Finally, their

understanding and reflection on the project are evaluated in a final lab report which demonstrates their in depth of understanding with each lab.

3.4.3 *The Laboratory Curriculum Goals*

The chemistry laboratory curriculum at this institution was designed to gradually move incoming high school students towards increased independence. This gradual independence is achieved through a General Chemistry (G-Chem) and Organic Chemistry (O-Chem) lab series. Each lab is conducted in a project-based/guided inquiry format and the level of inquiry of each lab increases when moving from the two semesters of G-Chem lab through the two semesters of O-Chem lab.

3.4.4 *Organic Chemistry II Lab Setting*

The second-semester Organic Chemistry Lab enrolls four sections of 44 students each semester, for a total of 352 students in each academic year (excluding summer). One of these sections incorporates an honors section of up to 20 students. To better facilitate the project-based laboratory experience and to maintain the continuity of a research-like experience, this laboratory course is a half-semester format. This means that students meet for five hours twice a week for seven weeks, instead of once per week for 13 weeks.

Objectives for the course are described in the lab manual as: 1) Handling and characterization of solids (including safety concerns and procedures), 2) isolation techniques of solids, planning and execution of chemical reaction, 3) connecting lab with literature search and 4) technical report preparation. Also, stated in the lab manual is a rationale for the design of the laboratory which includes: 1) Emphasize the connection between observation in the laboratory

In this laboratory course, students synthesize a unique chalcone and its derivatives (Figure 25). Students randomly pick a card with their starting ketone and aldehyde at the first laboratory session. Each of the starting aldehydes and ketones has different substituents, which create variations in the behavior of the compounds. Students do all of their work independently; no group work is involved. After synthesis of the chalcone, students are required to synthesize three additional derivatives – a dibromide, an epoxide, and an isoxazole. A significant part of the laboratory involves using the Carbon-13 NMR data and knowledge of Hammett constants to predict and then determine which isomer of the isoxazole was synthesized. Details on this portion of the lab are given in a previous publication (Stephens and Arafa 2006). Additionally, students are required to synthesize two or three additional compounds of their choosing from any of the derivatives they have already made (Figure 25). Students utilize Nuclear Magnetic Spectroscopy (NMR), Infrared (IR) Spectroscopy, and melting point data to fully characterize their compounds. They also perform their own melting point and IR spectroscopy. They prepare their samples for NMR analysis and receive the spectrum at the next laboratory period. Literature searches using an online database (*Reaxys*) are also used (Tomaszewski 2011). Students' use this database to search for their synthesized compounds in the literature that match their structure. They can compare melting point, appearance, and any spectral data listed for the compound to their own. Some of the compounds that are synthesized have not been reported in the literature. This provides an opportunity for some students to fully characterize and prepare these compounds for publication.

At the end of the semester, students submit a comprehensive laboratory report describing the compounds they synthesized. They use the data they collect on their synthesized compounds to support their conclusions. There are several quizzes throughout the seven-week session

regarding chemical concepts, laboratory procedures, chemical structure of reactants and products, and Organic Chemistry mechanisms. At the end of the course, students take a final exam. The exam is essay and short answer format only and it assesses students' proficiency in the following topics: Reaction mechanisms, laboratory safety, general questions regarding laboratory procedures, yield calculations, proton NMR, Carbon NMR and knowledge of Hammett Constants.

All instructors use the same grading rubric for assessing the laboratory report. The final report is graded on the required data collected for each compound, the quality of the writing, the quality of the discussion of the results, and how the data was used to draw conclusions about the structures of the synthesized compounds.

Both tenure and non-tenure track faculty are instructors of this laboratory. Although Graduate Teaching Assistants (GTAs) provide assistance to the instructor, they are not the main instructors for this course. During the laboratory session, the instructor and teaching assistants circulate the laboratory to give guidance to students as they perform their synthesis and other procedures. Since each student has a different derivative of the compounds, they can have very different reactivity, solubility and reaction yields. Hence, it is very important for the instructor and TAs to employ appropriate questioning and listening skills to best provide students' guidance when they have challenges. Because of the nature of the course, instructors will typically observe more experienced instructors teaching this course before teaching it themselves. Thus, instructors can better translate the goals of the course to students and maintain the pseudo-research like nature of the course without providing students with too much guidance or detailed step-by-step instructions.

3.5 Methodology

A qualitative approach using purposeful sampling (Patton 2002) was taken to answer the following research questions presented in this study.

3.5.1 *Participants and Setting*

This study was conducted at a large urban research institution in southeastern USA. This institution contains a diverse student population consisting of African American/Black (39%), White (35%), Asian (14%), Hispanic (9%), and two or more (5%). Gender distribution at this institution consists of 36% male and 64% female (Figure 27).

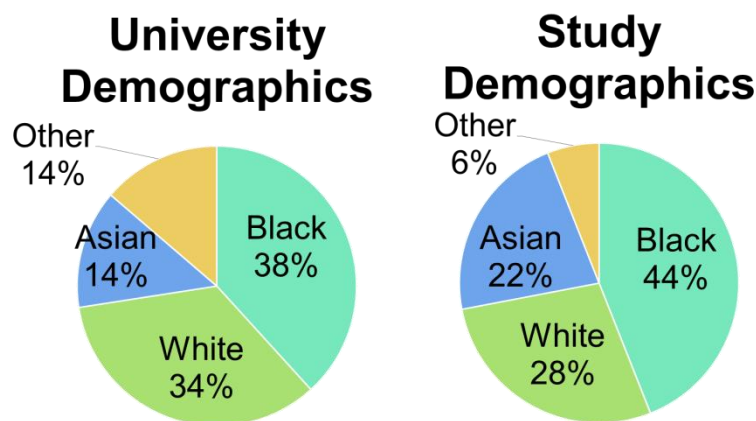


Figure 26: Demographics of student population in Institution vs. Demographics of the study

During the Fall 2013 and Spring 2014 semesters 21 students were voluntarily recruited on the first day from four Organic Chemistry (O-Chem) II lab sections to participate in the study. A qualitative approach using purposeful sampling (Patton 2005) was used to answer the research questions presented in this study. A homogeneous sample was chosen to address the research questions about student perspectives in a project based laboratory. To qualify for the study two requirements was met by each participant: 1) participants had to be 18 years or older, and 2) participants had to have taken both the General Chemistry (G-Chem) II and O-Chem I labs at the

study's institution. Students were selected based on these criteria to obtain students who have been previously exposed to the project-based style of chemistry labs at the institution of interest. Once qualified, informed consent was obtained and participants received a \$20 gift card for completion of both the pre and post laboratory interview. Of the 21 students, 18 participants completed both the pre and post lab interviews. De-identified demographic information can be found in Table 14. The student population interviewed consisted of African American/Black (44%), White (28%), Asian (22%), and two or more (6%) with a gender distribution of 28% male and 72% female. This distribution was similar to the overall demographic distribution of the student body at the host institution. Most students participating in the study were pre-med; however, a range of majors and a variety of student study classification levels participated in the study (Table 14). Students also gave self-reported G-Chem II and O-Chem I labs grades which ranged from "A+" to "C-" for both courses.

Table 13. Participant Demographic Information

Participants (Pseudonym)	Major	Classification	Research Experience
Catina	Biology	Sophomore	No
Dali	Chemistry	Junior	No
PrimRose	Biology	Junior	No
Daria	Psychology	Senior	No
Denika	Biology	Senior	No
Edward	Chemistry	Sophomore	No
Princess	Biology	Senior	No
Sterling	Chemistry	Sophomore	No
Valorie	Biology	Senior	Yes
Dusk	Psychology	Senior	No
Brandon	Chemistry	Junior	Yes
Claire	Biology	Senior	No
Futurama	Spanish	Sophomore	No
Cynthia	Chemistry	Senior	No
Anthony	Biology	Junior	No
Meyers	Chemistry	Junior	Yes
Dominique	Biology	Senior	Yes

Shaquille	Biology	Junior	No
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3.5.2 *Research Design*

Interviews

A complete set of 18 participants were interviewed within the first and last weeks of the mini-mester (7 week course) via a semi-structured interview protocol (see supplemental) to capture the students entry and exit points after experiencing the lab. However, based on the nature of our research questions focus will be placed on the post interviews for each student. Participants were interviewed and audio recorded in a private room removed from the laboratory environment. Pre-interviews ranged from 28 – 92 minutes with an average time of 60 minutes. In contrast, post-interviews ranged from 18 – 41 minutes with an average time of 30 minutes.

3.5.3 *Data Analysis*

Coding of Student Experiences

We decided to focus our data analysis on the post-interviews. The pre-interviews did not provide the same level of depth and instead addressed students' past experiences with labs rather than the lab under investigation. In addition, many students did not seem to have in-depth recall of their past laboratory experiences. The interviews were coded in several stages. First, interview transcripts were read and re-read and then coded by the first author via an open coding approach using the qualitative data software, NVivo 10. Codes were then revisited, revised, and elaborated as necessary using the constant comparison method (Glaser 1965). The second author then examined the transcripts with the developed codes to validate the initial codes further. The percent agreement for these initial codes generated was 94% (Säljö 1988; Sandbergh 1997). Codes were then further collapsed to organize the data into themes (Table 15). The organization

of codes was also discussed to ensure reliability. This first approach in analyzing the data helped sort and organize the data, which ultimately provided a base for more insightful data analysis. The interviews were then analyzed for semantic themes. Semantic themes attempt to identify the explicit overall meanings of interviews. This analysis involved a summarized interpretation of the data which attempted to theorize the significance of the patterns and their broader meanings and implications (Bruck et al. 2008) compared to previous literature. We were able to describe distinct student perspectives in the lab through this data analysis method. These student perspectives are valuable products of phenomenography research because they describe the various ways students experience labs.

Table 14. Example code table of emergent code names, descriptions and student interview quotations that informed distinct student perspectives

Code name	Code description	Example student quotations
Professional Skill	This code refers to student's mention of any professional skills that were learnt or developed in lab such as multitasking, organization, prioritizing, etc.	Princess: Let's say I only got a three percent yield. So, like, but like, everyone else is freaking out. They're like, "But should I get more? Like should I try to get more?" Like why would you waste your time? He's not even grading you on yield. But you know, they would just be like freaking out because like they want to do well but I think their definition of doing well is like getting really high yields and like making sure you do everything the first time correctly. And like yeah, that's important. That way you don't waste time.
Independence	This code refers to student's mention of independence in the lab.	Daria: And then during the actual lab process, we were very independent and could do synthesis on our own. And so, I don't know, it gave me freedom and I felt a lot more comfortable having known that information previously. I really enjoyed it and it worked really well. So, that made it even better. It wasn't – like everything I wanted to do got done properly, so it was nice.
Affective	This code refers to students mention of a feeling directly resulting from the lab such	Brandon: I was told keep it from lights, let it stir overnight, whatever. And I did it all. I came back Monday morning and it was so horrible, you know. So, stuff like that frustrates you. But as you go like in a research lab like you understand

	as confidence or frustrations.	it. You understand, oh yeah, it's supposed to be frustrating sometimes.
Laboratory Skills	This code refers to student's mention of lab skills such as NMR interpretation or recrystallizing.	Denika: I feel like with CNMR, HNMR stuff it makes no sense at all the first time you're exposed to it. Like it seems completely illogical. And every time you're exposed to it, it makes a little bit more sense. So, I already have like a pretty good understanding of it, but then like seeing like more characteristic peaks for different things and why it would shift this way or that way, it just like reinforces it.
Communication	This code refers to student's free communication in lab to other students, professors or TAs.	Cynthia: Let's say my compound looks weird you know. I'd be like hey do you think this is—because I know the one thing that the students do, I know we're not supposed to compare compounds, but somehow, we end up doing it anyway. And let's say I was supposed to get—let's say my compound was kind of yellow but it looks a little orange, I'd ask the TA if this looks correct.
Mistakes	Students mention of mistakes in the lab.	Catina: Because like some people do get a little, like everything has to be perfect and then that kind of leads you to make more mistakes I think, because I've done that in the past. But yeah, because mistakes defiantly do happening in the lab and you just have to accept that and then that would be more enjoyable
Motivation	This refers to students driving force in lab. This driving force was internal such as mastering or understanding a concept.	Dali: So, I was there every day, I asked questions and I made sure I took notes. So I did understand the material, I did understand what I was doing and I could fix it and make it better. So, I did feel like I was successful in this lab.

Coding for Purpose and Success in Labs

Upon completion of coding, interviews were then further coded based on student responses to common questions in the interview protocol (see Appendix). Specifically, student responses were coded from direct responses to the questions concerning the purpose and success they perceived inside of the lab. Analysis of interview transcripts led to an array of different

student perceived purposes of the project-based O-Chem II lab. In conjunction, student perceived successes in project-based labs were also uncovered. The percent agreement for the codes generated ranged from 94% - 100%.

3.5.4 *Validity*

Threats to the validity of interpretations were reduced by triangulating data across student interviews, observations of instructors, and the laboratory manual (Patton 2002). Primarily, interview transcripts informed the development of various student experiences. In-class observations of instructors were also made to better understand the perceptions students referenced inside of their interviews and to determine if these perceptions originated from instructors. Explicitly detailed quotations were used to support all points made when classifying a lab experience. In the analysis, broader meanings and implications were discussed in relation to previous literature.

3.5.5 *Instructor observations and interview*

Few students take the time to read laboratory manuals and syllabi. Instead, the professor often has to transmit this important information to the students verbally. In our study, laboratory instructors were observed to determine what information was being emphasized and conveyed to students in the laboratory. Laboratory instructors emphasized a variety of goals in the laboratory, which reflected the goals mentioned in the lab manual and discussed by the students in their interviews. This is not surprising since new instructors typically observed more experienced instructors before teaching the lab themselves; therefore, the goals of the lab are consistent among most instructors. Some of the goals emphasized by instructors in the pre-lab are reflected in excerpts from one instructor's interview below:

Productivity

“So, that’s been one of the strengths of the classes. That [students] can, even if [students] hate how we are doing it, you [students] can recover [from a mistake] and you [students] have to learn how to actually be productive and listen.”

Independence

“So, that’s what I think is the real secret, that students, by the end of a few weeks, are talking about their compound. They take ownership of it [their compound] and then they [students] do all the planning, we don’t plan for them.”

Decision-making

“The purpose of the class is decision making. How do you make good decisions, not do you follow directions?”

Professional Skills

“Teaching people to have professional attitudes is again I think the key to project oriented labs. Quit being a student. Quit having every excuse when it doesn’t work and say what? Say I want to be a professional and I want to get the most productivity for the least work. Not that I want to do the most possible lab work and get the lowest possible grade”

3.6 Research Findings

3.6.1 Student Perceptions of the Purpose and Success in Labs

At the beginning of each interview, participants were asked about their thoughts regarding the O-Chem II Lab. The majority of students ($n = 17$, 94%) stated that they enjoyed

the lab and had a great experience in the lab. Only one student expressed indifference about the lab.

Students were asked what they saw as the purpose of the O-Chem II Lab during the post interview session of the study. In response to that question, several codes were generated, and five main categories emerged (Table 16 and 17). It is important to note that most students mentioned more than one purpose to the Organic Chemistry II project-based lab. This overlap is important to note because it demonstrates that students can pick up on the multifaceted dynamics of a project based lab.

Table 15. Generated themes for student perceived purposes of the lab

Theme	Description	Example Quotes
Lab skills and techniques	Students described the purpose of the lab as an environment for discovering the world of synthesis and lab techniques.	Futurama: <i>[I think the purpose is] Organic synthesis. Like discovering what organic synthesis is, and how it can start by making one product and then going from there and just infinitely doing reactions and reactions and reactions. And seeing the purity of our compound along the way and checking ourselves through IR and NMR and spectra. So that's what I think the purpose was to discover what organic synthesis is.</i>
Theory to practice	Students described the purpose of the lab as a visualization and application of concepts learned in theory applied in a real lab setting.	Meyers: <i>I would say [the purpose is] applying...again applying techniques, what you've learned in Orgo I, applying it to now and how. It...I just think it came together when you're synthesizing a compound, like, everything came together from Orgo I. You're using all the techniques, everything you've learned. It's just to see the big picture, like how things were done</i>
Cultivating Independence	Students described the purpose of the lab as a forum for developing their independent skills as a scientist.	Denika: <i>[I think the purpose is] To have people -- I mean, I think it's the same with all of us. Just have people basically literate in lab work. You know, to have some sort of exposure. I think with this one more so than Orgo II there was like -- you felt like you were independent, that you were kind of just on your own doing your project because everyone was doing</i>

		<i>something -- a different synthesis.</i>
Problem solving	Students described the purpose of the lab as going beyond learning skills and techniques. Instead, they describe using these techniques learned to solve a problem presented in the lab.	Valorie: <i>You know, at the beginning of the class, I was like how in the heck am I going to determine which isomer, you know, I was like, he's lost his mind. I'm not going to know how to do this. And so, I – and so over the course of the lab, you know, of course they're teaching you different – it's like that, what is it? Karate Kid, the “wax on, wax off” thing. Like they teach you to do something without really teaching you how to, you know, how to do it. So, it puts it kind of like in your mind as far like the recrystallization because we recrystallized almost all of the compounds. So, it's like you don't realize that, oh, okay, I'm learning this at the beginning, because I'm going to use it later on.</i>
Does not know	Students did not know the purpose of the lab.	Dominique: <i>I don't know [the purpose]. Like I said, I think chemistry labs are like purposeless. So, I don't know I just kind of went and did it and left.</i>

Table 16. Student perceived purpose of the Organic Chemistry II lab

Code for Purpose	Participants with code (n=18)	
	Number	Percentage (%)
Lab Skills & Techniques	12	67
Theory to Practice	6	33
Cultivate Independence	4	22
Problem Solving	3	17
Did not know	2	11

In the laboratory manual, several goals were directly listed for the students. These include: 1) Handling and characterization of solids (including safety concerns and procedures), 2) isolation techniques of solids, planning and execution of chemical reaction, 3) connecting lab with literature search and 4) technical report preparation. In going through the lab manual, we

were able to uncover all implicit and explicit goals for the students (Table 18). Two students were not able to define the purpose of the lab resulting in the code "I don't know" (Table 17).

Table 17. Implicit and explicit goals in the laboratory manual.

Knowledge	Skill	Affective	Professional skill
Modern procedures and methods	Recrystallization	Sense of accomplishment	Critical Thinking
Lab Safety	Filtration	Feeling mastery over the subject	Independence
Proper way to keep lab notebook	Drying Solids	To have considerable initiative and judgement	Ability to draw conclusions out of observation
plan/outline lab work	Determining melting points	Feel familiar with synthesis and characterization of organic compounds	
Academic Honesty	Extraction	Confidence in determining whether the synthesized compounds are pure or not	
Formal report writing	Ability to look through Literature to obtain data		
NFPA Hazard Rating	Compound characterization by using ^1H and ^{13}C NMR		
Chemical literature search	Handling and characterization of solids		
Trouble-shoot recrystallization issues	Isolation techniques for solids		
Trouble-shoot filtration issue	Synthesis		
Some considerations for drying agents	Visualization of "structures on paper";		

Types of melting point apparatus	Technical report preparation
Trouble-shoot extraction issue	
General information about the Spectroscopic methods	

Not surprisingly, the majority of students ($n = 12$, 67%) (Table 17) perceived the purpose of the Organic Chemistry II lab as the teaching of lab skills and techniques associated with organic synthesis (Table 16). These findings agree with a recent study by DeKorver and Towns (2015), which found that General Chemistry students saw techniques and skills as one of the goals accomplished in the lab. Also, based on the implicit goals highlighted in the laboratory manual, there is a heavy emphasis placed on laboratory skills and techniques. The lab skills and techniques mentioned by students ranged from hands-on skills, such as recrystallization, to skills used to interpret proton (^1H) and carbon (^{13}C) NMR. Some students also discussed lab skills and techniques in the context of future employment. Shaquille, a post-baccalaureate student majoring in biology, discussed the lab in the context of future jobs and career preparedness. In his interview, Shaquille described his viewpoint of the purpose of the O-Chem II lab by saying,

As I said first off, [the purpose of the lab is] how to remember what you did in lab one, the procedures, the techniques, and everything. And once you have repeated them over and over it's like—I don't know what the expression for that is—but you have like a swift hand in doing everything. And it's good when you are applying for a job or are actually doing something in a research lab.

Other students discussed these lab skills and techniques from the perspective of discovering “the world of synthesis.” Students discussed their ability to see how synthesis could be used to modify compounds. Dusk, a senior psychology major, described visualizing organic synthesis as she explained the overall objective of the lab by saying,

I know the overall purpose was, I guess that earlier, was to go from your two starting reactants and going to make six products out of that. And using that first product you made four, and then using those products to make other ones. So, it was just like a, I don't know, like modifications branching off of a tree off of those two reactants. I know there was a point of it, it was just starting with those two and ended up with six. So yeah.

Students that identified lab skills and techniques as the purpose of the Organic Chemistry lab also mentioned other purposes for the lab that went beyond technical skills. These other purposes mentioned include cultivating independence, problem solving, and utilizing theoretical knowledge into practice (Table 16 & 17). This overlap is important to note because it demonstrates that students can pick up on the multifaceted dynamics of a project based lab.

In our project-based Organic Chemistry II labs, several elements of independence have been purposefully incorporated into the labs that are mutually exclusive of instructors. Independence was not an idea directly expressed by instructors to students, which was confirmed through classroom observations. Also, independence was not directly stated in the laboratory manual; however, several students specified independence as a purpose of the lab. When asked

about the lab's purpose, Denika, a senior majoring in Biology with no prior research experience, explained the purpose of the lab as follows:

*[having] people -- I mean, I think it's the same with all of us. Just have people basically literate in lab work. You know, to have some sort of exposure. **I think with this one more so than Orgo I there was like -- you felt like you were independent, that you were kind of just on your own doing your project, because everyone was doing something -- a different synthesis. I think it was more fun to synthesize as opposed to just like identify like you did in Orgo I.***

Denika along with other participants developed strong feelings of independence as the lab progressed. Students attributed these feelings of independence to their individual projects, reduced reliance on the instructor or TAs, and freedom to modify procedures.

Students that viewed the purpose of the lab as developing problem-solving skills also gave similar reasons. Dali, a junior in chemistry, discussed her newfound ability to troubleshoot issues (solve problems) in the lab. She described these as "different ways to do stuff" in her interview below:

Dali: Just like learning different ways to do stuff I guess because I mean like...

Interviewer: What do you mean by learning different ways to do stuff?

*Dali: **Like we would have a general procedure. But say your stuff came out like an oil, then you would have to extract it differently, instead of having like regular solids, and filtering it, and putting it back and filter.***

Other people had to use separatory funnels and try to do like liquid extraction instead. So, everybody didn't have like the exact same procedures. So, you learned like different ways. So, if it doesn't go the way you're expecting, how can you fix it to get it to go the way you want it to be? We learned about that, so yeah.

Students also mentioned 'theory to practice' as one of the purposes of the lab. Theory to practice describes students' feelings regarding the practicality of implementing theoretical knowledge into real science situations in the lab. This is better described as seeing the reality of science.

Sterling: I think it was a transition from theory to practical.

Interviewer: What do you mean by that?

Sterling: Because in the other labs, like Orgo I lab, most of what we do was mostly based on the theory, but we learned in Orgo II lab that that's not how you would do it in a real lab. It's not practical to do it. You take an IR; it's not going to tell you anything. So, we took IRs from our compounds and what did we learn from those IRs? We learned absolutely nothing. We only learned that compounds are different because they look different, but we can't identify anything from the IR. So, we learned that theoretically how things work, it's nice. It's nice to live in those fantasy worlds, but reality is a bit different. It's not practical to do all the extra stuff

when you have functional systems that will take you to the answers you desire. Like for identifying compounds, proton NMRs, and carbon 13 NMRs, those would tell us what they look like. And IR would tell us absolutely nothing.

Students were asked to state how they defined success in the lab and whether they felt successful or unsuccessful in the lab. Several codes were generated, and four major categories emerged (Table 19). Many students ($n=12$, 67%) (Table 20) defined their success in the laboratory based on the grade they would receive in the course. In part, these findings agree with findings by DeKorver and Towns (2015) in which students listed grades as one of their goals of laboratory. Descriptions of success in the project-based lab were then described as productivity ($n = 10$, 56%), understanding ($n = 7$, 39%) and independence ($n = 1$, 6%).

Table 18. Generated codes for the student perceived success in labs

Code	Description	Example Quotes
Grade	Students described their success in lab linked to the receipt of a good grade (A or B) in the lab.	Interviewer: So how successful do you feel with your project, your experiment? And what do you define your success as? Anthony: Oh, wait, of the experiment or the lab in general? Interviewer: The lab. Anthony: Oh, the lab, okay. Well, you know, I determine whether or not you've been successful in lab by the grade you get.
Productivity	Students described their success in lab as their efficiency, yield produced or completion of lab work.	Interviewer: So, do you feel that you'll be successful with this lab? Edward: If I did it again, yes, definitely because you know, before I kind of lagged a lot and I took a really long time just doing each step because I just wanted to know like if I was doing it correctly and seeing you know, if I did any errors.

Understanding	Students described their success as their ability to understand what they learned or reiterate that understanding to another person.	<p>Interviewer: Ok. So, what do you define your success as, like when you do enter a class? How do you define your success in the class?</p> <p>Catina: Basically, just understanding what you're being taught, and being able to like reiterate what you learnt. And just like an understanding of the subject really.</p> <p>Interviewer: So, what do you mean by reiterate?</p> <p>Catina: Being able to tell other people what you've learnt because that's how you know if you really know it.</p>
Independence	Students described their success in lab as the ability to perform lab work and understand material with little to no aid from the instructor.	<p>Interviewer: Do you feel that you were successful in any other way inside of this lab?</p> <p>Valorie: <i>I think I was successful in the sense of once we got into the semester. Well, not semester, but you know, the mini-mester. I kind of stopped relying on asking the TAs questions and asking the professor questions all the time. And you already know what you have to do, so it's like you go in a lab and you're independent.</i></p>

Table 19. Student defined success in lab

Participants with code (n=18)		
Success Definition	Number	Percentage (%)
Grade	12	67
Productivity	10	56
Understanding	7	39
Independence	1	6

In this study, defining success as grades was also linked to developing understanding. Six out of the seven participants that listed understanding as a measure of success also mentioned

that receiving a grade of A or higher was also an indication that they were successful in the lab.

Dali eloquently mentions these two measurements when she said:

*I guess in two ways I can define success is if **I understood the material** in the class and then also if **I got a decent grade** out of it.*

Aside from grades, students also viewed their productivity ($n=10$, 56%) as a measure of how successful they were inside of the lab. Productivity came in two main forms which both related to the successful completion of the project. Valorie, a post-baccalaureate student hoping to enter medicine, described success through productivity when she said: *“I always base my success on **my percent yield** because you know, that’s just what I do.”*

Students, like Valorie, typically based their success on percent yield or other experimental outcomes. On the other hand Edward, a senior chemistry student hoping to enter pharmacy school, based his success on his efficiency and correct completion of the project, which he described when he said: *“**I kind of lagged a lot and I took a really long time just doing each step** because I just wanted to know like if I was doing it correctly”.*

There was one student that defined their success based on how independent they felt inside of lab. This description of success was brought about is the quotation below on success by stating:

*“I think I was successful in the sense of once we got into the semester. Well, not semester, but you know, the mini-mester. **I kind of stopped relying on asking the TAs questions and asking the professor questions all the time.** And you already know what you have to do, so it’s like you go in a lab and you’re independent.”*

3.6.2 *Student Perspectives of the Project-Based Lab*

As stated by phenomenography, students can approach learning environments in a variety of ways, and labs are no different. This project-based lab is meant to simulate a quasi-research experience in which students are given a project to complete. This experience can differ from student to student. In our study, we have uncovered eight distinct ways that students perceived the project-based lab. It is important to emphasize that individual study participants do not only belong to one category of description since they tend to express their views among several. In our results section, we chose to describe each of the eight categories of description using one student who exemplified that experience.

Table 20. All described student experiences and focus in the project-based lab

Student Perspectives	Students' Focus
Explorer perspective	Exploring the unknown in science
Independent researcher perspective	Cultivating independence
Mastery perspective	Practical Understanding of concepts
Socialite perspective	Social Interactions
Skill developer perspective	Developing technical skills for future career
Detail oriented perspective	Gathering details of lab and experiments
Time saver perspective	Efficiency and saving time
Apathetic perspective	Uninterested in the lab

Explorer perspective

This student perspective focused on the unexplored aspects of science and embraces the unknown ambiguity of science. Sterling, a senior chemistry student who tutors chemistry and TAs other General Chemistry labs, typified a student who embraces the unknown nature of science. In these project-based labs neither the professor nor the student knows the outcome of the experiment or if the synthesis will be successful. Sterling's enjoyment of the lab was based on this element of the lab. Hence, discovering that there was more information to be uncovered in the world of chemistry fueled his excitement. Expanding knowledge and applying it to the unknown was a focus of Sterling:

It was nice to know that there's – it's nice to know that I don't know as much as I thought I knew. So, there's more to learn. Learning is fun to me because then you can use that information and have fun in laboratories.

Sterling gained enjoyment through the application of knowledge to new situations. Many of his decisions in lab were based on interest and discovering the unfamiliar. As noted previously, towards the end of the lab students are given the freedom to select two synthesis procedures of their choice. Sterling, driven by exploring the unknown, expressed his reasoning for choosing a procedure when he said:

*The structure looked interesting. Yeah, the structures looked interesting and then the synthesis routes required me using some **things I'd never done before, ever seen before.** And then I discussed with Professor X before I did it and **he said they may work or they may not work.** So, **I should just see if I can try my hands on them. I went for it.***

Ambiguity in lab was seen as a positive challenge to Sterling. To that extent, Sterling perceived working in the lab as a basis for exploration and questioning the science he was performing. In each experiment, Sterling was able to change the procedure and adjust chemicals based on his own decisions. This freedom in the lab not only allowed him to develop independence but it also allowed for him to assess the scientific knowledge that he had learned:

I got to learn that I can't just take science as it's – just accept science as it is. I have to look into it myself or look into it further than what is explained to me to see how it really is or if that's just a theory that hasn't been supported enough yet. Because so far, I think that most of science is just a theory.

Sterling exemplifies the student experience that is focused on further exploration of science in the laboratory experiments. This kind of student sees the lab as an environment to test and go beyond theoretical knowledge learned in lectures. Perceptions of the lab are based on the freedom to question the unknown nature of science. Also, this type of student experience is deepened from the ability to prove or disprove scientific knowledge, and enjoyment of lab is enhanced by the ability to explore the science in the lab.

Independent researcher perspective

This student experience focuses on the cultivation of independence and thrives in the quasi-research portion of this particular lab environment. Meyers, a junior chemistry student with prior research experience in biochemistry, provided an ideal example of a student experience

focused on the independence achieved in this lab. Technical skills used in this lab were developed in previous G-Chem and O-Chem labs. Meyers focused on her ability to relate past lab techniques to the current O-Chem II project-based lab. The previous exposure to techniques allowed her to focus on the cultivation of independence in lab. This point was highlighted when she said:

I don't know um they [the instructor] expect you [the student] to remember a lot of things from Orgo I lab and like how to run a reaction under reflux. Like they don't teach you that again in the pre-lecture. So, it's like, ok, we are going to run a reaction under reflux and it's like, oh, now I have to remember what that is. So, it's like a lot of independence stuff that you should know already. So, I just felt independent because you set up your own thing and you kind of know what you're doing already. They're not showing you.

Meyers discussed that she noticed how independent she was becoming in various activities inside and outside of the lab. When selecting a procedure, Meyers saw an opportunity gain additional independence in lab and further hone the lab skills taught to her over the years. This point was explicitly made when she discussed her views of the knowledge she gained from lab by saying:

I mean it [lab] made you think. Like [Professor X] made it– us think. Most of the quizzes and stuff that we had to do of the reaction or the mechanism wasn't necessarily taught. He just gave like a General path that it would go down but we would have to

like read about it and kind of figure it out for ourselves. I think a lot of the independence came in there... the two [experiments] where you actually have to learn it yourself. So, it was challenging enough that you have to figure out what's happening in the reaction.

Meyers perceived working in the lab as an opportunity to practice independent lab work. The unique reactant combinations each student received was perceived as one of the most valuable aspects in the lab. This difference was perceived as valuable because Meyers valued not having interference from other students in regards to her lab work. Meyers liked the separate nature of working on her own project. She explains this point when she said: *I did... I liked that everybody had something different because everybody was focused on their own stuff and not peeking over at what you're doing.*

Meyers represents a student experience that is focused on becoming an independent researcher. This type of student perceives the lab as an environment to cultivate independence. Perceptions on the lab were made based on aspects of the labs design that allowed students' lab work to be separate from others. Thus, a student that experiences the lab through the lens of an independent researcher develops understanding and finds enjoyment in the lab based on the ability to cultivate independence, unassisted by instructors.

Mastery perspective

This student experience was focused on using lab to deepen understanding of concepts. Valorie, a post-baccalaureate biology major with prior research experience in statistics, exemplified a student who developed a deepened understanding of concepts through lab work.

This focus was expressed when she said, “*So, you know, I have a real good understanding –an understanding as well as being able to apply it.*”

One skill that was a central focus of the lab was NMR interpretation. NMR facilitated students’ ability to identify and characterize synthesized compounds, therefore Valorie focused on understanding the concept of NMR. This point was highlighted when she said:

In Orgo I lab and lecture, you know, they tell us about NMR and we have to learn it. But I didn’t really appreciate it or understand what – I mean, I understood why I was learning it and what it’s used for. But I guess I didn’t understand how effective it could be until I got to the lab. So, to me, that kind of connected the dots, okay, like so NMR, especially the difference between H-NMR and C-NMR, like I know they’re different because you’re looking at the hydrogens, how many hydrogens and how many carbons you have. But in my mind, I kind of always kept like kind of isolated from each other. So, it kind of put it together for me...

As a post-baccalaureate student, Valorie was adamant about the importance of knowledge and concept mastery in lab. Valorie’s focus on understanding was also reflected in her perspective of lab work. This lab required a final report at the end of the course that assesses students’ ability to synthesize all the information they have gathered throughout the lab. Also, this report allows students to put their projects into perspective. Upon doing the final report Valorie recognized her connection to the information beyond surface understanding. This point was brought to light when she said:

But I actually understood, like I didn't – like with the other Organic classes, I understood the information, but I understood it just enough to do the final report. But with this class, it's like I understand it to do the report, and it was easy. I mean, I was shocked because normally it would take me days to do an orgo report just because I would have to gather all my notes and figure out, you know, this and this and figure out all this stuff. But it was just so much easier.

Valorie illustrated a student experience that focused on the lab as a way to deepen understanding of concepts learned in other chemistry courses. More specifically, this type of student was concerned about applying previous knowledge to solve problems in the laboratory and enhance their overall learning experience.

Socialite perspective

This student perspective focused on the social aspects and interactions with others in the lab. Anthony, a junior in biology, embodied the type of student. As previously noted in the lab design section above, individualized projects were given in this lab, which prevented students from relying on others when carrying out experiments. Despite this element of the lab's design, Anthony sought to develop friendships inside of the lab. He focused on the “fun” social side of the lab and this point was highlighted when he said: *It was just a fun lab in General, I made a lot of friends in that lab - it was just fun to be in there. It's just the reports and stuff that were killer.*

Anthony also saw student-student interactions as a way to learn more. The impact of communicating with other students in the lab provided him with new perspectives on his experiments. As such, the ability to compare and contrast different compounds and observe other student's results provided insight into other possibilities for the same experiments. Anthony highlights this in his advice for incoming students by saying:

Make friends, like for sure, make friends [is my advice]. Don't be afraid to you know put yourself out there and compare yourself to other peoples. To find out, you know, more about other people's substituents. I feel the biggest thing about working in Orgo II is being able to not only make all of your compounds and understand them but to be able to see the wide variety of compounds that you can form and what they look like.

In his interview, Anthony frequently referred to opportunities available in the lab to socialize with other students. This ability to socialize also affected his viewpoint of the lab work. Despite the fact that students had individualized work, Anthony's perception of lab work was group based and perceived through the amount of social interaction that was involved in the activity. When asked to describe what reactions he found easiest he replied by saying:

But along with [this lab being easy], it was just fun reactions I guess, in General almost all the reactions are fun to do. There wasn't anything too tedious. I think I did do the alpha bromination under reflux for like an hour or something. But again, we did the melting point and stuff like that and we had our group so we all sat there watched our stuff together.

Most of Anthony's interview focused on what he did in the "group". Anthony was aware of the lab was not group-based. However, he decided to pursue social interactions:

So, I think even if it is not necessarily group-based, maybe I still think that the lab sets up ample opportunities for you to be able to make groups and work with people that are friendly and stuff, so I think it was good in that regard.

Anthony generally enjoyed opportunities to form groups inside of the lab because he was able to work with other students. Anthony and other students like him perceived the lab as a social environment for pursuing social interactions. Their decisions in the lab were influenced on the volume and quality of interactions with other students. Also, this type of student gained understanding in the lab by comparing and contrasting with the experiences of other students.

Skill developer perspective

This experience focused on building technical skills for future employment. Shaquille, a post-baccalaureate biology major, represented a student focused on developing hands-on lab skills for his future career. O-Chem II lab is often the last laboratory course for non-chemistry majors and as such some students expect to learn more "real world" lab skills in this course. Throughout his lab experience Shaquille sought out direct applications and transferability of the

skills he was learning in this lab to careers outside of school. His excitement for transferability of these practical skills was highlighted in the following exchange:

Shaquille: Well if you remembered we talked about the professor's part in the lab and giving out more practical aspects of the lab.

Interviewer: Such as field trips and stuff?

Shaquille: Right. I don't know if you talked to him or not [the interviewer did not talk to the professor], but right after our interview he started talking about how we could use our, you know, understanding of this lab and the experience in our future careers. And he just introduced some kind of uses that would be useful that you know—and it's related to what you are doing now. So, it's not just a regular lab. You are actually going to use these techniques in the future. And it was exciting, yeah. And that's it.

Shaquille's focus on relating lab skills to future employment was also reflected in his perception of the lab. Shaquille was concerned about how the knowledge he was learning could be directly applied to future careers. His concern for skill development was geared towards skill sets that were easy to quantify (NMR interpretation, recrystallizing, using the rotary evaporator, etc.) and readily applicable to the workforce. Shaquille explicitly expressed how he paid attention to technical skills directly related to the workforce below:

Yeah exactly, because I knew that there are some careers by just names. But making a connection with what you're doing and what is your potential to do in the future, that was

exciting. It was really exciting for me and actually after that I tried to, you know, ask more questions and be more practical about what I'm doing, you know. Because maybe I may use this stuff, you know, that I've learned today.

He then later goes on to describe how these skills can be used to improve his resume:

If you are working in a chemistry lab you have to be able to read NMRs, IRs. That's something that you'd probably have to do a lot [in a chemistry lab] and that's not what everyone can do because—just ask my classmates. But if you learnt that then that's a really big plus on your resume.

Even when questioned on what he learned in the lab, Shaquille directly mentions employment:

*When I did the synthesis procedures I actually learned that, ok, even if you can't connect those, you know the information that you have, that ok now that I have the [compounds] that can react with something like water. And... aldehyde don't react for example or then if you add like water, solvent and the product it's going to be like separated from the other products or reactants. So, I could make that connection with what I learned in lecture. And the other thing, it was kind of basic, **but it prepared you for your future career.***

Shaquille's focus on the practicality of lab work for future employment also affected his perception of lab work in many aspects. Particularly, Shaquille saw lab as a place to develop skills for future employment and believed that assessment of these lab skills should be done in the lab course:

I prefer to be tested on those [lab skills] rather than the basic knowledge of what you know. Now, you definitely have to know your stuff from the lecture, but being tested basically on that—I don't think that's going to help for evaluating the students for the lab portion. I'd prefer that we left it in the lecture course.

Shaquille illustrated an experience focused on building practical skills for future employment. This experience perceived lab work through the lens of practicality and applicability of technical skills. Conceptual connections were developed based on the teachable skills that are applied to future careers.

Detail oriented perspective

This student is focused on the details of the experimental procedures and as such is overwhelmed by the ambiguity of the course. Primrose, a junior in biology with no prior research experience, epitomized the student who has difficulty dealing with the ambiguity of science and searches experimental details to avoid mistakes. As stated in the lab design section above, the outcome and results of the experiments were not outlined or defined. This element of the lab had a huge impact on Primrose's ability to cope with the unknown. Primrose focused on the mistakes that could be made in lab due to the lack of details provided for the students. Primrose expressed

her disdain for the ambiguity of lab procedures and the possibility of making mistakes and failure:

Interviewer: Did [your experiment] fail?

Primrose: It failed and then, that was also at the time that I was doing two reactions, the isoxazole and the isoxazoline... So, I had those on the same time and I just heated it just a little bit, but not boiling, and then added the KOH. And the instructor came over, and said that the reaction could fail and it did fail!

Interviewer: And how did you feel about that?

Primrose: I felt very sad, very mislead and just... kind of just frustrated that it [the lab manual] didn't say to boil. It didn't even have a note saying that this reaction could fail if you don't heat it properly.

Interviewer: So what particularly you felt mislead you?

Primrose: The word heat. And even again she [the instructor] had printed out an extra – some extra instructions that she had come up with. And it still said just heat, it didn't say boil, and I don't recall anytime that she said boil in the lab.

Interviewer: So did that experience affect anything you did later on inside of the lab?

Primrose: That experience, yes, because that put me behind. Now I was two reactions behind, I had less chalcone to make, so I couldn't just take the chalcone and just start all over again.

Primrose was slow in her lab work due to the uncertainty she experienced in the lab. From her experience in previous labs, Primrose found that focusing on details was a mechanism for avoiding mistakes. However, this current lab simulated a more research-like experience. As such, the ambiguity, uncertainty, and trial/error aspect of science hindered Primrose from using her detail-oriented approach to tackling labs to help avoid mistakes. She felt unable to rely on her abilities to interpret the correct way to carry out an experiment. Primrose spent time asking fellow students and the instructor about the procedures before she would carry out her experiments:

So, [the lab manual is] not really divided out into steps. So, for making the epoxide out of the chalcone, for example, it just says, add chalcone, add 20ml of ethanol, add 12ml of acetone, add 1.9ml of NaOH, add 2.9 ml of hydrogen peroxide; but it doesn't say that you need to dissolve the compounds right after you add each one individually. So...and I found that out through other students throughout the lab that are like, oh wait, and you guys need to add them and then shake it, and dissolve it, and just don't pour it all in at one time. So, I was like okay.

Primrose's attention to detail was reflected in her perception of the lab manual. As mentioned previously in the lab design section above, the procedures in the lab manual were taken from experimental procedures in peer-reviewed journals. Therefore, the language used in the lab manual reflected the language chemists use to communicate experimental procedures to other chemist in the community. This means that the amount of details was for that of a chemist

and not a student. This presented another level of scientific ambiguity that Primrose was not able to cope with, which resulted in her having a negative perception of the lab manual. When asked about her opinion on the lab manual, Primrose responded by saying:

*There was a need for more detail. It was necessary to know that your reaction could fail if you don't boil it. It was necessary to know that if you don't dissolve it you could have impurities. And it was necessary to know that if you just dump the bromine in it could overheat and your flask could crack and, you know, you could go back to your desk and your compound fall everywhere from your flask breaking. That was kind of important, because the instructor put emphasis on safety procedure **but they didn't really tell us things could fail**. I mean that kind of looks to me if things fail and you have a job you could get fired or sued. That's really important.*

Primrose exemplified an experience that focuses on getting sufficient details as a means of avoid mistakes. This type of student perceived the project-based lab as a cornucopia of pitfalls due to its ambiguous nature. Perceptions on the lab were made based on design aspects of the lab that mimicked a real scientific research experience. Also, this type of student's learning experience seemed hindered by the lack of explicit detail. Thus, this student's understanding and enjoyment of the lab were not enhanced due to these aspects of the lab.

Time saver perspective

This student experience focused on efficiency, thus resulting in a lab experience centered on saving time. Edward, a junior chemistry student pursuing a career in pharmaceuticals,

personified the type of student who experienced the laboratory environment with a focus on saving time. Typically, very few students in this project-based lab had an issue with spending five hours in the lab; however, Edward focused on how much time he devoted to an experiment. He even described his work in the lab based on how efficient he thought he was:

Like in the beginning, I felt like I was really slow at like all the experiments, like especially with the chalcone experiment, creating your chalcone. And as the labs progressed, I actually like picked up speed and I was able to, you know, do my experiments on time.

Edward saw his progression in the lab through the lens of efficiency, which he expressed through his recollections of experiments. Many of his decisions in lab were based on saving time in lab. This was noted towards the end of the lab when students were given the freedom to select two synthetic procedures to carry out independently. Edward's decision on which procedure to select was driven by time-saving factors:

*There were other [student selected additional] experiments, but I chose the 4-hydroxy because I had epoxide that I could use that was good for that experiment. **And plus, it was really fast. Well, just the preparation for everything was fast.***

His perception of lab work was also based on time spent performing experiments or procedures and on how much “involved” work he was required to do. Edward described the “involved” lab work as time-consuming and unfamiliar. This was viewed as his least enjoyed

aspect of the lab. This point was brought to light in his description of his least favorite experiments described below:

*[Epoxide was my least favorite experiment] because the epoxide experiment, that one was I think – yeah, that one was the one that took... for it you **had to be really patient** because you had to heat the experiment in a water bath for like 40 minutes, or 40 to 45 minutes for at about 40 degrees Celsius I think it was. And so, **that took a while** because you had to titrate... I forgot what solution into the compound...But you **just had to keep continuously heat and watch the compound from overheating or being under – yeah. So, you had to like make sure that you kept it about 40 degrees Celsius. And yeah, if it went over, you had to put in an ice bath and put it back in. It just took a lot of time. And the other one [least favorite experiment], yeah, I think that was the one I didn't like the most. Also, creating the chalcone, because mine did not dissolve properly in just one flask, so I had to put it several other flasks and it took a lot of time. But yeah. You know, the epoxide was the one I didn't like the most.***

Edward illustrated the experience of students that focused on aspects of time. Decisions in the lab were made based on saving time in the lab, as well as being efficient. Perceptions of the lab were made based on how much time involvement was required. Also, emotional satisfaction came from being efficient, and this experience viewed success based on productivity. Hence, this student experience was connected to the amount of time required to get the work done.

Apathetic perspective

This student experience is described as a lack of interest in lab work. Dominique, a senior biology student, exemplified a student that was disinterested in most aspects of the lab. Dominique had no focus in the laboratory and was unable to define a purpose for the lab. Her indifference to lab work was extended to all chemistry laboratories. She viewed chemistry laboratories as purposeless, which she described by saying:

Dominique: I don't know. Like I said I think chemistry labs are like purposeless. So, I don't know. I just kind of went and did it and left.

Interviewer: So, were there any purposes that the teacher emphasized?

Dominique: I can't remember. Like I literally went to class, reviewed my notes so I could do well on the exam and quizzes and left. Like I'm not a chemistry person, so I kind of went in there like "oh gosh, got to get this over with" and then I left.

Dominique's perception of the lab work presented itself as something that had to be done and over with. This perception influenced multiple aspects of her lab experience.

Interviewer: Can you tell me your experience you had with the Orgo II lab this semester?

Dominique: It was cool. Like it was a lot of tedious work, but it was cool.

Interviewer: So, what about it was tedious to you?

Dominique: Just waiting for everything. Like I told you before, I don't like to wait for labs. I don't like it. But yeah.

Interviewer: So, is there any...When you decided to do a new lab, what type of things were you thinking about when you were making that choice?

Dominique: Just so that I don't have to do it the next week. That's it...

Her avoidance of lab work and her need to get work done was also reflected in her perception of the lab work itself. When asked about how she felt about lab work she replied, "How do I feel about it? It was required, like I had to do it. That's about it". Based on her explanations for her decisions above, it could appear that Dominique's motivation was simply a matter of saving time. However, when probed further, Dominique revealed that science was not a career she was interested in and that her major was simply a choice made by her parents. When asked about the purpose of labs she responded:

Dominique: I think I wasn't trying to understand the lab. I just wanted to get it done, but I didn't go in there like I wanted to learn something because I don't think lab really benefits what I'm trying to do. So.

Interviewer: That's dental school, right?

Dominique: It was, but now I don't know what I want to do. So, I don't think it really benefits to anything that I want to do. So, I'm trying, I just want to get it done, like I graduate soon. So, I just want to get it done, so I can move on to that next step.

Interviewer: So, you have any direction you want to move in. Are you going to stay in science?

Dominique: I don't know. I have no idea. I might get in my Masters. I was going to get it in public health but I was like why waste money if I'm not sure if that's what I want to do. Just like this biology degree it was just something my parents thought of. I'm not sure if I would have chosen biology, but then I'm not sure what I would have chosen at this point. So, I'm just going to think about, reevaluating my life, and figure out what I want to do.

Ultimately, Dominique had no critique for the lab or any explanation as to why she was trying to save time on experiments. Her focus, decisions, and perceptions of the lab all linked back to her lack of motivation for the lab and science in General. Students like Dominique are likely to come through laboratory courses. She stated that the lab was not for her. She highlighted this point when she discussed improvements for the lab:

No [I do not have any improvements], because there's certain people who are actually genuinely interested in the stuff and it would be perfect for those people. So, I wouldn't say there is anything to be improved on, because I think it's pretty ok for the chemistry majors and people interested in doing research for the rest of their lives or even if you are interested in going to dental or medical. So, it's great for those people, just not me.

This student experience perceived the lab as irrelevant and purposeless. This experience lacked interest in the subject matter. Students with this type of experience seemed to have little to no observed enjoyment of the lab experience.

3.7 Discussion and Findings

An important part of using a phenomenographical framework is to define an outcome space that shows how these experiences are related and fit into the laboratory experience as a whole. The framework of situated cognition provided us a lens by which to connect various laboratory experiences. As previously described in the introduction, we believe that situated cognition is compatible with phenomenography since situated cognition “suggests that thinking (both in everyday life and in educational situations) is influenced by the immediate situations and cultural contexts in which it occurs.” In addition, we are able to connect our categories of description to the student learning and development based on the qualitative variations in students’ engagement as legitimate peripheral participants (LPP). We have arranged each category of description or perspective along a continuum of increased engagement in the laboratory learning environment (Figure 27).

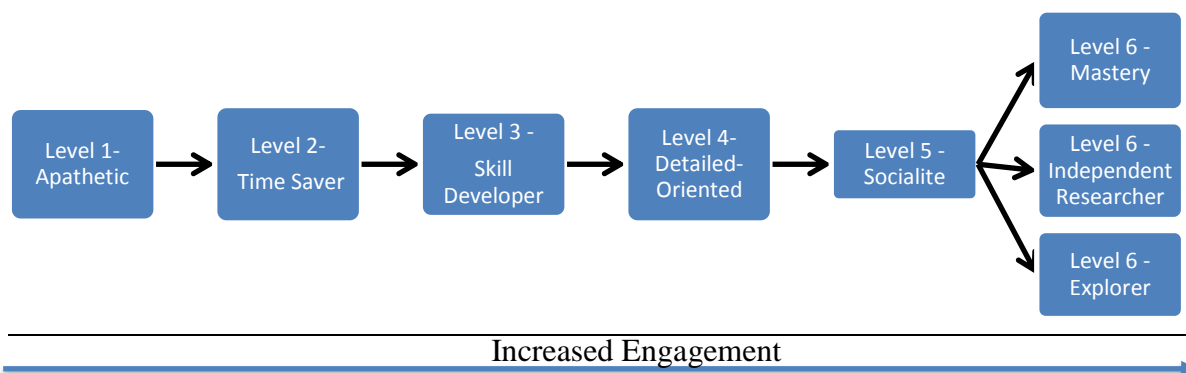


Figure 27. Outcome space that describes each perspective along a continuum of engagement in the lab environment.

We placed the ‘apathetic’ perspective at the lowest level of the engagement continuum since this category represents students who are not motivated to be engaged in the lab because of lack of interest in science. They are focused on doing just what is required to complete the lab and receive a good grade. This type of student is not interested in the purpose of the lab, how they can build additional skills for the future. Above the ‘apathetic’ perspective we place the ‘time saver’ category. Students with this perspective is slightly more engaged; however, they are limited in their perspective of the lab. Instead of focusing on the skills, practices, and concepts in more depth, they are primarily focused on being efficient and completing the lab experiments quickly. This type of student made decisions based on saving time and therefore ignored other important aspects like expert-like thinking and deeper learning. These types of passive experiences keep such students from being fully engaged in the laboratory experience.

In levels 3 and 4 we include the ‘detail oriented,’ and the ‘skill developer’ perspectives, respectively. The detail oriented student was concerned with avoiding mistakes in the lab and was hindered by the lack of detail in experimental procedures. Have trouble dealing with ambiguity in the course caused this student much frustration. This student was distracted by these challenges and instead of using these frustrations and ambiguity to pursue a more meaningful learning experience, they found it not enjoyable and they were not engaged in most

aspects of the lab. It is clear that this type of student wanted to seek further understanding but they missed the big picture searching for details. For the ‘skill developer’ perspective their major concern was gaining lab skills that can be used in a future career and was engaged in the lab along these lines. However, their perspective was limited to practical skills and not necessarily the other professional skills that are valuable in chemistry community such as independence, decision-making, and dealing with ambiguity.

We placed ‘socialite’ perspective on level 5 because this type of student focused on interactions with fellow students and seemed to gain enjoyment and increased learning opportunities as a result. Situated cognition views learning as social and that through interactions with others, students can learn and construct new knowledge.

We chose to put the ‘independent,’ ‘mastery,’ and ‘explorer’ perspectives on level 6 of the outcome space. These three perspectives represent students that were most engaged in the laboratory environment and those who were closest to LPP. They were focused on more than just one or two aspects of the lab experience and were concerned with developing mastery of skill and content, going beyond what is taught in the lab, and becoming independent in their lab experiences. In addition, these students seemed to embrace ambiguity and see it as an opportunity to learn more.

3.8 Discussions and Implications

For students to make meaningful connections and benefit from a lab, it is important that educators consider the variety of student perspectives. If we can design teaching laboratories with these student perspectives in mind, we can move our students into a deeper level of learning and more enjoyable experiences. To that end, we also must consider moving towards designing evidence-based laboratory curriculums. Below we describe the implications of each of the

categories of description for laboratory design.

From the explorer and mastery perspective. Based on both the ‘explorer’ and ‘mastery’ views, introducing elements of freedom and experimental ambiguity may be beneficial. Students with the ‘explorer’ perspective saw value in the opportunity to explore their experimental interests. This element of freedom allowed them to explore various experimental routes. When designing labs, students should be given an opportunity of freedom. One easy way to incorporate freedom into a lab is to provide students with the ability to choose an aspect of their project. Galloway and Bretz also noted that labs should be designed with increased opportunity for students to make decision and explore other possibilities without penalty (Galloway et al. 2015).

From the independent researcher perspective. Based on the independent researcher perspective, labs can be designed with an individual component to them. DeKorver and Towns showed that when students are paired for lab experiments, students sometimes share tasks or rely on one student to do a particular task (DeKorver and Towns 2015). This separation of tasks creates a problem where one student focuses on a task, and the other student rarely gets to perform that task. As a result, students learning of certain skills is decreased. Individualized projects may help to eliminate this issue because each student has to carry out all of the experiment rather than delegating parts to their partner. Independent work also gives students an opportunity to self-assess their work and skills and build responsibility and independence.

From the socialite perspective. According to Lave and Wenger, social interactions are necessary components of legitimate peripheral participation and in becoming an expert in a field (Lave and Wenger 1991). Also, professional agencies, industry, and academia describe the ability to collaborate as a desirable characteristic for a future employee (Lowden et al. 2011). Opportunities for collaboration should be incorporated into the lab. Some ways to facilitate

cooperation in the lab are group presentations, peer review, and group worksheets. Another interesting way to enable collaboration is through peer interviews. These peer interviews would consist of a student asking questions to a partner to write a summary of some aspect of the lab. These kinds of peer collaborations do not have to take a lot of time. Students typically respond positively when credit is given for assignments. Therefore, students can be asked to compare certain aspects of their compound with one other student and record the conversation on a smart device and then upload online for credit. This simple task can help students learn from their peers and make their laboratory experience more meaningful.

From the skill developer perspective. At minimum, chemistry labs focus on the hands-on development of lab skills. In the case of the skill developer perspective, the instructors may need to provide a context of how these skills are relevant to future careers. Students that are focused on the “hands-on” aspects of the laboratory are more concerned about interactions with equipment, development of skills, and interpretation of their data. These “hands on” aspects of the lab are often centered on uncovering the practicality of these skills in a real-life scenario. Thus, chemistry instructors should consider incorporating these ideas into their lab curriculum.

From the time saver perspective. Based on the time saver perspective, labs should be designed to prevent or reduce “clock watching.” In their studies, DeKorver and Towns (2015; 2016) described that many students were heavily driven by the incentive of leaving lab early. They alluded to the possible benefits students can have if the time factor was removed. The project-based laboratory in our study, to a large extent, eliminated this time factor. Although there were students that focused on leaving lab early, this was only a small number of students. Project-based labs are intended to simulate a continuous project that a student would face in a research lab. As such, there are no clear starting and stopping points for the project. Therefore, to

prevent student's developing the goals of leaving lab early, labs should be designed to provide students with ambiguous finish points and produces other motivational aspects that put the time factor into the background.

From the detail oriented perspective. Based on the detail oriented perspective, labs should be designed to display the reality of science. Work in a research lab is not smooth, and many mistakes occur along the way; however, current "cookbook" labs rarely show this reality to students. Uncertainty is an emotion that is associated with science; however, students do not encounter this feeling with traditional laboratories that are designed with 100% success rate (Galloway et al. 2015). Instead, teaching laboratories should facilitate the development of this emotion in students along with providing tools on how to deal with uncertain moments or mistakes in the lab. Many aspects of the lab can be modified to provide moments of ambiguity and uncertainty. A few of them include: providing lab manuals with less specific procedures similar to those in the research literature, analyzing real data, the inclusion of experiments with a higher failure rates. Educators also need to think of ways to show students that feelings of frustration, and dealing with ambiguity are part of the science process and these feelings that give students and opportunity for deeper learning and exploration.

This study shows that the design of a lab can have a significant effect on students' work ethic and their perception of the lab. Our project-based lab was able to decrease the contradictory student goals that were typical of expository labs (DeKorver and Towns 2015). Another consideration is that a well-designed laboratory curriculum can move students from lower level of engagement, as depicted by the outcome space, through higher levels of engagement in the laboratory environment. We hope that the results of this study will prompt faculty to think about

reforming their own laboratory curriculum to include multi-week projects with elements of inquiry.

4 OVERALL CONCLUSIONS

Curriculum change through evidence based research has the potential to radically transform chemistry education and reduce the perception of Organic Chemistry as a “gateway course”. Most chemistry curricula follow a course format that does not explicitly connect the various concepts in chemistry and little focus is placed on understanding students’ prior foundational ideas. In addition, traditional laboratory curriculums have a poor reflection of the true nature of science

The findings of this study seem to imply that students can do well in chemistry courses without developing a thorough understanding of core chemistry concepts. It should be reiterated that the Organic Chemistry students in this study had already been taught bonding concepts, took ACS accredited examinations and received passing grades in General Chemistry. Information about student’s grades gave no indication of how well a student understood a concept when assessed with problem solving and concept maps. The use of alternative assessments in addition to traditional testing can be implemented to gather more extensive information on student’s prior knowledge of topics. Concept maps highlighted incorrect links students made across concepts, which would not have been witnessed in traditional formative assessments. Admittedly, student-generated concept maps can be difficult to grade, especially with the multiple connections that students can make. However, the use of concept mapping in smaller settings with less than 30 students such as tutorials, recitation, and peer-led sessions can be valuable. Students can both

individually and cooperatively make concept maps during these sessions as a way of connecting prior knowledge with new ideas. In addition, concept maps can be used in these types of sessions to assess students' progress at the beginning and at the end of a topic.

As an alternative to concept maps, Lewis (2011) identified so-called creative exercises that can promote connection of concepts within students' knowledge structures. In creative exercises, students are given a prompt or statement to which they can respond with as many statements as they can. Students are awarded credit for statements that are correct and relevant. As with concept maps, incorrect answers can give insight into students' misconceptions. Although these creative exercises are easier to grade, they are still time consuming. To address the large amount of time associated with grading concept maps, the C-TOOLS research group, the same developers behind the CMap tool software used in this study, has developed a new web-based automatic scoring tool for concept maps called the Concept Connector (Luckie et al. 2004). The tool was especially designed for large introductory science classes and provides automatic and immediate scoring of concept maps. The Concept Connector has a flexible scoring system, based on concept maps developed by instructors that contain numerous expert-generated propositions connecting two concepts together with a linking phrase. This tool can make the grading of concept maps more efficient and have wider use in large enrollment courses. The utility of this tool and developing others like it will be worth considering for future research projects.

The findings in our project-based lab study indicated that a project-based Organic Chemistry undergraduate laboratory was a beneficial laboratory course for developing student perceptions of the reality of science. Students in research-based laboratories consistently have more positive attitudes about science.; Further, students in inquiry-based courses also have

generally more positive attitudes and perform better on average than traditional students. These points were also noted in our project-based laboratory which follows a guided-inquiry format. More nuanced and higher-performing options are available when looking at traditional laboratories; however, some institutions may not be ready to fully adapt completely open-ended inquiry laboratories. The data in this study on project-based lab has shown that institutions can achieve positive goals, perceptions, and engagement in students without completely diverting their laboratory curriculum to an open-based format. These findings can be used to inform the development of professional skill aspects of laboratory design.

Future work should move in four directions: 1) Developing in depth assessments that can be applicable to large classroom formats, 2) Investigating how prior knowledge affects students' progress through guided inquiry labs, 3) Uncovering the essence of a research experience to further improve the project-based lab pseudo research laboratory experience and 4) A longitudinal study to investigate students' perceptions and goals after experiencing a project-based lab.

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APPENDICES

Appendix A – Recruitment Protocol

Appendix A.1 – Recruitment protocol for understanding chemical concepts

Recruitment Presentation for Undergraduate Students

The recruitment will be conducted during the Organic Chemistry lecture session.
(Hand out consent document to students)

Hello! My name is Nikita Burrows and I am a graduate student in the Department of Chemistry. My research area is in the area of Chemistry Education. Therefore, I am interested in how students learn chemistry and why students may have difficulty in chemistry and how we can improve students' understanding of chemistry. I am looking for several students who are willing to meet with me to talk about your understanding of certain General Chemistry concepts. You will be financially compensated for your participation. If you are willing to assist me with my research, please provide me with your name, email, and/or cell phone number on the sheet provided. Thank you for your attention and for considering this opportunity to assist me with my research.

Follow-up Recruitment Email for Undergraduate Students Participant: Thank you for taking a few moments to listen to me speak recently in your Organic Chemistry course. As mentioned then, I am conducting a research study to improve General Chemistry and Organic Chemistry instruction. I would like to conduct interviews with several of you about your understanding of General Chemistry concepts. If you are interested in participating in the study or have questions about the study, please respond to smoothing@gsu.edu or nburrows1@student.gsu.edu. After we have received your email, we will contact you about setting up an opportunity for us to meet. Thank you for considering your involvement in this study.

Appendix A.2 – Recruitment protocol for project-based labs

Recruitment Presentation for Undergraduate Students in Chemistry Lab courses

The recruitment will be conducted on the first day of Organic Chemistry lab sessions during the pre-lab lecture.

We are interested in understanding student experiences in lab courses at Georgia State University. If you decided to participate in this study, you will be asked to participate in two interviews about your experience in chemistry labs at Georgia State University. One interview will be conducted at the beginning of this course and one towards the end of this course. Each of the two interviews will require one hour of your time, for a total of two hours. The interviews will be audio recorded. You will be given a \$20 gift card at the end of the second interview for your participation. You can only participate in this study if you are at least 18 years of age and you are enrolled in a General Chemistry or Organic Chemistry lab at GSU. Your participation in the study is completely voluntary. Your decision to participate or not will not affect your grade in the course. Only the interviewer will know who participated in the study. Your name will be removed and replaced by a pseudonym when we analyze and present the data. If you are willing to assist us with this study and have your collected data used in the study, please provide your name and contact information on the sheet of paper I am passing around. I will contact you further and determine if we can schedule a time for the interview. If you have further questions about this research study, I will be available at the end of your lecture. You can also contact me at nburrows1@student.gsu.edu, 404-413-5656) or Dr. Mooring at smoothing@gsu.edu, 404-413-5527)

Follow up email.

Recently I presented to your Organic Chemistry lab class an invitation to participate in a research study entitled: "Investigating the impact of project-based chemistry laboratory activities on student motivation and persistence". As stated previously, the study would discuss your experiences in lab courses at Georgia State University. You provided your email address indicating that you were interested in participating in the study. Attached is the informed consent form. Please read and sign the consent form if you are willing to participate in the study. If you have any questions about the consent form, please feel free to contact me via this email address (nburrows1@student.gsu.edu) or call me at 404-413-5656. Please see the attached scheduling sheet and pick one of the times listed for your interview.

Thank you again for agreeing to participate in this research study.

Appendix B – Consent Forms

Appendix B.1 – Consent form for understanding chemical concepts

Georgia State University
Department of Chemistry

Informed Consent

Title: Organic Chemistry Students' Understanding of General Chemistry Concepts

PI: Suazette Reid Mooring
Student PI: Nikita Burrows

I. Purpose

You are invited to participate in a research study. The purpose of the study is to investigate student understanding of certain general chemistry concepts. You are invited to participate because you are currently an undergraduate student enrolled in the first-semester organic chemistry course. A total of 80 students will be recruited for this study. Participation will require up to 8 hours of your time over the semester at one to two hours per session.

II. Procedures:

If you decide to participate, you will be asked to take part in an interview where you will be asked to complete a concept map on certain general chemistry topics and participate in a semi-structured interview to explain and think-aloud as you solve problems on general chemistry topics. The interview will be videotaped. Completion of all portions of the study will be done in a designated interview room. Nikita Burrows will conduct the study. You will be asked to complete four 1-2 hour interviews. The first interview will be conducted within 2 weeks of the start of the semester and two additional interviews will each be conducted at 1 - 2 week intervals after the first interview. The last interview will be conducted 2 - 3 weeks before the end of the semester. You will be compensated with a \$10 gift card at the end of each interview.

III. Risks:

The things that we will be doing have no major risks. Your grade in the Organic Chemistry course will not be affected whether you decide to participate in the study or not.

IV. Benefits:

Participation in this study may not benefit you personally. Overall, we hope to gain information about how student understanding of certain general chemistry concepts affect their performance in Organic Chemistry and therefore help in the creation of interventions to improve student performance in both general chemistry and organic chemistry.

V. Voluntary Participation and Withdrawal:

Participation in research is voluntary. You do not have to be in this study. If you decide to be in the study and change your mind, you have the right to drop out at any time. You may stop participating at any time. Your grade in the Organic Chemistry course will not be affected whether you decide to participate in the study or not.

VI. Confidentiality:

We will keep your records private to the extent allowed by law. Dr. Suazette Mooring and Nikita Burrows will have access to the information you provide. Information may also be shared with those who make sure the study is done correctly (GSU Institutional Review Board, the Office for Human Research Protection (OHRP)). We will use study number and a pseudonym rather than your name on study records. The information you provide will be stored in a locked cabinet at 519A Science Annex and on a password and firewall protected computer. The key (code sheet) used to identify the research participants will be stored separately from the data to protect privacy. The key code will be kept in a locked cabinet and destroyed after 5 years. Your name and other facts that might point to you will not appear when we present this study or publish its results. The findings will be summarized and reported in group form. You will not be identified

APPROVED

Consent Form Approved by Georgia State University IRB September 06, 2012 - September 05, 2013

personally.

VII. Contact Persons:

Suzette Mooring can be contacted at smooring@gsu.edu or 404-413-5527 if you have questions, concerns, or complaints about this study. You can also call if think you have been harmed by the study. Call Susan Vogtner in the Georgia State University Office of Research Integrity at 404-413-3513 or svogtner1@gsu.edu if you want to talk to someone who is not part of the study team. You can talk about questions, concerns, or suggestions about the study. You can also call Susan Vogtner if you have questions or concerns about your rights in this study.

VIII. Copy of Consent Form to Subject:

We will give you a copy of this consent form to keep.

If you are willing to volunteer for this research and be video recorded please sign below.

Participant

Date

Principal Investigator or Researcher
Obtaining Consent

Date

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Consent Form Approved by Georgia State University IRB September 06, 2012 - September 05, 2013

Appendix B.2 – Consent form for project-based labs

Georgia State University

Informed Consent

**Title: INVESTIGATING THE IMPACT OF PROJECT-BASED CHEMISTRY LABORATORY
ACTIVITIES ON STUDENT MOTIVATION AND PERSISTENCE**

PI: Suazette Reid Mooring
Student PI: Nikita Burrows

I. Purpose

You are invited to participate in a research study. The purpose of the study is to understand your experience in chemistry labs. You are invited to participate because you are currently an undergraduate student enrolled in the second-semester Organic Chemistry lab course. A total of 25 students will be recruited over the next year for this study. You must be at least 18 years or older to participate in the study. In addition, you must have taken both the General Chemistry II and Organic Chemistry I labs at Georgia State University. Participation will require up to two hours of your time over the semester. That is, one hour for each interview - one at the beginning and at the end of the lab course. You will receive a \$20 gift card at the end of the second interview.

II. Procedures:

If you decide to participate, you will be asked to consent to the following: participate in two interviews to discuss your experiences in chemistry labs. One interview will be conducted at the beginning of the course and another interview towards the end of the course. The interview will be audio recorded.

III. Risks:

The things that we will be doing have no major risks. Your grade in the lab course will not be affected whether you decide to participate in the study or not.

IV. Benefits:

Participation in this study may not benefit you personally. It is our hope that through this study we can improve general and organic chemistry lab activities to better promote student learning. Data from this and other interviews will be used to evaluate the laboratory experience you had and to inform the development and improvement of labs for future students.

V. Voluntary Participation and Withdrawal:

Participation in this research study is voluntary. You do not have to be in this study. If you decide to be in the study and change your mind, you have the right to drop out at any time. You may stop participating at any time. Your grade in course will not be affected whether you decide to participate in the study or not.

VI. Confidentiality:

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Consent Form Approved by Georgia State University IRB August 16, 2013 - August 15, 2014

We will keep your records private to the extent allowed by law. Only Dr. Suazette Mooring and Nikita Burrows will know who participated in the study. Information may also be shared with those who make sure the study is done correctly (GSU Institutional Review Board, the Office for Human Research Protection (OHRP)). We will use study number rather than your name on study records. The information you provide will be stored in a locked cabinet at 519A Science Annex and on a password and firewall protected computer. The key (code sheet) used to identify the research participants will be stored separately from the data to protect privacy. The key code will be kept in a locked cabinet and destroyed after 10 years. Your name and other facts that might point to you will not appear when we present this study or publish its results. You will not be identified personally. In addition, your instructor will not have access to the result of the survey until all final grades have been submitted to the registrar.

VII. Contact Persons:

Suazette Mooring can be contacted at smooring@gsu.edu or 404-413-5527 if you have questions, concerns, or complaints about this study. You can also call if think you have been harmed by the study. Call Susan Vogtner in the Georgia State University Office of Research Integrity at 404-413-3513 or svogtner1@gsu.edu if you want to talk to someone who is not part of the study team. You can talk about questions, concerns, or suggestions about the study. You can also call Susan Vogtner if you have questions or concerns about your rights in this study.

APPROVED

Consent Form Approved by Georgia State University IRB August 16, 2013 - August 15, 2014

Appendix C – Interview protocols

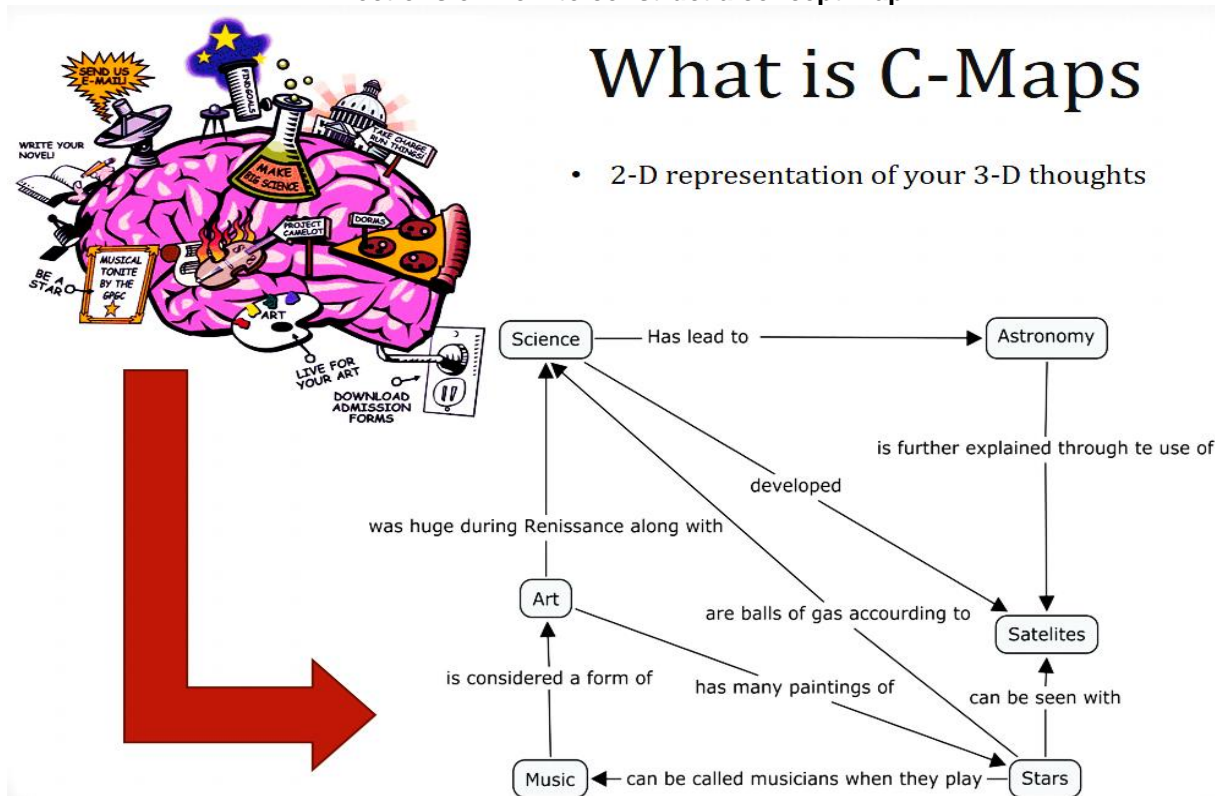
Appendix C.1 – Interview protocol for understanding chemical concepts

Interview protocol

- I. Student will be asked to sign consent form and given a copy to keep.
- II. Completion of Concept Map.

Student will be given explicit directions on how to complete a concept map and then asked to complete the concept map on the given topic.

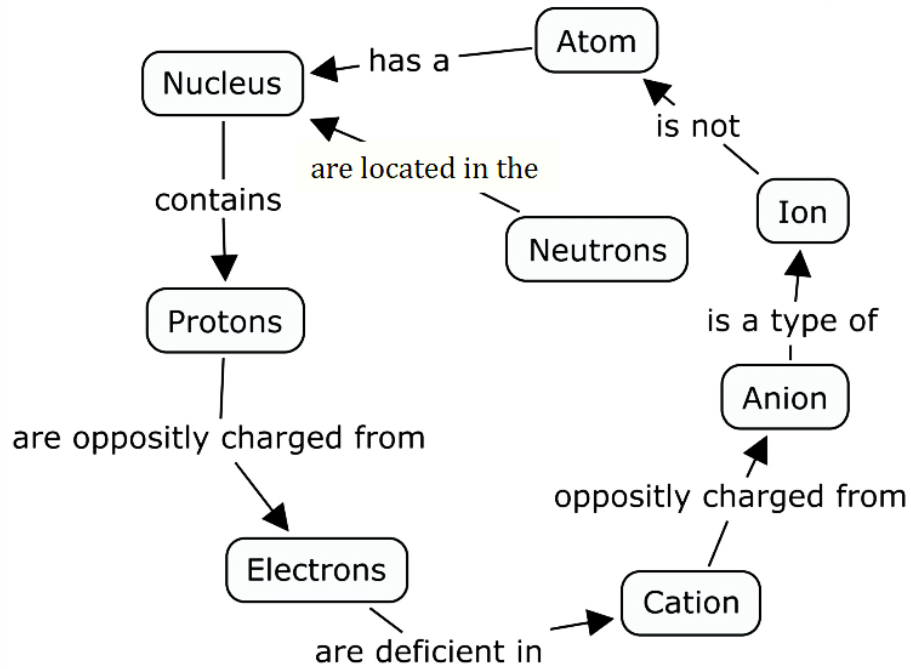
Directions on how to construct a concept map



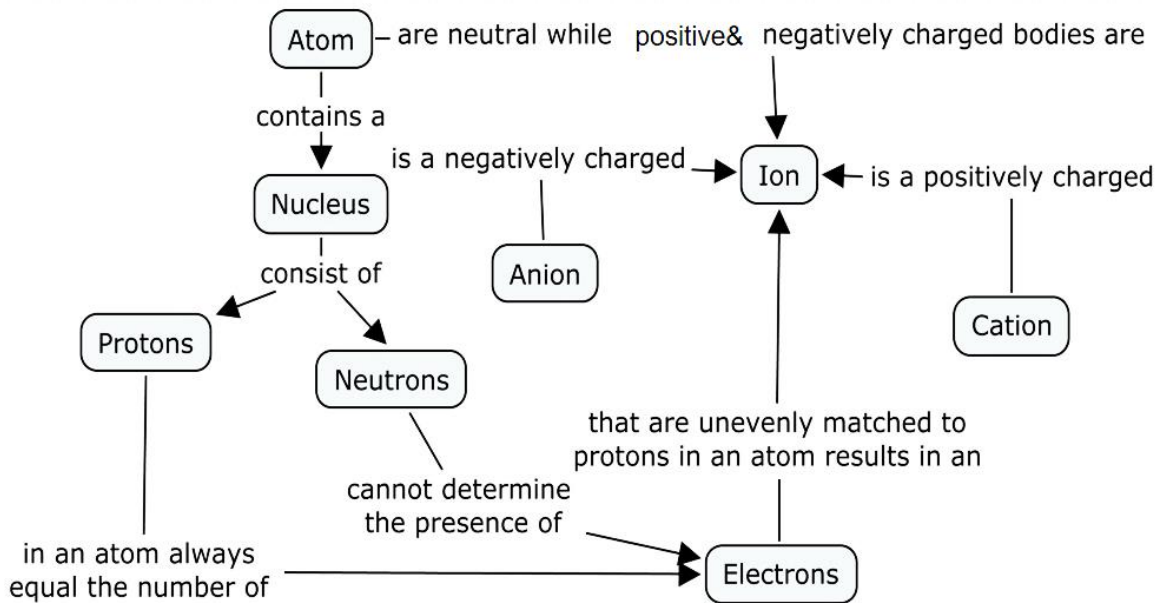
What do Concept Maps Consist of?

- Concepts - Mental representation, which the brain uses to denote a class of things in the world.
 - Example: Water, Molecules
- Linking Phrases - Set of words used to join concepts to express the relationships between the two concepts
 - Example: Molecules → that contain two Hydrogen and one oxygen atom are → Water

Example: Simple C-Map



Example: Complex C-Map



Using the C-map Software Demo

- o List
 - o Rose
 - o Flower
 - o Plant
 - o Florist
 - o Love
- o Go through
 - o How to create phrase
 - o Erase phrase
 - o Dragging arrows
 - o Arrow direction
 - o Filling in link on arrow
 - o Deleting entire phrase
- o Specifically state
 - o Not a continuous sentence
 - o Maps can be complex and intertwining
 - o You can use pen and paper before using c-maps

Please complete this concept map on _____ with the terms given on this sheet.

III. Semi-structured Interview

After completion of the concept map the student will be asked to think-aloud – that is, say what they are thinking and explain what they are doing as they solve typical General Chemistry problems related to the topic described in the concept map.

The purpose of this part of the interview is to determine your understanding of General Chemistry concepts. I am going to present you with at two problems on _____. As you solve each problem, I would like you to verbally describe what you are doing and what you are thinking. After taking a few minutes to solve each problem, I will ask you a series of reflection questions.

Prompts during think-aloud interview:

1. Can you talk about that a little more?
2. What do you mean when you say _____?
3. Why did you pick that answer?
4. Were there any choices you dismissed immediately?
5. Was there anything confusing about the question?

Post Questions:

1. Describe how you solved the problem?
2. What was hard/easy about a problem like this?
3. How is this problem similar/dissimilar to ones you have solved in General Chemistry course?

Appendix C.2 – Interview protocol for understanding the impact of project-based labs

INVESTIGATING THE IMPACT OF PROJECT-BASED CHEMISTRY LABORATORY ACTIVITIES ON STUDENT MOTIVATION AND PERSISTENCE

Interview Protocol – Beginning of the Semester

Thank you for agreeing to participate in a study on student experiences in general and Organic Chemistry labs. The purpose of this interview is to learn about what students do in the laboratory, how they complete the laboratories, and what they have learned from the laboratory experiences. It is our hope that through this study we can improve general and Organic Chemistry lab activities to better promote student learning. Data from this and other interviews will be used to evaluate the laboratory experience you had and to inform the development and improvement of labs for future students.

1. Can you describe to me what you did inside of you past laboratory courses? This includes what you did inside your lab and prelab. (essentially your lab project, how you were assessed in this lab, everything you had to fulfill for this assessment as well as any possible lab experiences/skills/opportunities you didn't have prior to your past chemistry courses)
2. What do you see as the purpose of your chemistry lab courses?
 - i. Loosely probe to see if student has a purpose specifically for the lab skills vs overall skill builder skill gained during the lab such as lab report writing
 - ii. Follow up question: Do you see any other purposes for the lab other than (what student stated)
3. What do you define as success in your laboratory courses?
4. How successful were you in your past chemistry laboratory courses?
 - a. Describe some of the most successful things that happened in the lab.
 - b. Describe some of the most unsuccessful things that happened in the lab.
5. Describe some of the things that made your past chemistry laboratory courses easy.
6. Describe some of the things that made your past chemistry laboratory courses hard.
7. Ask student to recall all pre-lab and lab experiences inside of Organic Chemistry I
8. For Organic Chemistry I lab, you had a project that you had to complete, what did you think about the project?
 - a. Can you describe the project you had in Organic Chemistry I Lab?
 - b. What were some of the easy parts of the project?
 - c. What were some of the hard parts of the project?
 - d. How do you think the project contributed to your learning?
9. If you could offer advice to a student taking either General Chemistry II Lab or Organic Chemistry I Lab, what you suggest they do to be successful in the courses? Follow up question: Why?
10. If you could change anything about your past lab experiences, what would it be?
11. The Organic Chemistry II Lab has a project that will last the entire semester. How do you think you will do in this lab?
 - a. What leads you to believe that you will do (insert students response to first question)?
 - b. How do you define success in lab?
 - c. Do you sense that you will be successful or unsuccessful? Why?
 - d. How do you think your experiences in General Chemistry II Lab and Organic Chemistry I Lab have prepared for the project this semester?

Demographic Questions

1. What is your major?
2. What year of study are you in? (i.e., freshman/first-year, sophomore/second-year, ...)
3. Is Organic Chemistry required for your major?
4. Are you currently enrolled in the corresponding lecture course?
5. What grades did you receive in your previous chemistry courses?
6. How do you see this laboratory course relating to your future career?

7. Have you participated in any research projects outside of your coursework?
 - a. If yes, what did you do?
 - b. What were some of the easy aspects of doing research?
 - c. What were some of the hard aspects of doing research?

End of the Semester

Thank you for agreeing to participate in the second part of a study on student experiences in Organic Chemistry labs. The purpose of this interview is to learn about what students do in the laboratory, how they complete the laboratories, and what they have learned from the laboratory experiences. It is our hope that through this study we can improve Organic Chemistry lab activities to better promote student learning. Data from this and other interviews will be used to evaluate the laboratory experience you had and to inform the development and improvement of labs for future students.

1. Please tell me about what you did in Organic Chemistry II Lab this semester.
2. Describe your project in Organic Chemistry II lab this semester?
 - a. Probe: Can you tell me a little bit about your experience in lab this semester?
3. What did you see as the purpose of your Organic Chemistry II Lab?
4. How do you define success in your Organic Chemistry II Lab?
5. How successful were you in Organic Chemistry II Lab?
 - a. Describe some of the most successful things that happened in the lab.
 - b. Describe some of the most unsuccessful things that happened in the lab.
6. For Organic Chemistry II Lab, you had a project that you had to complete, what did you think about the project?
 - a. What were some of the easy parts of the project?
 - b. What were some of the hard parts of the project?
 - c. How do you think the project contributed to your learning?
 - d. How do you think your experiences in Organic Chemistry I Lab helped prepare you for Organic Chemistry II Lab?
7. If you could offer advice to a student taking Organic Chemistry II Lab, what would you suggest they do to be successful in the course?
8. If you could change anything about your Organic Chemistry II Lab experience, what would it be?
9. Since your first interview, have you participated in any additional research projects outside of your coursework?
 - a. If so, what did you do?
 - b. What were some of the easy aspects of doing research?
 - c. What were some of the hard aspects of doing research?

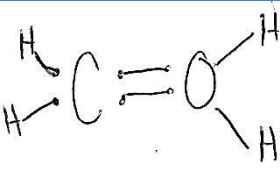
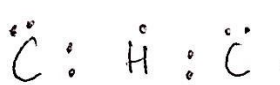
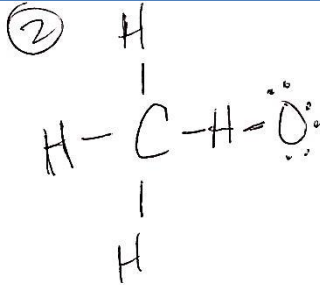
Appendix D – Lewis Structure Code book

Lewis Structure Misconstruction: How Students Use and Interpret Rules to Construct Lewis Structure

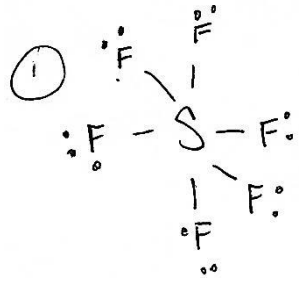

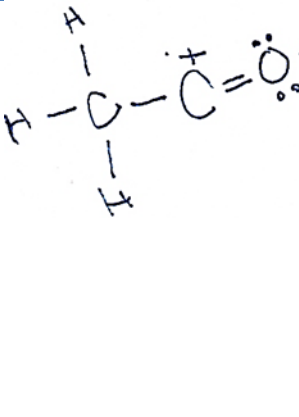
Nikita L. Burrows and Suazette R. Mooring

Department of Chemistry, Georgia State University, Atlanta, GA

Examples of Codes

Code	Description	Paired Lewis Structure	Paired Interview Quote
Double Bond Oxygen	Students described a requirement to double bond oxygen in a molecule regardless of total valence electron available for the molecule		And then O would be -- in there somewhere, that's the only thing I'm thinking. I believe when you have between carbon and oxygen is usually a double bond so I'll probably do it like here. And then each one -- because this has four electrons so it's like one, two, three, four, so it's sharing.
Inappropriate Valence Electrons on Carbon	Students' drawings show carbon with too many or too little electrons. This is especially emphasized when students drawings contradict their awareness of the 4 bond rule for carbon		Yeah, and I know carbon has four valence electrons, so that's two and that would be the four. And this one has one, I believe. But yeah I'm just trying to make it be something on the paper mainly and not just leave anything blank. So I think I got all these wrong
Terminal Atoms	Students' drawings and explanations show a lack of understanding of connectivity for terminal atoms such as hydrogens and halogens		<u>Interviewer:</u> Yes. Any particular reason why you set it up that way [draw CH ₄ O with a C-H-O bond]? <u>Interviewee:</u> Not really, except for I know this is terminal, hydrogen's always terminal, and carbon's always internal, I guess. Carbon, hydrogen,

<p>Charge = Lone Pair</p>	<p>Students described that a charged species is charged because of the addition of a lone pair</p>		<p>oxygen.</p> <p>Like it if it has a negative formal charge I would think it would have a lone pair. That's just what I think because how else would it have been extra negative unless it had extra electrons or electron but usually it comes in the shape of a lone pair.</p>
<p>Invoked Octet Rule</p>	<p>Students discussed the use of the octet rule when drawing; however, their structures did not reflect an understanding of the octet rule</p>		<p>So the Cls I find interesting because if you had three Cls and they each had hydrogen each they would have their octet completed. And then two carbons have four each so if they shared electrons, they would have their octet complete. I just don't know how these --</p> <p><u>Interviewer:</u> Are all linked together?</p> <p><u>Interviewee:</u> Exactly. So like maybe if these are double bonds between these chlorines. And then I'm just trying think about my carbon because typically carbon is the central atom so even if I have my carbon like C double bond C, I'm wondering how this is linking to these.</p>

<p>Central atom</p>	<p>Students brought up “choosing the central atom” as one of the steps to drawing a Lewis structure</p>		<p>Do the first letter first, the first element’s usually the central element, and then the second usually surround it, so I’d just do the first one.</p>
<p>Structural Cues</p>	<p>Student’s implied or directly stated that the way a formula was written should directly hint to the way a structure should be drawn. This includes items such as how atoms are connected or which atom is a central atom</p>		<p><u>Interviewee:</u> Sorry. It just occurred to me how interesting it is that like CH3, it means all these hydrogens go with this C. But then something like this, C2H3O2, how come that’s not denoted like this?...Well, C, C, so it’s basically two C, and then the H stays the same. And how it’s written affects how it looks like. So in that manner, the H is attached to C. And then is that automatically assuming there are H’s attached here, or is it more like this or something?</p>
<p>Arrangement Issues</p>	<p>Students described their inability to decide where to connect atom in a molecule that had more than one central atom.</p>		<p><u>[Oxygen]</u> It’s not next to the C. I don’t know whether to attach the oxygens to each other, or to one on each side of this carbon. I guess for now, I’ll just put something down. I’ll attach an oxygen to both sides.</p>

VITA

Nikita Lauren Burrows was the first child born to Nigel Edwin and Dorette Monique Burrows in Nassau, Bahamas at Doctors Hospital. She grew up and went to high school in Nassau, Bahamas and she developed a love of science with help from Mr. and Ms. Rowe, her high school science teachers. As with any person typically interested in science, Nikita began to pursue a career towards becoming a medical doctor. To achieve this goal, she began involving herself in many extra-curricular activities that included her schools debate team, volleyball team, the governor general youth award program, Junior Achievers, and volunteer tutoring. Her interest in education had sparked here but she continued down her medical school path. This led her to seek a Ph.D in Chemical Education under the direction of Dr. Suazette Mooring.