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IONIC BONDING CURRICULUM UNIT: AN ELECTROSTATIC FRAMEWORK

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Mary Frank Lamar, Student

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IONIC BONDING CURRICULUM UNIT: AN ELECTROSTATIC FRAMEWORK

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Education
at the University of Kentucky

By

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Lexington, Kentucky

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2020

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ABSTRACT OF DISSERTATION

IONIC BONDING CURRICULUM UNIT: AN ELECTROSTATIC FRAMEWORK

This mixed methods study compared two groups of high school students' understanding of the ionic bond and the dissolving process. A 5 lesson curriculum unit was developed using Taber's electrostatic framework (1997) focusing on the electrostatic forces between ions compared to a molecular framework (business-as-usual) and the Next Generation Science Standards (NGSS Lead States, 2013). The lessons were developed to integrate spatially integrated experiences. Experimental (new curriculum unit) and business-as-usual (criss-cross method) students had their spatial skills tested before and after learning about the ionic bond using the Purdue Spatial Visualization-Rotations Test (PVST-Rot; Bodner & Guay, 1997). Students' content was tested (pre and post) using the Chemical Bonding and Dissociation Diagnostic Assessment (CBDDA; Jang, 2003; Tan & Treagust, 1999; McBroom, 2011). Part of the assessment had two-tiered multiple-choice questions. Another part focused on dissolving of ionic compounds in water (dissociation equations and drawing ionic compounds dissolved in water). This study had one group of students using the new curriculum unit focused on ionic crystals, and the second group used more traditional methods of lab plus lecture.

Research Question 1: How does the understanding of the ionic bond and dissolving of ionic compounds in water compare for students using a unit focused on an electrostatic framework to students utilizing a molecular framework (business-as-usual) related to their spatial ability and using the spatial ability as a covariant with treatment group?

Research Question 2: How do spatial visualization skills compare for students using an electrostatic framework and students focused on a molecular framework?

A model using multiple linear regression was developed for Research Question 1 with the post score for the CBDDA as the dependent variable with pre score on the (CBDDA), Treatment, PVST-Rot Gain (post score minus pre score), and Treatment * PVST-Rot Gain as the independent variables. The null hypothesis was rejected, $F(4, 87) = 4.674$, $p < .05$. The model shows statistically evidence that it may predict the score on the post content test. Only the constant and the treatment group were the only statistically significant slopes.

Multiple linear regression was used to develop a model using the pre PVST score and the treatment group as the independent variables with the post PVST score as the dependent variable. The null hypothesis was rejected for Research Question 2, $F(2,89) = 26.732$, $p < .05$. Only the constant and pre PVST score slope were significant.

The qualitative portion of this study utilized the following sources: pre and post student interviews, drawings and dissociation equations from the CBDDA, classroom observations, and teacher logs. Some experimental students were able to improve their dissociation equations and/or the drawings compared to the business-as-usual group. The business-as-usual teacher logs reflected a more molecular framework of teaching. Interviewed students from both groups showed a lack of understanding of the difference between covalent and ionic bonding. Students from both groups did not comprehend that a molecule is used for only covalent compounds.

The approximate 3.2 experimental students to one business-as-usual student may be a limitation of this study. The new unit has potential to aid with the understanding of the ionic bond and the dissolving process.

KEYWORDS: Ionic Compounds, Dissolving, Chemistry, Formula Unit

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(Name of Student)

May 7, 2020

Date

IONIC BONDING CURRICULUM UNIT: AN ELECTROSTATIC FRAMEWORK

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and projects with Caroline help to lower my stress and allowed me another creative outlet.

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CHAPTER 1. INTRODUCTION

Today, athletes use Gatorade to replenish themselves. Gatorade was originally introduced in 1965 at the University of Florida to help with the Gator football team. After one game, twenty-five football players were admitted to the hospital due to dehydration and exhaustion. Due to the high temperatures and humidity in Florida, some players were losing fifteen pounds throughout a game from perspiration loss. "Sweat is mostly made up of water and various salts (or electrolytes) – sodium, potassium and magnesium – which are essential to the electrical and chemical balance of the body and aide muscle and nerve function" (Rovell, 2006, p. 17) Dr. Robert Cade, Dr. Dana Shires, Dr. Alejandro de Quesada, and Dr. H. James Free developed Gatorade to help the players replenish their electrolytes and sugar lost during sweating and exercise (Rovell, 2006; Stokely-Van Camp, Incorporated, 2016).

An electrolyte solution results when a substance is dissolved in water, and this solution conducts electricity (Chang & Goldsby, 2014). The dissolved substance is an ionic compound for example sodium chloride. Ionic compounds (also known as salts) can form ions by the separation of the solid compound and hydration of ions (positive and negative) in water allowing for these solutions to conduct electricity. On the other hand, sugar, a polar molecule, can also dissolve in water. Since no positive and negative ions form in solution, sugar does not conduct electricity, and sugar solution is categorized as a nonelectrolyte. Both sugar and sodium chloride are compounds which can dissolve in water, but the formation of ions depends upon the type of chemical bonding involved in the compound: sugar has covalent bonds and sodium chloride has ionic bonds.

Research has shown that students struggle with the topic of chemical bonding (Ben-Zvi, Eylon, & Siberstien, 1986, 1987; Birk & Kurtz, 1999; Boo & Watson, 2001; Burrows & Mooring, 2015; Butts & Smith, 1987; Coll & Taylor, 2001; Coll & Treagust, 2002, 2003; Harrison & Treagust 2000; Luxford & Bretz, 2013; Nicoll, 2001; Othman, Treagust, & Chandrasegaran, 2008; Taber, 1994, 1997,1998, 2002a; Taber, Tsaparlis, & Nakiboglu, 2012; Waldrip & Prain,, 2012). Covalent bonds form when two atoms share electrons. Metallic bonds occur between cations (positive ions) of the same metal with the electrons being a sea around the cations and mobile allowing for conduction of heat and electricity (Zumdahl & Zumdahl, 2014). An ionic bond is formed due to the electrostatic attraction between oppositely charged ions (Tro, 2010). Several diagnostic assessments and concept inventories have been developed to explore covalent, ionic and metallic bonds misconceptions (Hanson, 2015; Karacop & Doymas, 2013; Luxford, 2013; Othman Treagust, & Chandrasegaran, 2008; Taber, 1997, 2002b, Tan & Treagust, 1999). Although these instruments provide a way to probe students' knowledge about misconceptions, they do not address a possible way to change these misconceptions.

The current study introduces a unit focusing on the electrostatic framework for the ionic bond. The unit cell of an ionic crystal serves as the introduction to balancing the ionic formula unit, dissociation in terms of the ionic crystal, and ion formation with respect to ionization energy and electron affinity. By focusing on the electrostatic framework and the unit cell, this research explores the students' gains on a content assessment for students using a curriculum based on an electrostatic framework (experimental [Elm]) compared to students using a molecular framework (control: business-as-usual [Ash]- ions are formed to have the same electron configuration as noble gases: formula units are balanced using the criss-cross method – using the absolute value of the ion charges as the oppositely charged ion's subscript or showing electron transfer using Lewis Electron Dot Diagrams, LEDD; and dissociation equations are explained conceptually; Figure 1). Teaching logs were used to verify the molecular framework was used in the control classrooms. Since students will be working with crystals and particulate diagrams requiring spatial skills, this research will also investigate the potential for increasing students' spatial skills with this curriculum unit.

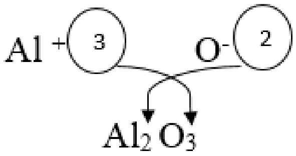


Figure 1. Example of the Criss-Cross Method

Statement of the Problem

Tan and Treagust (1999) developed a concept map about chemical bonds showing the complexity of this topic as a whole (Figure 2). This dissertation's research chose to focus only on ionic bonds. An ionic bond is formed due to the electrostatic attraction between oppositely charge ions and exists in a solid crystalline lattice (Tro, 2010). A positive ion forms ionic bonds with all of the neighboring negative ions. A similar statement can be made for a negative ion forming ionic bonds with all of its neighboring positive ions. Several student misconceptions have been identified in a review of literature related to ionic bonding including viewing ionic compounds as molecules, ionic bond as the transfer of ions, representing the ionic bond using only one cation with one anion, focusing only on the octet rule for ion formation, thinking ionic bonds are weak, and formed by the sharing of electrons (Ben-Zvi, Eylon, & Siberstien, 1986, 1987; Birk &

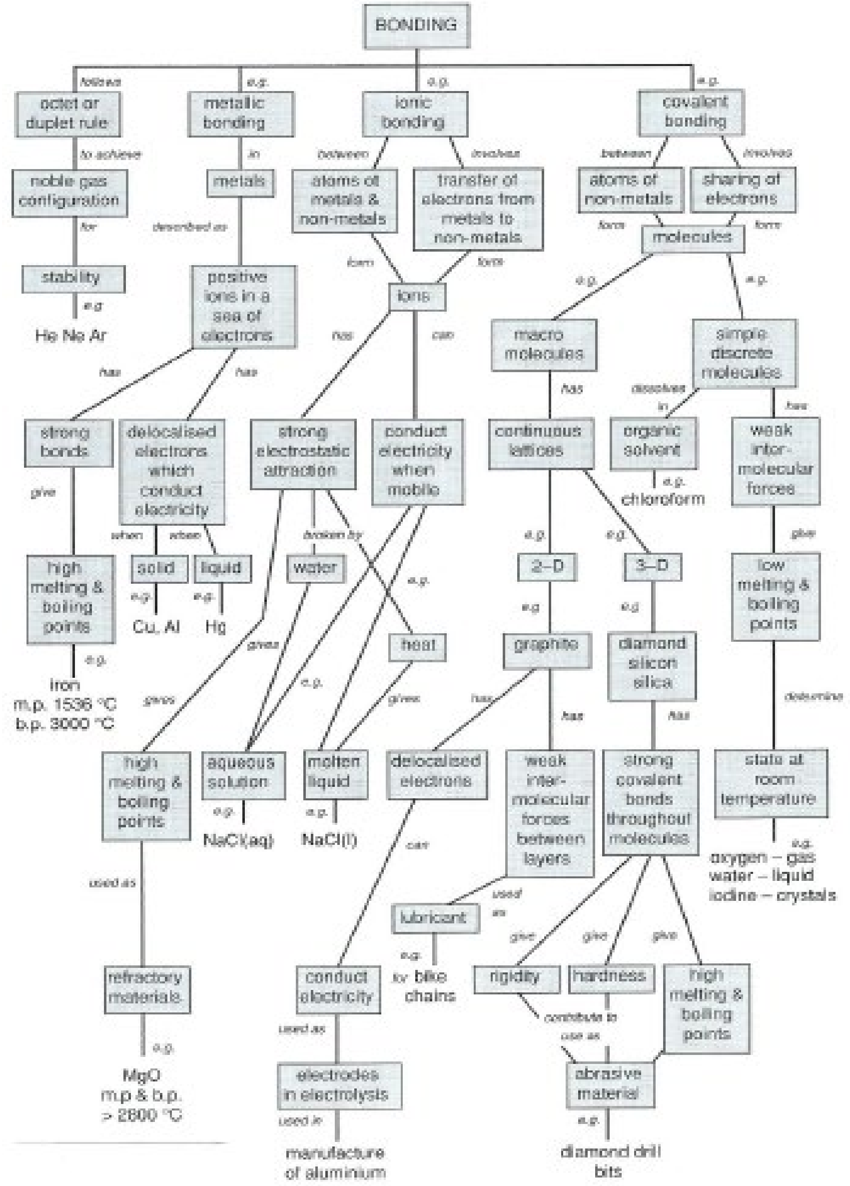


Figure 2. Concept map covering the complex topic of chemical bonding including metallic, ionic, and covalent from Tan and Treagust (1999)

Kurtz, 1999; Boo & Watson, 2001; Burrows & Mooring, 2015; Butts & Smith, 1987; Coll & Taylor, 2001; Coll & Treagust, 2002, 2003; Harrison & Treagust 2000; Luxford & Bretz, 2013; Nicoll, 2001; Othman, Treagust, & Chandrasegaran, 2008; Taber, 1994, 1997,1998, 2002a; Taber, Tsaparlis, & Nakiboglu, 2012; Waldrip & Prain,, 2012). Students' difficulties with balancing ionic formula units initiated the development of several different games/activities (Chimineo, 2000; Chimeno, Wulfsberg, Sanger, & Melton, 2006; Kavak, 2012; Logerwell, & Sterling, 2007; Ruddick, & Parrill, 2012; Wirtz, Kaufmann, & Hawley, 2006), but these are just algorithmic techniques to learn the mathematics behind balancing the formula unit for an ionic compound. Students still do not understand the basis of the formula unit creating misconceptions with dissolving of ionic compounds. Taber (1994) stated that an electrostatic framework should be the focus of ionic bonds not molecular because students create the misconceptions that when ions are formed the positive and negative ion create a molecule (discrete entity) instead of individual ions not linked together. Table 1 is Taber's comparison of a molecular framework versus an electrostatic framework for ionic bonding. This research focuses on the electrostatic framework by using the unit cell of a crystal as an introduction for balancing the ionic formula unit.

By not understanding the ionic bond in terms of crystals, students also create misconceptions with the dissolution of ionic compounds and how water interacts with the ions. Students have difficulties to balance the dissociation chemical equations and draw particulate diagrams representing the dissolving process for ionic compounds (Davidowitz, Chittelborough, & Murray, 2010; Kelly & Jones, 2007; McBroom, 2011; Naah & Sanger, 2012, 2013; Nyachwaya et al., 2011; Sanger, 2005; Smith & Metz, 1996; Treagust, Chittleborough & Mamiala, 2003). Visualizing the dissolving process is necessary for understanding the concept and being able to represent the ions formation using dissociation equations. Since students do not understand the ionic formula unit, they have difficulties balancing these equations and representing the process using particulate diagrams (Davidowitz, Chittelborough, & Murray, 2010; Kelly & Jones, 2007; McBroom, 2011; Naah & Sanger, 2012, 2013; Nyachwaya et al., 2011; Sanger, 2005; Smith & Metz, 1996; Treagust, Chittleborough & Mamiala, 2003).

Table 1: A comparison of two frameworks for understanding ionic bonding from Taber (1997)

Status	Molecular framework Alternative framework	Electrostatic framework Curricular science
Role of Molecules	Ion pairs are implied to act as molecules of an ionic substance	Ionic structures do not contain molecules – there are no discrete ion-pairs in the lattice
Focus	The electron transfer event through which ions may be forced	The force between adjacent oppositely-charged ions in the lattice
Valency conjecture	Atomic electronic configuration determines the number of ionic bonds formed (e.g., a sodium atom can only donate one electron, so it can only form an ionic bond to one chlorine atom)	The number of bonds formed depends on the coordination number, not the valency or ionic charge (e.g., the coordination is 6:6 in NaCl)
History conjecture	Bonds are only formed between atoms that donate/accept electrons (e.g., in sodium chloride a chloride ion is bonded to the specific sodium ion that donated an electron to that particular anion and vice versa)	Electrostatic forces depend on charge magnitudes and separations, no prior configurations of the system (e.g., in sodium chloride a chloride is bonded to its neighboring sodium ions)
'Just forces' conjecture	Ions interact with the counter ions around them, but for those not ionically bonded – these interactions are just forces (e.g., in sodium chloride a chloride ion is bonded to one sodium ion, and attract to a further five sodium ions, but just forces – not bonds.	A chemical bond is just the result of electrostatic force – ionic bonds are nothing more than this (e.g., the forces between a chloride ion and each of the neighboring sodium ions are equal)

Taber (1997)

Conceptual Framework

With the study of chemistry, students have to consider phenomenon such as the ionic bond and the dissociation process in terms of different representations:

macroscopic, sub-microscopic and symbolics. For the macroscopic representation, students can physically see these compounds such as sodium chloride and the disappearance of this compound when added to water. In chemistry courses, students learn the symbols to represent a compound and the formation of ions in water. For the sub-micro representation, students have to visualize the solid crystalline structure of an ionic compound and the hydration of ions with the dissolving process. Johnstone (1991) discussed the difficulties students have with connecting all three representations with their explanations of chemical phenomenon. When chemistry concepts are taught, the teacher has to connect these representations. This unit attempts to address students' difficulties with the ionic bond and dissociation process in terms of the three different representations hopefully increasing students' spatial skills compared to students who learn this material in a more traditional format. With this unit, students will explore the dissolving of ionic compounds (macro) as the initial phenomenon. For the sub-micro representation, students examine ionic unit cells and draw particle diagrams for the dissolving process. The symbolics representation was addressed by balancing the formula unit and writing the dissociation equation.

Purpose of this Study

The purpose of this research study was to investigate a curriculum unit focusing on the ionic unit cell and dissolving of the ionic compound. Students' understanding of ionic bonding, ionic compound's formula unit, and dissociation of ionic compounds are predicted to be higher for students introduced to ionic unit cell for balancing the formula unit compared to students who are mainly introduced to the criss-cross method and octet rule for balancing ionic formulas.

Research Questions

Research Question 1: How does the understanding of the ionic bond and dissolving of ionic compounds in water compare for students using a unit focused on an electrostatic framework to students utilizing a molecular framework (business-as-usual) related to their spatial ability and using the spatial ability as a covariant with treatment group?

Research Question 2: How do spatial visualization skills compare for students using an electrostatic framework and students focused on a molecular framework?

Relevance of Study

Taber (1994) called for several changes with the way ionic bonding is taught using an electrostatic framework. In addition, researchers (Ben-Zvi, Eylon, & Siberstien, 1986, 1987; Birk & Kurtz, 1999; Boo & Watson, 2001; Burrows & Mooring, 2015; Butts & Smith, 1987; Coll & Taylor, 2001; Coll & Treagust, 2002, 2003; Harrison & Treagust 2000; Luxford & Bretz, 2013; Nicoll, 2001; Othman, Treagust, & Chandrasegaran, 2008; Taber, 1994, 1997,1998, 2002a; Taber, Tsaparlis, & Nakiboglu, 2012; Waldrip & Prain,, 2012) have studied the variety of misconceptions involving ionic bonding. Studies (McBroom, 2011; Nyachwaya et al., 2011; Nyachwaya, Warfa, Roehrig, & Schneider, 2014; Smith & Metz, 1996) have shown that students have trouble with the concept of dissociation including mistakenly thinking that compounds melt into water. When an ionic compound is dissolved in water, students have difficulties understanding and drawing particulate diagrams (Ebenezer, 2001, Kelly & Jones, 2007,2008; McBroom, 2011; Naah & Sanger, 2012). Students are more successful with balancing chemical equations mathematically than using particulate diagrams. This curriculum unit attempts to address the changes Taber (1994) suggested while emphasizing the ionic unit cell for balancing ionic formula units and dissociation of ionic compounds in water.

Assumptions of the Study

1. The Ash teachers reported their lesson plans accurately.
2. Since a pre/posttest design was used as part of the research methodology, the Ash teachers did not restructure their lesson plans to focus on the assessments.
3. Students may have been exposed to ions but not in terms of ionization energy and electron affinity.
4. Elm teachers implement the 5E lessons with minor changes

Organization of the Remainder Study

This research study is organized in six chapters. Chapter 1 introduces the study, research questions and includes the theoretical framework utilized with the study. Chapter 2 discusses the literature background supporting the need for this study in terms of ionic bonding, dissociation of ionic compounds and spatial visualization in chemistry. Since this study was performed at the high schools (ninth through twelfth grade), the United States Next Generation Science Standards (NGSS; NGSS Lead States, 2013) have been used as the lessons' objectives. In Chapter 2, a learning progression was developed for both ionic bonding and dissociation of ionic compounds in terms of NGSS. Finally, the new unit and lessons used in this study are outlined at the end of this chapter. Appendix A has the 5-E lessons for this unit with supporting material (worksheets) in Appendix B. The NGSS Performance Expectations for each lesson are located in Appendix C. Chapter 3 discussed this study's research methodology including both the quantitative and qualitative portions. The dependent and independent variables are discussed along with data collection procedures, instrument design, data analysis, and demographics of the classrooms and schools. The study's limitations for the research design are examined. Appendix D has the Chemical Bonding and Dissociation Instrument. Chapter 4 analyzed and explained the quantitative data collected as part of the study gathered using the CBDDA as the content instrument and for the Purdue Spatial Visualization Test: Rotations (PSVT-Rot; Guay, 1977) as the spatial instrument. In Chapter 5, the qualitative data was examined for the ways the Elm students' learning compared to Ash methods. Teachers' logs and student interviews exploring their answers on the assessment are used as artifacts from both groups. Researcher observations and discussions with teachers are artifacts to explore the research questions. Chapter 6 has conclusion including limitations of this study and future research.

CHAPTER 2. REVIEW OF RELATED LITERATURE

Literature discusses problems students have learning chemistry especially the conceptual aspect of the subject (Nakhleh, 1992; Nakhleh & Mitchell, 1993). Students must visualize the particulate level to understand chemical concepts such as the ionic bond and the dissociation of ionic compounds. This chapter starts with a discussion of the spatial skills needed for chemistry in terms of visuospatial and the possibility for improving these skills. Next, the relevant research concerning ionic bonds is discussed in terms of misconceptions, ion formation and crystals. Then the chemical equations and dissociation of ionic compounds in water is addressed with an emphasis on the visualization needed to draw particulate diagrams. Using the Next Generation Learning Standards (NGSS), the learning progression for ionic bonds, formula unit and dissociation equations will be examined and used to develop the curriculum unit associated with this dissertation. A synopsis of the lesson's will be given in terms of the standards, different chemical representations, and spatial integration of the activities.

Spatial Skills in Chemistry

Johnstone (1991) developed the concept of three different representations (sub-micro, symbolics and macro) used in chemistry as a triangle (Figure 3) with experts being able to transition between these three areas without issue and being to utilize all three areas to explain concepts. Experts could reside in the middle of the triangle with ease. On the other hand, students have trouble moving from apex to apex and being able to be in the middle of the triangle. Students tend to think of chemistry problems as the reactions they observe and using symbols to represent these reactions. The third representation refers to the particulate level (atoms, ions, and molecules) requiring students to visualize bond formation and bond breakage in the case of chemical reactions. To understand chemistry, all three representations must be taken into account, but students tend to stay at the apexes and not in the middle merging these three representations.

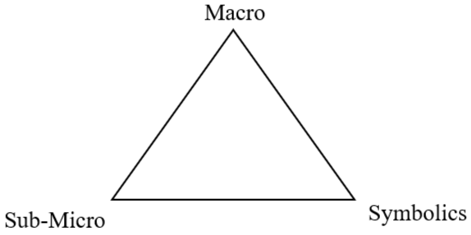


Figure 3. Three representations of chemistry (Johnstone, 1991)

Diagrams can aid with visualization at the particulate level. Chittleborough and Treagust (2008) studied seventeen university students who were non-chemistry majors. Eight students graduated from high school the previous year and nine attended high school two to 15 years previously. These students were interviewed about using chemical diagrams with some of these diagrams being at the particulate level. Students were not at ease using these diagrams and did not understand these diagrams fully. Even though visualization tools are useful, particulate diagrams have to be emphasized and their usefulness explained.

Diagrams are not always available for students to be used as visualization tools. For students working isomeric problems (same structure but either different connections and/or different spatial orientation), three-dimensional mental images have to be developed from two-dimensional representations. Students may have to rotate and/or manipulate the three-dimensional image to solve their problem/task. The student has to again manipulate the image from three-dimensional to two-dimensional. If a student does not have well-developed spatial skills, the student may become confused with all these different changes with images (Copolo & Hounshell, 1995). For students already having trouble moving between Johnstone's three representations, asking these students to manipulate particulate level images is increasing the difficulty level.

Kozma, Chin, Russell and Marx (2000) observed three chemists in an academic laboratory and six chemists in a pharmaceutical laboratory to determine how representations are used by chemists. For both laboratories, diagrams and drawings were used extensively. Chemists use diagrams of molecular structures to indicate synthesis of compounds, and this thinking with diagrams was illustrated in an interview with a member of the pharmaceutical laboratory who had a doctoral degree and had worked in the setting for 10 years. Another example involved the academic laboratory and conversation between a second-year doctoral student and their faculty advisor. During the conversation, they used drawings to depict their synthesis route and discussing an NMR spectrum which can be interpreted to infer a molecule's structure. Kozma et al. (2000) state that chemists have a repertoire of representational skills allowing them to move between different representations to explain chemistry at the particulate (sub-micro) level.

Pribyl and Bodner (1987) also indicate the variety of images/diagrams (Newman projections, Fisher projections and space-filling models) can make organic chemistry difficult for students with low spatial ability. Students who draw figures (preliminary or extra) performed better on chemistry exams as did students who had a high spatial ability based on the Purdue Visualization and Rotations test and Find-A Shape-Puzzle instrument.

Harle and Towns (2010) discussed the use of spatial ability with learning a variety of chemistry concepts including molecular geometry, chirality, different representations of organic structures (Newman, Fisher, Haworth) and biomolecule structures. All of these topics require complex mental manipulations. Students with poor spatial visualization skills may struggle with these concepts. In addition, students with poor spatial skills may have trouble representing molecules and crystals from different perspectives (Galasso, 1993).

Bodner and McMillen (1986) correlated spatial ability to success with chemistry concepts that are spatially related for ionic and metallic solids (multiple choice exam questions on crystal structure, $r = .32$, $p < 0.001$; free-response quiz on crystal structure, $r = .35$, $p < 0.001$). Their research also found a correlation between high spatial ability and performance on a stoichiometry problem requiring little spatial ability ($r = .29$, $p < 0.001$). Kleinman, Griffin, and Kerner (1987) studied the images used by faculty, graduate and undergraduate students for a variety of chemical concepts including equilibrium and solubility with faculty using a higher number and more abstract images in their interviews than undergraduates and graduates. Wu and Shah (2004) hypothesized examining the feasibility of a solution process and manipulating the relevant information relates to a students' spatial ability. In a first semester general chemistry course for agriculture and health science majors, Carter, LaRussa, and Bodner (1987) found that students' ($N = 850$) spatial skills correlated for areas requiring problem-solving skills such as stoichiometry problems ($r = 0.20$, $p < 0.001$) and crystal structures ($r = 0.29$, $p < 0.001$). The Purdue Visualization of Rotations Test has been used to test students' spatial ability especially with chemistry majors (Bodner & Guay, 1997). Visuospatial is a necessary skill for studying chemistry, but what does this term mean?

Visuospatial.

Merriam-Webster's (2015) definition for visuospatial relates to both visualization and spatial aspects of objects. Wilhelm (2009) stated that visuospatial aptitude can be split into spatial orientation and spatial visualization categories. As Wilhelm (2009) stated, spatial visualization has been used as a "catch-all term that encompasses mental rotation, spatial perception and visualization" (p.2107). A variety of definitions and terms have been associated with spatial ability (Ekstrom, French, Harmon, & Derman, 1976; Guilford & Lacy, 1947; McGee, 1979; US Employment Service, 1957). Table 2 contains different spatial visualization definitions as cited in McGee (1979).

Table 2: Definitions of spatial visualization

Investigator	Spatial visualization factor description
Guilford and Lacey, (1947)	An ability to imagine the rotation of depicted objects, the folding or unfolding of flat patterns, the relative changes of position of objects in space, the motion of machinery. This visualization factor is strongest in tests that present a stimulus pictorially and in which some manipulation or transformation to another visual arrangement is involved.
Thurstone (1950)	An ability to visualize a configuration in which there is movement or displacement among the internal parts of the configuration.
French (1951)	An ability to comprehend imaginary movements in three-dimensional space or the ability to manipulate objects in the imagination.
Ekstrom, French, Harman and Derman (1976)	An ability to manipulate or transform the image of spatial patterns into other arrangements; requires either the mental restructuring of a figure into components for manipulation or the mental rotation of a spatial configuration in short term memory, and it requires performance of serial operations, perhaps involving an analytic strategy.

Note: As cited in McGee (1979) p. 891.

Gilbert (2005) spoke of visualization in terms of metavisualization. A person is said to have good metavisualization when a person has a range of skills with conventions associated with representations for a specific area and general knowledge of visualization. For representations, one has to understand limitations of the models used with visualizations whether mental or written. Gilbert stated that metavisual capabilities involve spatial visualization (understanding objects in three-dimensional and their two-dimensional representations), spatial orientation (being able to visualize a three-dimensional representation from a different perspective), and spatial relation (effects of reflection and inversion). For these three skills, a student is skilled when:

- being able to 'translate' (transmediate) between modes or sub-modes e.g to be able to move fluently between two-dimensional and three-dimensional representations of a given model, that is, to be able to produce a material mode presentation from a virtual mode representation, and vice versa ;
- being able to mentally change the perspective from which a given three-dimensional representation is viewed;
- being able to operate on the representation itself, particularly in terms of taking mirror images of it. (Gilbert, 2005, p. 21)

For metavisualization, the main chemistry modes can be concrete (an actual physical representation such as molecular models), verbal (description of the model), symbolic (using symbols to describe the model) and visual (can be diagrams representing the model). Sub-modes refer to codes or ways representations are expressed within these modes. Each mode can have a variety of sub-modes (Gilbert, 2005). For example, chemical equations can be represented with words or symbols and the information conveyed can be very general or specific based on the sub-mode. If students do not develop these three skills, then the student may experience learning difficulties with symmetry of molecules and crystals.

The National Research Council (NRC) has called for spatial literacy involving the following characteristics:

> 1. They have the habit of mind of thinking spatially—they know where, when, how, and why to think spatially.
> 2. They practice spatial thinking in an informed way—they have a broad and deep knowledge of spatial concepts and spatial representations, a command over spatial reasoning using a variety of spatial ways of thinking and acting, and well-developed spatial capabilities for using supporting tools and technologies.
> 3. They adopt a critical stance to spatial thinking—they can evaluate the quality of spatial data based on its source and its likely accuracy and reliability; can use spatial data to construct, articulate, and defend a line of reasoning or point of view in solving problems and answering questions; and can evaluate the validity of arguments based on spatial information. (NRC, 2006, p. 4).

In addition, the NRC emphasizes the learning of spatial skills for all levels of education to increase spatial literacy. While there is no one term to describe visuospatial, this skill is necessary to understand chemistry concepts relating to previous chemistry research with visualization used with organic chemistry (Harle & Towns, 2010) and stoichiometry (Bodner & McMillen, 1986).

Possibility of improving students' visuospatial skills.

Is it possible for students' visuospatial skills to be improved with practice? Sorby (2007) studied the effects of a spatial skills course for engineering. The Purdue Spatial Visualization Test: Rotations (PSVT:R; Guay, 1977) was administered in the initial year of the study to a total of 96 students with only three females score perfect on the PSVT:R while 42 males received a perfect score with this difference between females and males being statistically significant ($p < .0001$). Failing scores were also statistically significant ($p < .001$) based on gender. From the 96 students in the initial year, 24 students were selected for a spatial skills course with 72 students became the control group for this study. For visualization, students in the course built models using snap cubes or used hand-held objects allowing the students to be able to modify their view and perspective physically. A computer component of the course using CAD software allowing for computer images to be rotated. Pre/posttest scores were compared with a dependent t-test showed the gains were statistically significant different ($p < .0001$). The small experimental group has the potential to bias the results, but these results were repeatable. For the five years after the initial course, the gains from pretest to posttest were statistically significant different for each year (1994: $p < .0005$; 1995: $p < .005$; 1996, 1997, 1998: $p < .0005$). Retention rates between students taking and not taking the spatial skills course was computed from 1993-1998. For male students, the retention rate in the College of Engineering was not statistically significant different between the control group (52.0%) and the spatial skills course group (61.2%). Across the five year, the retention rate for females in the College of Engineering was statistically significant ($p < .0002$) between the control group (47.8%) and the spatial skills course group (76.7%).

For engineering students, a course focusing on spatial skills helped with retention especially for females (Sorby, 2007).

Lord (1985) found that students who attended sessions on the way horizontal, vertical and oblique planes slice through a variety of shapes (ball-like, rectangular-like, cylindrical-like and conical-like) increased their spatial ability. A total of twelve sessions were held with the shapes and planes differing for sessions. Spatial ability was tested using measures from *Manual for Kit of Factor Referenced Cognitive tests* (Ekstrom et al., 1976). A control group and an experimental group were formed with 42 undergraduate science majors in each group. The number of males and females were roughly the same within each group. The initial spatial ability was not statistically significant different. The instrument used for this study tested the ability to predict the surface created after a plane passed through a solid. Pretest and posttest scores were compared with a t-test but the scores for the control group were not statistically significant different, but the experimental group showed statistically significant different between tests ($p < .05$). For posttest scores on spatial aptitude, t-test was statistically different between the experimental and control group ($p < .05$).

The ability to rotate a molecule is an important concept for organic chemistry. At the University of Bophuthatswana 31 students (20 males and 11 females) participated in a study about basic aspects of three-dimensional modeling for ball-and-stick molecules including reflection and rotation. Pre/posttest consisted of two types of items with Part A (24 items) testing overall competence of three-dimensional thinking based on literature and Part B had 45 items developed using a stepwise methodology for solving these items. Some topics covered in Part B were identifying XY, XZ and YZ planes, recognition of the meaning for rotation around an axis, ability to use depth cues, and ability to visualize atoms after rotation. Students were divided randomly between a control (*N* = 16) and an experimental group (*N* = 15). A two-hour remedial instruction program was performed focusing on some basic skills and competences after the pretest for the experimental group. An analysis of covariance (ANCOVA) was performed for scores on the standard items (Part A) with pretest scores as covariates, $F(1,28) = 10.67$, $p < .01$ (Tuckey, Selvartnam, & Bradley, 1991). Visualization skills can be taught to students allowing them the opportunity to succeed with concepts requiring spatial abilities.

Misconceptions in Chemistry with the Ionic Bond

Ionic, covalent and metallic are three types of bonding, and students have trouble understanding the differences between the bond types (Coll & Taylor, 2001). Covalent bonding occurs when two atoms share electrons. Metallic bonding occurs between cations (positive ions) of the same metal with the electrons being a sea around the cations and mobile allowing for conduction of heat and electricity (Zumdahl & Zumdahl, 2014). An ionic bond is formed due to the electrostatic attraction between oppositely charged ions (Tro, 2010). While students have trouble with all three types of bonds (ionic, covalent and metallic), this research focuses only on ionic bonds. Several student misconceptions have been identified in literature related to ionic bonding (Ben-Zvi, Eylon, & Siberstien, 1986, 1987; Birk & Kurtz, 1999; Boo & Watson, 2001; Burrows & Mooring, 2015; Butts & Smith, 1987; Coll & Taylor, 2001; Coll & Treagust, 2002, 2003; Harrison & Treagust 2000; Luxford & Bretz, 2013; Nicoll, 2001; Othman, Treagust, & Chandrasegaran, 2008; Taber, 1994, 1997,1998, 2002a; Taber, Tsaparlis, & Nakiboglu, 2012; Waldrip & Prain,, 2012). Students viewing ions as a molecule is a popular misconception with students thinking that one atom donates a electron to another atom of a different element these two atoms are always linked (Ben-Zvi, Eylon, & Siberstien, 1986, 1987;. Boo & Watson, 2001; Coll & Treagust, 2002, 2003; Harrison & Treagust 2000; Othman, Treagust, & Chandrasegaran, 2008; Taber, 1994, 1997, 1998, 2002a; Taber, Tsaparlis, & Nakiboglu, 2012). Even though an ionic bond is defined as the electrostatic attraction between ions, textbooks and teacher resources periodically still refer to the ionic bond as the transfer of electrons and represent an ionic bond only using one cation with one anion (Ben-Zvi, Eylon & Siberstien, 1986, 1987; Taber 1994). Figure 4 is from *Argument-Driven Inquiry in Chemistry* by Sampson et al. (2015) showing the misconception of the ionic bond being formed due to the transfer of electrons instead of ion formation. With only two atoms being shown, the electrostatic attraction between ions in a crystal is not being conveyed to students. This diagram may be linked to the history conjecture of the molecular framework as students may conclude that the two ions will always be paired together indicating a directionality of the bond. The covalent bond in the diagram is shown correctly with the electrons being shared between the two atoms. Both of the diagrams are only showing two atoms which would be correct for covalent bonding, but for ionic bonding students may not realize that the ionic bond exists between an ion and all the oppositely charged ions directly surrounding that ion.

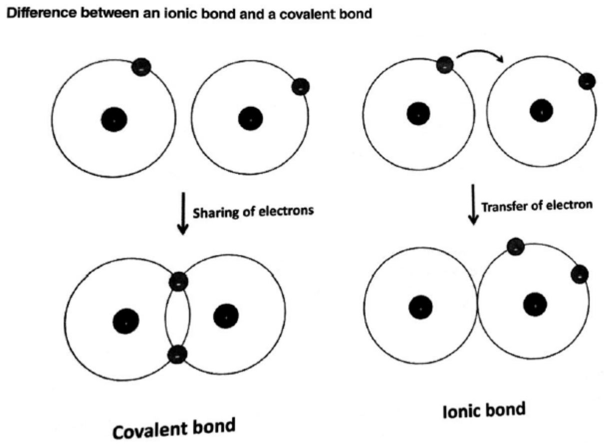


Figure 4. Correctly showing covalent bond and displaying the misconception of ionic bond formed due to transfer of electrons. (Sampson et al., 2015)

Students tend to focus on the octet rule (eight electrons in the outer shell to obtain noble gas configuration equating a stable ion formation) and the need for main group elements to have a full outer shell as the reason for forming ions instead of ionization energy for positive ions (Coll & Taylor, 2001; Coll & Treagust, 2003; Robinson, 1998; Taber, 1994, 1997, 1998, 2002a; Tan & Treagust, 2009; Waldrip & Prain, 2012). Instead of forming ions, covalent bond theory (sharing of electrons) has been mistaken for ionic bonding (Coll & Taylor, 2001; Coll & Treagust, 2002, 2003; Luxford & Bretz, 2013; Robinson, 1998; Taber, 1994, 1997, 1998, 2002a). Students also think ionic bonding is weak because it is comprises electrostatic forces; and ionic crystals are brittle and can be shattered (Coll & Taylor, 2001). Due to these variety of misconceptions, an alternative way of teaching about ionic bonding is needed. Ion formation (transfer of electrons), ionic bonds (utilizing the electrostatic attraction in an ionic crystal), and dissociation equations are subjects addressed by this alternative curriculum unit.

Taber's (1997) electrostatic framework addresses the misconceptions for the ionic bond. The role of molecules status states that molecules are not part of ionic structures.

The electrostatic focus concerns the oppositely charged ions forming unit cell of the lattice. There is no valency conjecture with forming a unit cell, and the lowest whole number ratio of cations to anions in a unit cell represents the ionic formula unit. Ionic solids can be separated into ions in water, and the solid can be recrystallized by evaporating the water. In the reformed solid, the ions will not form ionic bonds with the same exact ions as in the original solid. Ionic bonds are formed due to electrostatic attractions between oppositely charged ions. This framework differs from the molecular framework. The new unit's lessons will have to challenge students' thinking from the molecular framework to the electrostatic framework such that this new framework will be assimilated into their thinking and not adapted (Posner, Strike, Hewson, & Gertzog, 1982).

Ion Formation

For the modern periodic table, the elements are arranged by the number of protons. From Dalton's Law, all atoms of the same element are identical meaning that these atoms have the same mass, size, and chemical properties. While the mass and size may differ slightly due to isotopes of the element (same number of protons and electrons but different number of neutrons), chemical properties of elements remain the same. These chemical properties follow trends for the periodic table including ionization energy and electron affinity. Ionization Energy is the minimum amount of energy required to remove an electron from an element while in the gaseous phase. A higher Ionization Energy value means the electron is tightly held by the nucleus. The First Ionization Energy is the amount of energy to remove the first electron, and the Second Ionization Energy is the amount of energy to remove the second electron and so forth. The First

Ionization Energy values overall trend is increasing as one moves to the right along a row of the periodic table. A jump between Ionizations Energy values can occur for example sodium has a First Ionization Energy value of 495.9 kJ/mol and a Second Ionization Energy value of 4,560 kJ/mol (Chang & Goldsby, 2014). This jump is an indication that a sodium atom will form a +1 ion readily but not a +2 ion. Magnesium has a small increase between First Ionization Energy (738.1 kJ/mol) and the Second Ionization Energy (1,450 kJ/mol), while the Third Ionization Energy (7,730 kJ/mol) is much larger than the Second indicating that a +2 ion is formed. For the periodic table, main group columns (families) follow this trend of jump between Ionization Energy values meaning that all the first column elements (except hydrogen is not considered part of the first column family) have a jump in Ionization Energy values from the First to the Second.

Electron affinity is also a property that affects anion formation. Electron affinity is “the negative of the energy change that occurs when an electron is accepted by an atom in the gaseous state to form an anion” (Chang & Goldsby, 2014, p. 268). The overall trend for electron affinities is to increase from left to right in a row of the periodic table. Two dips occur for Main Group 2A and 5A due to electron configurations of elements in these groups. Group 2A requires the extra electron to be placed in a higher p orbital. For Group 5A, the extra electron would have to be paired in a p orbital. For the neutral element in Group 5A, each p suborbital has one electron, a more stable state then adding an extra electron and pairing two electrons in a suborbital.

Crystals

When ionic compounds are solids, they form crystals with the smallest, regular repeating pattern called the unit cell. One way to describe unit cells is by the coordination number, the number of nearest neighbors to a point/particle. Figure 5 shows a simple unit cell and the discussion will be focused on the black center particle. The center particle has six neighboring particles shown in gray (top, bottom, and the four sides) giving a coordination number of six. The center particle is shared between eight unit cells causing only one-eighth of the particle is counted for a single unit cell. Most crystal unit cells have particles on the eight corners of the cube. Thus, one particle is associated with a single unit cell because multiplying eight corners providing one-eighth of a particle results in one particle. With the unit cells, particles can be in the center of the unit cell called body-centered unit cell with the whole particle being counted as part of a single unit cell. A face-centered unit cell can contain a particle for each face (side) of the unit cell, but some may only have certain faces containing particles. Only half of a face-centered particle is counted for a single unit cell (Silberg, 2018). The edges of the unit cell can also contain particles with only a fourth of the particle is counted for a single unit cell. By understanding the fraction for each type of particle (ion for an ionic compound). A unit cell can be used to determine the number of cations to anions ratio. This ratio from the unit cell is the formula unit for an ionic compound after reducing the ratio to the lowest whole number ratio if necessary.

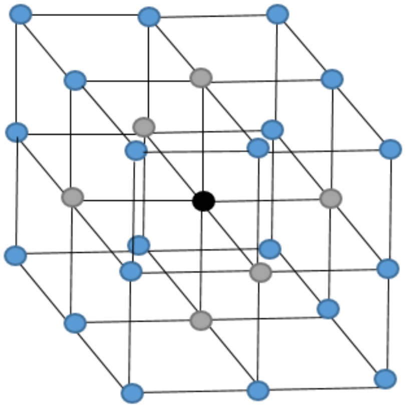


Figure 5. Simple unit cell of crystal displaying coordination number = 6

Mineralogy is a geology course covering some of the same concepts involving crystals with chemistry such as symmetry, structures, close packing and coordination numbers. Ozedmir (2010) studied the impact of a mineralogy course on students' spatial abilities using the cube comparison test and surface development test (Ekstrom et al., 1976). Results from pre/post t-tests were statistically significant ($p < .05$) with a moderate effect size ($d = .44$) for the surface development test and large ($d = .86$) for the cube comparison test. Interviews from eight students showed that students had issues with visualizing closed packed crystals. "The most challenging part for the students was to transform 3D images into 2D representations" (Ozedmir, 2010, p. 750). Using observations over the course of the semester, students' ability to transform images improved, and students' comments that mineralogy helped to improve their spatial abilities. The ability to transform images between two-dimensional and three-dimensional is a factor with student success for learning chemistry and mineralogy. Both of these areas involve mentally manipulating symmetrical structures. For students' to succeed, NRC’s (2006) call for an emphasis on spatial literacy should be incorporated throughout the levels of education including visuospatial aptitude.

Grove et al. (2009a) attempted to teach a unit on symmetry and crystallography at the high school level for 36 students. The symmetry portion focused on chirality and mirror symmetry for enantiomers with a discussion on the importance of enantiomers. Another lesson discussed the topics of rotation, reflection and inversion with symmetry. Basic point group classification with students constructing snowflakes to illustrate point groups was the final topic for the symmetry for this part of the unit. In addition, students were encouraged to identify symmetrical objects in their life.

The crystallography portion first reviewed solid, liquid and gas phases. “The concept of translational symmetry was also introduced as the fundamental definition of the crystalline phase” (Grove et al., 2009a, p. 947). Discussions occurred about the variety of crystalline material in the world with students growing their own crystals. After examining their crystals with the naked eye and stereomicroscopes, students had to draw and describe their crystals using symmetry terms. Single-crystal diffractometer was also explained using photographs as part of PowerPoint slide show. The culminating activity was to visit a geological museum to view crystals and tour an X-ray diffraction facility.

Grove et al. (2009a) evaluated this unit using a pre/posttest with five items focusing on symmetry and five items focusing on crystallography. This test consisted of ten two-tier questions using a multiple-choice question for the first tier worth one point and a paired question requiring elaboration for the second-tier worth two points. The post test was administered three weeks after the unit. The symmetry and crystallography portions were not normally distributed per the Komogorov-Smirnov normality test. The nonparametric Wilcoxon signed-rank test was used for the pre/post comparisons. A significant increase for the pre/post scores was found for the symmetry portion (M_{pre} = 1.37; M_{post} = 3.17; $p < .001$), the crystallography portion (M_{pre} = 2.00; M_{post} = 3.57; $p = .001$) and the overall test (M_{pre} = 3.37; M_{post} = 6.74; $p = .001$). Even though the results showed significant increase, each section had a possible score of 15 points with the overall test having a possible score of 30 points. From the distribution plots included in the paper, the highest overall score by a student was 13 points out of a possible 30 points with students having a higher test gain for the symmetry portion of the test. The unit's information was included in the on-line supplemental material. While some hands-on activities were performed like identifying point groups for snowflakes and growing crystals, most of the information about symmetry and crystallography appeared to have been conveyed using PowerPoint slides (Grove et al., 2009b). Even though the overall test showed a significant difference between pre and post, the gain associated with visually observing and hands-on activities is unable to be determined, but this study does show the subject of crystals can be a difficult subject for students to grasp.

Crystals and chemistry.

Crystals and symmetry are part of general chemistry textbooks, but only a casual mention is given of the unit cell when ionic compounds are first discussed with the balancing of the formula unit and naming. Crystals are usually discussed after intermolecular forces are covered. For a variety of general chemistry textbooks, Table 3 shows the chapter containing ionic formula units balancing with naming, and the chapter(s) covering crystal solids topic. Kotz, Treichel, Townsend and Treichel (2015), and Zumdahl and Zumdahl (2014) are Advance Placement textbooks. Burdge and Overby (2015), and Tro (2015) are Atoms first approaches to teaching chemistry with electron configuration presented before naming compounds and stoichiometry. D. Hanson (2010) is a Process Oriented Guided Inquiry Learning (POGIL) activity textbook. The remaining textbooks in Table 3 are traditional textbooks with naming compounds and stoichiometry presented before electron configuration. The general chemistry students using a textbook either from Table 3 or a similar textbook would only experience one to four sections about crystals several chapters after they had learn to balance the ionic formula unit and named ionic compounds.

Table 3: General Chemistry Textbooks- Chapter Information about Formula Unit and Crystals

Author	Chapter Formula Unit Balancing + Naming	Chapter Crystals (Number of Sections)
Burdge & Overby (2015)	5	12 (2)
Chang & Goldsby (2014)	2	12 (2)
Hanson (2010)	3	10 (1)
Kotz, Treichel, Townsend, Treichel (2015)	2	12 (3)
McMurray & Fay (2008)	2	10 (3)
Silberg (2010)	2	12 (1)
Tro (2015)	5	13 (4)
Zumdahl & Zumdahl (2014)	2	10 (3)

While Galasso (1993) agrees with NRC (2006) visualizing structures should be started early in education, most general chemistry textbooks do not cover crystals in-depth but discuss packing arrangements (Chang & Goldsby, 2014; Silberg, 2010; Tro, 2015). Crystallography is a subject taught more in-depth in upper-level inorganic or physical chemistry courses (Pett, 2010). From Grove et al. (2009), molecular and crystal symmetry (with point groups) are difficult topics for high school students. Coll and Taylor (2002) do suggest that higher level models should be taught in advanced level courses in college, because non-chemistry majors will not need these advanced models with their majors. Students need to understand the basics of the ionic crystal lattice such as unit cell, the repetition of the unit cell forming crystals, and analyzing the ratio of cations to anions in the unit cell to help reduce misconceptions about the ionic formula unit which will also aid with balancing and drawing particulate diagrams for dissociation equations.

Games/Activities.

Due to the students' difficulties with balancing ionic formula units, several different games/activities have been developed attempting to teach students this topic (Logerwell & Sterling, 2007; Kavak, 2012; Ruddick & Parrill, 2012; Chimeno et. al, 2006; Wirtz, Kaufmann & Hawley, 2006). These activities could be considered an analogy for balancing ionic compounds (Harrison & Treagust, 2000). The activities are not using actual compounds for balancing but manipulatives are used. These games are more focused on the mathematics behind balancing the ionic formula unit and not explaining the ionic formula unit is the lowest whole number ratio of cations to anions in an ionic crystal unit cell.

Wirtz, Kaufmann and Hawley (2006) describe four different activities introducing the rules for naming compounds. These activities are discovering-learning models for both ionic compounds and binary covalent compounds. Rules are reinforced with traditional practice problems. These activities build up from simple rules to more complex rules for ionic compounds. The first activity deals with binary ionic compounds of main group elements with only a single charge possibility. Variable charge cations rules are the subject for the second activity module. Some cations of transition metals can form cations with different charges due to the complex nature of transition metal electrons and the possibility of having more than one stable electron arrangement. Polyatomic ion rules are developed in the third activity. The fourth activity involves the rules for naming binary covalent compounds, which have a different set of rules than ionic compounds. The first three activities describe the different combinations of rules mentioned by other activities in this literature review for ionic compounds (Wirtz et al., 2006).

ChemOkey is a game using tiles to make sets of cations and anions to form compounds. The activity allows students to practice with 169 ionic compound formulas. Students from both control and experimental groups took a pre and post test of fifty questions were given. The pre test scores for both groups were comparable (*M* = 20.44 – control group versus *M* = 20.00 – experimental group), and the two groups were not statiscally significant different for the pre-test (t(47)=0.377, p=.708). The students from the experimental (ChemOkey) scored higher (*M* = 38.67) on the posttest compared to the control group (*M* = 32.72) indicating a positive effect on student learning by this activity. On the post-test, the experimental group showed a significant difference from the control group (*t*(47) = 5.368, *p* = 0.000; Kavak, 2012).

The Rainbow Matrix game developed by Chimeno (2000) is a computer program for teaching ionic compounds using blocks for cations and anions based on another game the Rainbow Wheel, which uses blocks to balance ionic compounds. Students can either access practice (3 attempts) or a test (1 attempt) to balance compounds with the program. To solve an ionic compound, students manipulate cation and anion jigsaw icons with saw teeth. Two different ions (a negative ion and positive ion) fit together to form a block. The game can provide one hundred combinations for problems. The game's effectiveness was checked using a pre-assignment quiz, post-assignment quiz and an exam. Three classes were used for participants with one class utilizing traditional learning techniques, another class used the Rainbow Wheel game, and the final class used the Rainbow Matrix program. The Rainbow Wheel class had the lowest means on the pre-quiz with 6.3 compared to 7.8 for traditional and 8.3 for Rainbow Matrix. After the lesson for the post-assignment , the Rainbow Wheel class had the highest mean with 17.5, the traditional class had a post-quiz mean of 12.9, and the Rainbow Martrix had a mean of 17.0. The exam means had the Rainbow Matrix passing the Rainbow Wheel class (13.6 versus 13.0). "An analysis of covariance (ANCOVA) for the post-assignment quiz scores (using the pre-quiz scores as the covariate) revealed a statistical difference amount the three groups [$F(2,36) = 8.62$, $p = 0.001$]" (Chimeno et. al, 2006).

Ruddick and Parrill (2012) developed an activity using LEGO blocks to demonstrate the interlocking of ions. Two different colors of blocks are used to represent cations and anions respectively. The knobs of the LEGO pieces indicate the value of the ion's charge. Thus, one knob has a value of 1, two knobs represents a value of 2 and so forth. Ionic compounds are balanced when the LEGO model has no extra knobs when the blocks are joined. One class used the hands-on LEGO activity, a second class was taught using traditional technique, and the Rainbow matrix game was used for a third class in an urban school setting. The different teaching methods were evaluated using a 10 item multiple choice posttest. "A significant difference in posttest scores among the three groups is seen using a one-way ANOVA test: $F(2,49) = 4.18$; $p = 0.021$" (p. 1437,Ruddick & Parrill, 2012). From the results of a Tukey-Kramer post-hoc, the LEGO class ($M = 7.79$; $SD = 2.04$) outscored the traditional class ($M = 6.12$; $SD =2.20$) and the

Rainbow Matrix game class (*M* = 5.77; *SD* =1.48). While the results are statistically significant, the means from the post-hoc only show a 1.67 point differences between the Lego and traditional teaching methods and a 2.02 point difference between Lego and Rainbow Matix teaching methods.

Several different types of hands-on activities were described in "Fun with Ionic Compounds" by Logerwell and Sterling (2007). No research studies were presented in this article. Cards are used for a variety of games. One activity has the cards cut out into sawteeth allowing anions and cations to interlock similar to the Rainbow Matrix game. Formula Rummy and Fishing for Formulas are two other card games used for teaching students balancing ionic formulas. Chemical board game deals with students landing on spots and then pulling cards to attempt to make a balanced ionic compound. From the article, the rules for the board game sound difficult. Wheel of Formulas involves a wheel sectioned with anions as the slices. Students spin the wheel to obtain an anion and then have to formulate a balance compound using either a cation the teacher or the student picks.

While these activities are good for learning and reinforcing balancing and naming ionic compounds, students still have to memorize the ions. These activities are in the portion of the triangle proposed by Johnstone (1991) closer to the macroscopic and symbolic points. Students can not use these games for their tests. The activities/games do not help with the microscopic representation which will be useful for dissociation equation and understanding the ratio of ions formed in an aqueous solution.

Chemical Equations and Ionic Dissociation.

Chemical reactions occur when a substance or substances change into new substance or substances. Chemical reactions can be classified as a chemical change which occur when bonds are broken and/or formed. Chemical equations explain chemical reactions using symbols. Proust's Law of Definite Proportions states that different samples of a compound will have the same ratio of elements (Chang & Goldsby, 2014). Lavosier's Law of Conservation of Mass states that matter is neither created nor destroyed in a chemical reaction (Tro, 2010). For a chemical equation to be balanced, the number of each type of element has to be the same for the reactants and products. The same number of atoms for each element is an example of the Law of Conservation of Mass. The only items that can be changed are the coefficients in front of the compounds or elements. Subscripts for the elements in their natural state such as O_2 or compounds such as H_2O can not be changed because the element or compound would be different violating of the Law of Definite Proportions (Yarroch, 1985).

Types of Chemical Reactions.

The following shows the variety of chemical equations (Chang & Goldsby, 2014) students encounter in general chemistry, but these equations are not all encompassing. Precipitation reactions involve the combinations of two substances resulting in the formation of a solid based on solubility rules. These reactions are also known as double displacement or metathesis reactions:

$$\mathrm{Pb(NO_3)_2(aq) + 2KI(aq) \rightarrow PbI_2(s) + 2KNO_3(aq)}$$

Precipitation reactions can also be represented by net ionic equations showing the appropriate ions as reactants and the resulting solid. Any ions not involved with the solid formation are called spectator ions and are not shown in the net ionic equations.

$$\mathrm{Pb^{2+}(aq) + 2I^-(aq) \rightarrow PbI_2(s)}$$

Acid-Base neutralization reactions combine an acid and a base forming water and a salt (ionic compound):

$$\mathrm{HCl\ (aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)}$$

The following reactions can be considered part of a large reaction called reduction-oxidation reactions involving the change in oxidation numbers for elements.

Combination reactions involve two or more substances reacting forming one product:

$$\mathrm{S(s) + \ O_2(g) \rightarrow SO_2(g)}$$

Decomposition reactions represent the breakdown of one substance into two or more substances:

$$\mathrm{2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)}$$

Combustion reactions are when a substance reacts with oxygen involving the release of heat and light producing a flame in addition to products:

$$\mathrm{C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)}$$

Displacement reactions are when an atom or ion displaces another atom or ion.

Hydrogen displacement is one type of these reactions:

$$\mathrm{Ca(s) + 2H_2O(l) \rightarrow Ca(OH)_2(s) + \ H_2(g)}$$

Metal Displacement is another type of these reactions:

$$\mathrm{Zn(s) + CuSO_4(aq) \rightarrow ZnSO_4(aq) + Cu(s)}$$

Dissociation equations can be considered chemical equations as they have to obey Lavosier's Conservation of Mass. even though these equations involve the separation of a compound into its respective ions:

$$\mathrm{NaCl(s)} \xrightarrow{\mathrm{H_2O}} \mathrm{Na^+(aq)} + \mathrm{Cl^-(aq)}$$

Dissociation Equation.

While balancing the ionic formula unit is an important aspect of ionic compounds, the dissociation equation is another area that students' struggle to understand and apply. The dissociation equation involves the dissolution of the ionic solid in water. Ions are formed from the dissolving of ionic compounds allowing these mixtures to conduct electricity and to be classified as electrolytes. The dissolution process involves water molecules interacting with an ionic solid to break the ionic bond. Water is a polar covalent compound with the oxygen having more of the electron cloud due to the lone pairs of electrons on the oxygen. Since oxygen has more of the electron cloud, hydrogen then carries a slight positive charge. The oxygen portion of water will attract and separate the positive ions into solution. The hydrogen portion of water will attract and separate the negative ions into solution. As these ions are dissolved in water, the water molecules will orientate accordingly around the ions such that opposite charges attract. This process is known as hydration. Some of the same concepts apply to dissociation equations as well as chemical reactions.

Misconceptions.

Students have misconceptions with balancing chemical equations and the meanings behind these equations. From a study of 337 students 15 years in age and older, Ben-Zvi, Eylon and Silberstein (1987) identified students struggling with treating the reactants and products as discrete units, and using an additive viewpoint instead of a dynamic viewpoint of breaking or forming bonds. Additive viewpoint is concerned with the mathematical balancing of chemical equations. Dynamic viewpoint of chemical reactions discusses the number of bonds breaking and forming with the different arrangements of the particles (atoms, ions and molecules) or the way electrons move with electrochemistry. Ben-Zvi et at. (1987) pointed out that textbook authors do not go into full detailed explanations but only focus on the relevant concept of balancing potentially creating misconceptions by students.

Nakhleh and Mitchell (1993) stated that students who can solve algorithmic problems in chemistry may not always understand the concepts involved with these problems. A more algorithmic (mathematical) method instead of a conceptual (particulate) method has been the focus leading to the possible development of conceptual errors and misconceptions (Hinton & Nakhleh, 1999). From their qualitative study, Treagust, Chittleborough, and Mamiala (2003) found that in Year 11 (average age was 16 years) students in Australia do not always understand representations for different concepts, and unfortunately the teacher assumes that the students do comprehend these concepts thoroughly. This study recommend the use of both symbols and representations with chemical explanations. When Yarroch (1985) asked 12 high school students to draw representations of four chemical equations that they had previously balanced, five of the 12 students were able to draw representations correctly. These students did communicate that the reaction arrow was not just an equal sign to satisfy the Law of Conservation of Mass but the arrow represented a chemical change occurring. The other seven students made diagrams consistent with the total number of particles being equal, but their representations were not correct per the subscripts and coefficients such as have six hydrogen atoms linked together instead of three sets of two hydrogen atoms linked representing $3H_2$.

Ben-Zvi, Eylon and Silberstien (1986) studied 1,078 students with an average age of 15 years from 10 high schools across Israel for a total of 35 classes. From pretests, achievement test, and a conceptual test, their results found that students do not think of chemical reactions in terms of bond breakage and formation, but as a mixture of atoms gluing to each other. Boo and Watson (2001) interviewed 48 students in Year 12 and a second time in Year 13. These students had difficulties explaining the changes in chemical bonds and identifying bonds broken/formed for chemical reactions. Small gains in knowledge did occur between these two years.

Hesse and Anderson (1992) interviewed 3 students (either in their junior or senior year of high school) in-depth about chemical reactions by explaining the process of an iron nail rusting. The students did not discuss atoms or molecules, or use conservation of mass to explain if the nail's mass increased. While students may be able to mathematically balance chemical equations, they do not always understand these equations in-depth.

Kern, Wood, Roehrig and Nyachwaya (2010) reported on 1,337 high school students attempt to balance and then draw a diagram to represent the complete combustion of methane. The chemical equation ($CH_4(g) + O_2(g) \rightarrow CO_2(g) + H_2O(l)$) was given to the students with blanks in front of each compound/element for coefficients. Only 65% of the students could balance the equation with coefficients and fewer than half could draw the particulate representation. Nyachwaya et al. (2011) performed a study with 70 freshmen general chemistry students utilizing balancing chemical equations and drawing particulate diagrams. Ninety-nine percent of the students could balance three different chemical equations (combustion of methane, double displacement/precipitation, and acid-base gas-formation) with each chemical equation was on a different exam. Thirty percent of the students could draw an appropriate representation for the combustion reaction. Only 1% could draw an appropriate representation for the second (double displacement) and third (acid-base gas formation) situations (Nyachwaya et al., 2011).

Sanger (2005) found that 68 students out of 156 students were confused by the use of subscripts and coefficients relating to a particulate drawing and choosing the correct option for the corresponding balanced equation. By not being able to understand the particulate level, students had issues with the stoichiometric aspects of these questions too. Davidowitz, Chittleborough, and Murray (2010) also investigated the issue of understanding the particulate view of chemical equations and using them for stoichiometric calculations. After focusing on the particulate level in instruction during class, correct answers for balancing the same equation increased from 11.1% (N=117) to 52.5% (N=120), but the percentage of correct answers for the moles of reactant remaining after reaction was low, 3.4% (N=117) and 15.8% (N=120).

Naah and Sanger (2013) also investigated using static pictures and animations of the dissolving process for four different compounds to probe students' (N=98) knowledge using a two-tier multiple-choice test for balanced equations with one tier being the symbols and the other tier displaying the dissociation equation as particles. The interaction of visualization type (animation or static), representation order (balance equation or particulate), and answer was shown to be significant with a log linear analysis, $\chi^2(3) = 11.50$, $p < .05$. The static visualization performed had a higher number of correct answers than the animations. The motion of particles in the animations may have been distractive to the students unlike the static representation of the reactants and then the products. Kelly and Jones (2007) investigated the thought processes behind dissolution of sodium chloride by having 18 students draw the process before and after watching animations. Students understanding of the ionic solid with the alternating charges and the different sizes of ions improved with 10 of 18 students modifying their drawings after watching animations. The students' verbal explanations still showed lack of comprehension with understanding the dissolution process even if the students had included the aspect in their drawings.

Misconceptions with dissociation equations.

Dissociation equations are a category that does not fall directly into the chemical change category. Naah and Sanger (2012) discussed this ambiguity as how one perceives the ionic solid. If the solid is considered an intact entity, then the process can be considered to be chemical with new species ions versus the original solid. On the other hand, the ionic compound can be recovered by physical means (evaporating water), and the dissolution process can be classified as a physical change. Ebenezer and Gaskell (1995) also discussed this ambiguity when students were trying to explain why both sugar and salt dissolve in water. Naah and Sanger (2012) used balanced equation instead of balanced chemical equation to attempt to clarify the difference between a chemical reaction and dissolving of an ionic compound. They studied 105 students' free-responses for balancing equations for the dissolution of LiCl, $CaCO_3$, $BaBr_2$, and K_2SO_4. After analyzing the responses, the results and most common errors were tabulated with LiCl had the highest correct percentage with 44% and K_2SO_4 had the lowest percentage with 8%. In addition, 34 students were interviewed to explain their thought processes with balancing these equations. From both activities, the misconceptions encountered were water reacting, charges missing, subscript errors, incorrect charges, polyatomic ion dissociated, atoms not balance, and charge not balanced. Students have also had difficulties with representing precipitation equations both the reactants (ions) and products (ions plus solid; Smith & Metz, 1996).

Smith and Nakhleh (2011) investigated students' understanding of the difference between melting and dissolving. Seven graduate students and 25 undergraduates were interviewed about the melting of salt, chalk ($CaCO_3$), sugar, and butter. Students thought salt and chalk are composed of discrete molecules, and the covalent bonds within sugar and butter were broken. In addition, students misidentified the intermolecular forces for salt, chalk, and butter. For dissolving these items in water, students' misconceptions were covalent bonds forming between the solute and solvent, and misidentifying the intermolecular forces. Students used the terminology melting and dissolving incorrectly. Even some of the graduate students displayed bonding misconceptions. Smith and Nakhleh (2011) suggested linking the particulate level with observations to deal with these misconceptions.

Specific visualization problems with dissolution process.

To draw particulate diagrams, students need to visualize the dissolving process. Students have trouble visualizing the dissolving process with some students discussing this change as melting (Adadan & Savasci, 2012; Ebenezer, 2001; Ebenezer & Erickson, 1996;

Othman, Treagust & Chandrasegaran, 2008; Smith & Nakhleh, 2011). Some students also have an inappropriate view of ionic compounds by referring to them as molecules and discrete units instead of a highly symmetric array of cations and anions (Boo & Watson, 2001; Butts & Smith, 1987; Coll & Taylor, 2001; Coll & Treagust, 2002; Luxford & Bretz, 2014; Robinson, 1998, Taber, 1994, 1997, 1998; Taber, Tsaparlis & Nakiboglu, 2012; Vladusic, Buscat & Ozic, 2016; Warfa, 2013). Due to these misconceptions, students have difficulties drawing particulate diagrams (Ebenezer, 2001, Kelly & Jones, 2007,2008; McBroom, 2011; Naah & Sanger, 2012). Misunderstanding of the ionic bond causes these misconceptions. The ionic bond, formula unit and dissociation equations are covered in chemistry courses. Thus, NGSS has to be analyzed to determine the way these concepts are covered.

Ionic Bonding NGSS Learning Progression

Smith, Wiser, Anderson, and Krajick (2006) define a learning progression "as a sequence of successively more complex ways thinking about an idea that might reasonably follow one another in a student's learning" (p.5). Learning progressions are based on instruction allowing for many different ways to teach concepts, but prior instruction will influence these paths. Current instruction and background are interconnected. *Taking Science to Schools: Learning and Teaching Science in Grades K-8* by National Research Council (NRC; 2007) stress the use of learning progressions to connect topics in curriculum to promote more in-depth coverage of certain topics (big picture) instead of shallow coverage of many concepts. In addition, learning progressions are anchored meaning that the topic is introduced in one grade and then continued in one or more grades until the topic has been thoroughly covered. Learning progressions are based on constructivist theory by having the students' use their previous knowledge and continue to build their understanding of concepts (Fosnot & Perry, 1996). Posner, Strike, Hewson and Gertzog (1982) discuss learning as a form of inquiry using assimilation and accommodation. Assimilation occurs when students incorporate new knowledge into existing concepts. When previous concepts do not explain new knowledge, accommodation develops new concepts attempting to help the student to understanding, but a student has to realize that their existing concepts do not work. These new concepts have to be plausible and should not include misconceptions. In the end, these new concepts have to be assimilated into the current knowledge base.

A Framework for K-12 Science Education: Practices, Crosscutting Concepts and Core Ideas (NRC, 2012) continued the call for learning progressions with teaching science by introducing Disciplinary Core Ideas (DCI) for physical science, life science, earth and space sciences, engineering and technology, and applications of science. DCI are major topics focusing the performance expectations (PE). In addition to these core ideas, two other areas were stressed to be developed crosscutting concepts (CC), and science and engineering practices (SEP). While the core ideas link concepts between grades, SEP help students to apply some of the same skills used by scientists and engineers. CC can be applied across all the science domains. This framework was a basis for NGSS. Scientists, engineers, education professors, and master teachers were involved in the development of NGSS. The public also had the opportunity to comment on the new standards through different iterations (NGSS Lead States, 2013). This learning progression is based on the November, 2013 edition of NGSS. This learning progression is split by DCI demonstrating the way these major concepts are built using the grade bands: K-2, 3-5, Middle School, and High School. Instead of using standards, NGSS uses PE to indicate the topic/key skill to be met by the student. These PE can be met in a variety of ways dependent on teacher and curriculum.

Table 4 lists the PE covered by this learning progression. A variety of concepts beyond the definitions of ionic bond and ionic compounds were used to develop this progression including: particles (ions), charge, properties (both chemical and physical), balancing chemical equations, change (both physical and chemical), energy, conservation of mass, periodic table trends, and equilibrium. The second, fifth and middle school PE builds the platform for students to begin to understand the ionic bond in high school. While ions may be introduced in middle school, the understanding on exactly why these ions are formed does not occur until high school with HS-PS1-1, because the periodic trends are introduced at this level. The DCIs and their relationships will be explained with the final overall learning progression for ionic bonding presented at the end of this section.

Table 4: Learning Progression for Ionic Bonding – Performance Expectations

Number	Performance Expectation
2-PS1-1	Plan and conduct an investigation to describe and classify different kinds of materials by their observable properties
2-PS1-2	Analyze data obtained from testing different materials to determine which materials have the properties that are best suited for an intended purpose
2-PS1-3	Make observations to construct an evidence-based account of how an object made of a small set of pieces can be disassembled and made into a new object.
2-PS1-4	Construct an argument with evidence that some changes caused by heating and cooling can be reversed.
3-PS2-3	Ask questions to determine cause and effect relationships of electric or magnetic interactions between two objects not in contact with each other.
5-PS1-1	Develop a model to describe that matter is made of particles too small to be seen.
5-PS1-2	Measure and graph quantities to provide evidence that regardless of the type of change that occurs when heating, cooling or mixing substances, the total weight of matter is conserved.
5-PS1-3	Make observations and measurements to identify materials based on their properties

Table 4 cont'd: Learning Progression for Ionic Bonding – Performance Expectations

Number	Performance Expectation
5-PS1-4	Conduct an investigation to determine whether the mixing of two or more substances results in new substances
MS-PS1-1	Develop models to describe the atomic composition of simple molecules and extended structures
MS-PS1-2	Analyze and interpret data on the properties of substances before and after the substances interact to determine if a chemical reaction has occurred.
MS-PS1-5	Develop and use a model to describe how the total number of atoms does not change in a chemical reaction thus mass is conserved.
MS-PS1-6	Undertake a design project to construct, test, and modify a device that either releases or absorbs thermal energy by chemical processes
MS-PS2-3	Ask questions about data to determine the factors that affect the strength of electric and magnetic forces.
MS-PS2-5	Forces that act at a distance (electric, magnetic, and gravitational) can be explained by fields that extend through space and can be mapped by their effect on a test object (a charged object, or a ball, respectively).
HS-PS1-1	Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms.
HS-PS1-2	Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties.
HS-PS1-3	Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.
HS-PS1-4	Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy.
HS-PS1-7	Use a mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction.
HS-PS2-4	Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.

NGSS Lead States (2013)

PS1.A Structure and Properties of Matter.

This DCI category deals with the structure and properties of different types of matter. Particles make up matter, and ions are a type of particle. This DCI can be broken into four different subcategories: physical properties, conservation of mass, bond energy and trends in the periodic table. Table 5 displays the PE and the explanations for Structure and Properties of Matter DCI.

Ionic bonds are formed from the electrostatic attraction of ions. To classify ionic compounds, several different physical properties can be used such as high melting points (magnesium oxide: 2800°C; sodium chloride 800°C) compared to covalent compounds of similar molar mass (propane: -189°C; butane: -138°C), and conductivity. Ionic solids form a lattice containing a repeating unit cell pattern echoed in the resulting crystal shape. A unit cell is the basic repeating structure of a crystalline sold. For an ionic crystal, the shape of the unit cell depends on the ions. The most common unit cell configurations are simple cubic, tetragonal, orthorhombic, rhombohedral, monoclinic, triclinic, and hexagonal (Chang & Goldsby, 2014). Several textbooks only concentrate on unit cells for sodium chloride (NaCl), cesium fluoride (CsF) or cesium chloride (CsCl) and zinc sulfide (ZnS; Chang & Goldsby, 2014; Tro, 2010; Kotz, Treichel, Townsend, & Treichel, 2015). The lowest whole number ratio of cations and anions in these unit cells represent the formula unit for the ionic compound. An ionic solid has an overall charge of zero resulting in a neutral compound (Kotz, et al., 2015). Ionic compounds are hard and brittle. Ionic solids are poor conductors of electricity and heat. Some ionic compounds can dissolve in water with the ionic compound dissociating (separating into) cations and anions. Solubility rules predict whether an ionic solid dissolves in water in an appreciable amount. When the ions are in solution (water) these aqueous solutions can conduct electricity classifying them as electrolytes (Chang & Goldbsy, 2014). Conductivity probes can be used to determine a relative amount of ions in solution meaning nonelectrolyte (low conductivity; no ions), weak electrolyte (some conductivity; ions and molecules), or strong electrolyte (high conductivity; mainly ions). Solubility, conductivity, hardness, and brittle are physical properties based on the interactions of the ions and can be seen macroscopically (bulk scale).

Table 5: DCI PS1.A Structure and Properties of Matter

Number	Performance Expectation
2-PS1-1	Plan and conduct an investigation to describe and classify different kinds of materials by their observable properties
2-PS1-2	Analyze data obtained from testing different materials to determine which materials have the properties that are best suited for an intended purpose
2-PS1-3	Make observations to construct an evidence-based account of how an object made of a small set of pieces can be disassembled and made into a new object.
5-PS1-1	Develop a model to describe that matter is made of particles too small to be seen.
5-PS1-2	Measure and graph quantities to provide evidence that regardless of the type of change that occurs when heating, cooling or mixing substances, the total weight of matter is conserved.
5-PS1-3	Make observations and measurements to identify materials based on their properties
MS-PS1-1	Develop models to describe the atomic composition of simple molecules and extended structures
MS-PS1-2	Analyze and interpret data on the properties of substances before and after the substances interact to determine if a chemical reaction has occurred.
HS-PS1-1	Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms.
HS-PS1-2	Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties.
HS-PS1-4	Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy.

NGSS Lead States (2013)

Lavoisier's Law of Conservation of Mass can be stated as mass is neither created nor destroyed in a chemical reaction. Another way to state this law: If a system has a specified mass, then any changes whether physically or chemically will not change the mass of a closed system (no mass crosses the boundaries in or out of the system). When an ionic solid is dissolved in water, the mass of the original solid plus water remains constant (Chang & Goldsby, 2014).

Ion formation used in this new unit is taught in terms of ionization energy and electron affinity explained earlier in this chapter. For the modern periodic table, the elements order is based on increasing number of protons. From Dalton's Law, all atoms of the same element are identical meaning that these atoms have the same mass, size, and chemical properties. While the mass and size may be differ slightly due to isotopes of the element (same number of protons and electrons but different number of neutrons), chemical properties of elements remain the same. These chemical properties follow trends for the periodic table including ionization energy and electron affinity.

PS1.B Chemical Reactions.

This DCI (Table 6) can have two subcategories for this learning progression: conservation of mass and identifying the chemical reaction. Lavoisier's Law of Conservation of Mass states that matter is neither nor destroyed in a chemical reaction (Tro, 2010). Thus, students have to understand how to balance these chemical equations but also how to balance ionic formula units. Proust's Law of Definite Proportions states that different samples of a compound will have the same ratio of elements. This Law holds true for ionic formula units as the overall charge has to be zero for the solid phase. One of the physical properties of an ionic solid is the lack of electrical conductivity. Ionic compounds will conduct electricity when dissolved in water or in the liquid phase when the ions are mobile (Chang & Goldsby, 2014).

Table 6: DCI – PS1.B Chemical Reactions

Number	DCI
2-PS1-4	Heating or cooling a substance may cause changes that can be observed. Sometimes these changes are reversible, and sometimes they are not.
5-PS1-2	No matter what reaction or change in properties occurs, the total weight of the substances does not change. (Boundary: Mass and weight are not distinguished at grade level.)
5-PS1-4	When two or more substances are mixed, new substances with different properties may be formed.
MS-PS1-2	Substances react chemically in characteristic ways. In a chemical process, the atoms that make up the original substances are regrouped into different molecules, and these new substances have different properties from those of the reactants.
MS-PS1-5	Substances react chemically in characteristic ways. In a chemical process, the atoms that make up the original substances are regrouped into different molecules, and these new substances have different properties from those of the reactants. The total number of each type of atom is conserved, and thus the mass does not change.
MS-PS1-6	Some chemical reactions release energy, others store energy.
HS-PS1-2	The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions.
HS-PS1-4	Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy.
HS-PS1-7	The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions.

NGSS Lead States (2013)

Ionic compounds are involved in a variety of chemical reactions represented by a chemical equation. Chemical reactions occur when bonds are broken and/or formed. For a chemical reaction, a chemical change has to occur producing new substances from original substances. Chemical equations are used to explain chemical reactions using symbols. Ionic compounds dissolve in water forming electrolyte solutions. Dissociation equations represent the ionic compound dissolving process, but this equation can have some ambiguity about what type of change is occurring. For an ionic compound, a bond is broken with ions being produced which could be considered a chemical change. On the other hand, the solid ionic compound can be recovered from the solution by evaporating the water, and the evaporation process would be considered a physical change. This ambiguity with dissociation equations has caused misconceptions with students especially with identifying the difference between melting and dissolving (Ebenezer and Gaskell, 1995; Naah and Sanger 2013). PE 2-PS1-4 begins the point of addressing this physical change. The following is an example of a dissociation equation:

$$\mathrm{NaCl(s)} \xrightarrow{\mathrm{H_2O}} \mathrm{Na^+(aq)} + \mathrm{Cl^-(aq)}$$

These compounds also participate in precipitation (double replacement) reactions:

$$\mathrm{Pb(NO_3)_2(aq)} + \mathrm{2KI(aq)} \rightarrow \mathrm{PbI_2(s)} + \mathrm{2KNO_3(aq)}$$

and reduction-oxidation reactions such as the metal displacement (Chang & Goldsby, 2014):

$$\mathrm{Zn(s)} + \mathrm{CuSO_4(aq)} \rightarrow \mathrm{ZnSO_4(aq)} + \mathrm{Cu(s)}$$

PS2.B Types of Interactions.

Ionic bonds are formed from the electrostatic attractions of ions (positive and negative ions). This DCI is concerned with the development of the electrostatic forces between ions and Table 7 explains this DCI for the associated PE. Cations are formed when electrons are removed. Ionization energy is related to this formation. Electron Affinity is the negative energy change for the addition of an electron to an element in its gaseous state forming an anion. Coulomb’s law states “the potential energy (E) between two ions is directly proportional to the product of their charges and inversely proportional to the distance of separation between them” (Chang & Goldsby, 2014, p. 291) where k is a proportionality constant.

$$\mathrm{E} = \mathrm{k} * \frac{\mathrm{Q_{cation}} * \mathrm{Q_{anion}}}{\mathrm{r}}$$

As the distance increases, the potential energy decreases. As the ionic charge (either positive or negative) increases the potential energy increases. This DCI's progression starts with students understanding the notion of charge including the attraction/repulsion, three types of charge exist (positive, negative and neutral), and distance between charges. Ion formation for the main group elements can be developed using the notion of charge and knowledge of atomic structure. The definition for an ionic bond can then be explained as the bond formed due to the electrostatic attractions between oppositely charged ions. Finally, the ionic solids can be discussed as the arrangements of ions due to the attraction and repulsion of ions in highly symmetric form.

Table 7: DCI – PS2.B Types of Interactions

Number	DCI
3-PS2-3	Electric and magnetic forces between a pair of objects do not require that the objects be in contact. The sizes of the forces in each situation depend on the properties of the objects and their distances apart and, for forces between two magnets, on their orientation relative to each other.
MS-PS2-3	Electric and magnetic (electromagnetic) forces can be attractive or repulsive, and their sizes depend on the magnitudes of the charges, currents, or magnetic strengths involved an on the distance between the interacting objects.
MS-PS2-5	Forces that act at a distance (electric, magnetic, and gravitational) can be explained by fields that extend through space and can be mapped by their effect on a test object (a charged object, or a ball, respectively).
HS-PS1-1	Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.
HS-PS1-3	Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.
HS-PS2-4	Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects. Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. Magnets or electric currents cause magnetic field; electric charges or changing magnetic fields cause electric fields.

NGSS Lead States (2013)

Overall Learning Progression

While there are three different DCI involved with developing ionic bonding and compounds these can be placed in a systematic order linking concepts from each DCI. This overall NGSS learning progression (Figure 6) has incorporated the different aspects of ionic bonding. The curriculum unit that has been designed for this dissertation uses the High School portion of the learning progression with some attributes of the Middle School PE. High School was chosen because periodic trends are not part of Middle School. Ion formation will be explained in terms of these periodic trends and not by the misconception of electrons are transferred from one atom to another atom forming an ion molecule (Ben-Zvi, Eylon, & Siberstien, 1986, 1987; Boo & Watson, 2001; Coll & Treagust, 2002, 2003; Harrison & Treagust 2000; Othman, Treagust, & Chandrasegaran, 2008; Taber, 1994, 1997, 1998, 2002a; Taber, Tsaparlis, & Nakiboglu, 2012).

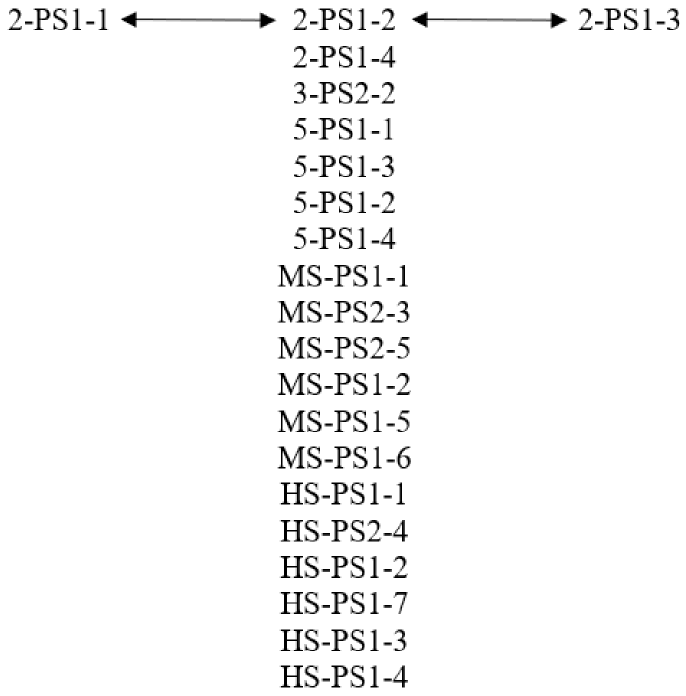


Figure 6. Overall Learning Progression for Ionic Bonding (NGSS Lead States, 2013)

For the overall order, the learning progression follows the increasing numerical with a couple of exceptions. PE 2-PS1-1, 2-PS1-2, and 2-PS1-3 can be interlinked with one another while investigating the physical properties of ionic compounds. PE 5-PS1-3 was moved up in the order because properties and measurement techniques from this PE can potentially be used for 5-PS1-4 and 5-PS1-2. PE MS-PS2-3 and MS-PS2-5 will occur after MS-PS1-1 because part of the atomic structure deals with the attraction and repulsion of charges and an introduction to the differences in charge fits in this location of the learning progression. Then PE MS-PS1-2, MS-PS1-5, and MS-PS1-6 are concerned with the conservation of matter and chemical reactions. PE HS-PS1-1 has to be addressed first because this PE explains trends in ionization energy (cation formation) and electron affinity (anion formation). PE HS-PS2-4 discussing Coulomb's law and the potential energy due to ionic bond formation. Then reactions involving ionic compounds can be addressed along with the Law of Conservation of Mass (PE HS-PS1-2 and HS-PS1-7). PE HS-PS1-3 will address insoluble ionic compounds and the strength of the ionic bond is strong in these substances.

Ionic Bonding Unit

While NGSS provides guidance for designing this unit, Taber's electrostatic framework (1997) was also used to help determine content for the lessons. The lessons integrate spatial opportunities for students to visualize data and models. The unit starts with the overall driving question for the phenomenon: "Why does solid salt (sodium chloride) from a grocery store shows such a low conductivity compared to salt dissolved in water and Gatorade?" This question started the students considering solutions around them and what it takes for solution to be considered conductive. Ionic Bonding was the overall topic for the unit with ion formation, crystal lattice with emphasis on unit cell and ratio of ions, Coulomb's Law, electronegativity to predict bond type (nonpolar, polar and ionic) and dissociation of ions.

With this unit, students must have the following background information: general periodic table information such as element's name plus symbol and if an element is a metal or nonmetal, structure of an atom, electron configuration for main group elements, covalent bonds, and drawing of Lewis structures (expanded octet and not obeying the octet rule such as $AlCl_3$ are not necessary). This unit does not depend upon whether Bohr theory or quantum was used to teach electron configuration. The unit was designed for high school Chemistry course containing the majority of eleventh grade students with some twelfth-grade students. NGSS was the reason for choosing this education level because periodic trends, explaining bulk scale properties, balancing chemical equations, and Coulomb's Law are High School PE not Middle School PE. Evaluation of this unit used the Purdue Spatial Visualization test and a content assessment. The content assessment was piloted with a group of students prior to unit implementation because the content assessment utilized portions of three other assessments (Jang, 2003; McBroom, 2011, Tan & Treagust, 1999).

Lesson Descriptions.

The unit started with the opening driving question and using conductivity probes to test a variety of substances (solid salt, distilled water, solid sugar and Gatorade) engaging students with trying to understand why certain substances such as Gatorade conduct electricity. Students observe the dissolving process on a macroscopic level which is part of Johnstone's triangle (1991). By starting at the macroscopic representation, students experience a concrete experience that they can connect to their lives (Gatorade, salt water, and sugar water). Students are asked to draw particulate diagrams of their ideas about what is occurring in solution for dissolving salt in water and sugar in water. The particulate diagrams require students to visualize the dissolving process. When students drew their ideas of the dissolving process, they are using symbols to represent the ions for sodium chloride in solution. Students are utilizing both the symbolics representation and sub-micro representation with the particulate diagrams. This lesson integrates spatial activities with both the conductivity probe and drawing the particulate diagrams.

In the second lesson, students investigated ion formation in terms Bohr Theory by modeling the electron shells using a posterboard, and small pieces of cardstock representing the subatomic particles (sub-micro). The posterboard has the nucleus in the center with three circles around the nucleus representing the three electron shells closest to the nucleus. Students modeled the formation of ions by adding or removing the appropriate number of electrons. They were supposed to extend the charge (number and sign) for the rest of the main group column (symbolics). The second lesson also had students producing two periodic trends graphs for each of the following: atomic radius, ionic radius, first ionization energy, and electron affinity. Periodic trends required students to utilize sub-micro representation of Johnstone's triangle for differences between elements/ions. One of the graphs was for Group IA so that students are able to analyze the trend for a column. The second graph has students analyzing the trend across the second period (row) of elements. Students then use the large increase in ionization energies to determine cation charges (number) and observe that for main group elements especially Group IA and IIA is a trend. Students then read about transition metals which may have more than one charge and naming these transition metals with Roman numerals. Lesson 2 involved the symbolics representation of Johnstone's triangle in a variety of ways including: locating and using information from the periodic table to model the atom and ion using Bohr theory calculating the number of protons, electrons and neutrons for each example; plotting the periodic trends for atomic radius, ionic radius, electron affinity and ionization energy; predict cation formation for ionization energy; predict anion formation; and name some of the transition elements using the charges and Roman numerals. Students are also using the sub-micro representation with the Bohr Theory. Given ionic and atomic radius, the students should visualize the size of the ions and atoms with the trends.

The third lesson had students exploring crystal structure incorporating spatial-based activities by having students analyze unit cells to determine the formula unit. Using marshmallows, students made the basic unit cell, a body-centered cell and face-centered cell. For the basic unit cell, the structure was a three marshmallow in height by a three marshmallow in width by a three marshmallow length cell. The expectation was for students to determine the fraction of the center marshmallow for each of the eight unit cells that was part of the structure. Also this example shows the symmetry of crystals and the repeating of structures. With the body-centered unit cell, students made only one cell keeping in mind that only one-eighth of each corner is assigned to that unit cell, but the particle in the middle is only assigned to that particular unit cell. For the face-centered unit cells, students build two adjacent unit cells but focus on the face that the two cells share to determine that only one-half of the particle (marshmallow) is associated with a unit cell (Figure 7). Then students watch a video (https://www.youtube.com/watch?v=KNgRBqj9FS8&t=107s; Van Wyk, R. 2012). This video again shows the different unit cells and the fraction of each particle for the unit cells by splicing the particles. The video also discusses the coordination number for corner, body-centered, and face-centered particles. The video relates the different representation of Johnstone's triangle by starting from the overall structure (macro) then zooming into the particles of the unit cell (sub-micro). Students then analyze pictures of different ionic compounds unit cells to determine the ratio of cations to anions in the lowest whole number ratio for the compound's formula unit. Then students determine the formula unit from names and are introduced to polyatomic ions. Students are utilizing the sub-micro representation with the different unit cells both making and analyzing. The symbolics representation of Johnstone's triangle is from the students with writing the formula units from their analysis and then extending their knowledge to write formulas by balancing charges.

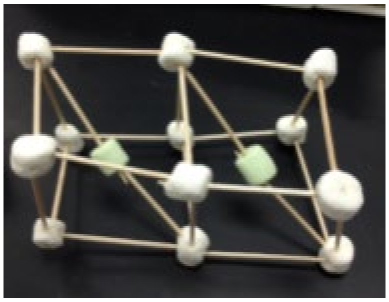


Figure 7. Student example of a body-centered unit cells

Since not all substances in the first lesson conducted electricity, students in the fourth lesson used electronegativity difference to classify the type of bond to be either nonpolar covalent, polar covalent or ionic bond for two elements. Students then draw the

Lewis Electron Dot Diagrams for methane and water to begin to distinguish between polar and nonpolar covalent compounds that have polar covalent bonds. With exploring the bonds and Lewis Electron Dot Diagram, students are utilizing the symbolics and sub-micro representation of Johnstone's triangle. Students also predict which part of water would attract the sodium ion and the chloride which falls into the sub-micro representation. With this lesson students, also learn about Coulomb's Law in terms of both charge and distance between particles.

Finally for the fifth lesson, students model the dissolving of sodium chloride using the water kit and sodium chloride lattice models from 3D Molecular Designs (http://www.3dmoleculardesigns.com/3DMD.htm). These kits have magnets with the opposite poles of the magnets allowing for positive sodium ions to be attracted to the negative oxygen of a water molecule and the negative chloride ion to be attracted to the positive hydrogen of a water molecule. Students then watch a video from Vischem (CADRE Design Pty Ltd & Tasker, R., 2010) is shown explaining the dissolving of sodium chloride as a dynamic process at the particulate level. This video can be found using the following steps:

1. Access the website: http://vischem.com.au/
2. Click on the Online Resources menu at the top of the screen.
3. Scroll down til the Scootle site link is viewed. This link is above the "Types of Vischem Resources" title.
4. Another window will open with a variety of videos. Note these videos are not in numeric order.

5. Scroll down to the video title - M008653 VisChem topic 2: dissolution of an ionic salt
6. Click the title and another window will open. Click on the video which is about middle of the webpage and starts off as a blue screen with fish.

The video also explains different physical properties of ionic compounds including a high melting point. Dissolving was shown with sodium chloride and water before and then after mixing demonstrating the macro aspect of Johnstone's triangle. Dissociation equations are also explained using this video. Students then revisit and drew the particulate diagram for sodium chloride and write the corresponding dissociation equation falling into the symbolics representation. Students draw and write dissociation equations for a variety of ionic compounds including compounds that were a 1:1 ratio for the formula unit (lithium fluoride), not a 1: 1 ratio for the formula unit (calcium chloride), and compounds containing polyatomic ions (potassium sulfate) with one having a transition element [copper (II) nitrate] allowing for students to explore the symbolics representation. The sub-micro representation of the triangle is part of this lesson with both the video showing the dissolving process and the hands-on modeling with the water molecule kit. The macroscopic vertex of the triangle was represented when the video demonstrates the physical dissolving process of sodium chloride and the melting of sodium chloride. This lesson cumulates answering the overall unit driving question explaining the reason for conduction of electricity of some substances. Spatial skills were integrated in this lesson using the water kit, viewing the video, and drawing the particulate diagrams.

Electrostatic Framework Aspects of the Lessons.

This unit used Taber's electrostatic framework as the basis. Different aspects of the framework are addressed in different lessons. The Roles of Molecules discussed that ionic structures do not have discrete ion-pairs. In the third lesson, the students explored the ionic unit cell by modeling different unit cells and watching the video about unit cells. For Lesson 5, students used models of sodium chloride lattice. One of the activities was for the students to separate the sodium and chloride ions then mix these ions reassembling the solid. Students had to answer the question: When the lattice was assembled the second time, was every sodium ion connected with the exact same chloride ions from when you first assembled the lattice?

The Focus status of the framework was concerned with oppositely charged ions providing the force to hold the lattice together instead of the formation of ions holding the lattice together. The History conjecture examined the electrostatic forces in terms of charge magnitude plus separations and not in terms of exchange of electrons between specific ions. Both of these categories of the electrostatic framework were addressed by parts of Lessons 3 and 4. Lesson 3 concentrated on the unit cell being composed of a ratio of cations to anions. Several different unit cells for ionic compounds were investigated such that the students had to understand that the ratio involved more than one ion with at least one type of ion (anion and/or cation) being part of the unit cell as a corner, face, and/or edge. The fourth lesson discussed Coulomb's Law relating the charges of cations and anions with the distance between the ions:

$$\mathrm{E} \propto \frac{\mathrm{Q_{cation}} * \mathrm{Q_{anion}}}{\mathrm{r}}$$

The Valency conjecture was not explicitly addressed with the unit as this status focuses on coordination number, but the unit does mention unit cell coordination number with a video in lesson 3. Students also examined unit cells showing that the number of bonds depend on the cation to anion ratio, which depends on the ions contained within the unit cell. Students had to examine and determine the ratio using the fraction of the ion for the unit cells if the ion was on the corners, faces or edges. Students did not use the electron configuration to determine the ratio of cations to anions. Students also learned in Lesson 2 that ionization energy helped predict cation ion formation while electron affinity was associated with anion formation.

The 'Just Forces' conjecture discussed that the ionic bond resulted from electrostatic forces between a ion and the surrounding oppositely-charged ions. This conjecture was addressed using the sodium chloride models and mixing in Lesson 5 that was discussed with the Role of Molecules aspect of the electrostatic framework.

Summary

Students have trouble distinguishing between the three types of bonds: ionic, covalent, and metallic (Coll & Taylor, 2001). Covalent bond theory and ion formation can be confused by students (Coll & Taylor, 2001; Coll & Treagust, 2002, 2003; Luxford & Bretz, 2013; Robinson, 1998; Taber, 1994, 1997, 1998, 2002a). Ionic bonding is also perceived weak, which is not true (Coll & Taylor, 2001). Students stated that force can just break ionic bonds because some can be crumbled/shattered, but ionic compounds have high melting points (magnesium oxide: 2800°C; sodium chloride 800°C). The octet rule has been the focus by students instead of ionization energy (Coll & Taylor, 2001; Coll & Treagust, 2003; Robinson, 1998; Taber, 1994, 1997, 1998, 2002a; Tan &

Treagust, 2009; Waldrip & Prain, 2012). Ionic compounds exist as crystals with the formula unit representing the lowest whole number ratio of cations to anions in a unit cell. Crystals are usually taught after the formula unit in Chemistry textbooks (Table 3). The dissolving process has been mistaken for melting (Adadan & Savasci, 2012; Ebenezer, 2001; Ebenezer & Erickson, 1996; Othman, Treagust & Chandrasegaran, 2008; Smith & Nakhleh, 2011). In both cases, a solid is becoming a liquid, but at the particle level different processes are taking place. Naah and Sanger (2012) discussed that dissolving and dissociation equations could be classified as chemical and/or physical changes as the ionic solid separates to form a new substance, but the solid can be reformed by evaporation. Dissolving covalent compounds is only a physical change as the molecules of covalent compounds remain as discrete entities. This difference between ionic compounds and covalent compounds challenge students (Ebenezer & Gaskell, 1995). Dissolving can be represented by dissociation equations and particulate diagrams. Naah and Sanger (2012) documented students' errors with dissociation equations such as water reacting.

Chemistry requires a student to visualize at the particle level and is referred to as sub-micro in Johnstone's (1991) triangle. Diagrams can be used to communicate the particle level and any changes to particles (ions, molecules, and atoms). Students have trouble drawing these diagrams (Ebenezer, 2001, Kelly & Jones, 2007, 2008; McBroom, 2011; Naah & Sanger, 2012). Dissociation equations can be used to represent the particle level requiring students to translate their visualizations into the symbolics level of Johnstone's (1991) triangle. Dissociation equations are similar to chemical reaction equations as they have to follow Proust's Law of Definite Proportions and Lavosier's

Law of Conservation of Mass. Students can use an algorithm to balance these equations (Hinton & Nakhleh, 1999; Nakhleh & Mitchell, 1993). They may not be able to visualize the actual representation of bonds breaking and forming (Ben-Zvi, et al., 1986,1987; Hess & Anderson, 1992; Kern, Wood, Roehrig & Nyachwaya, 2010; Treagust, et al. 2003; Yarroch, 1985).

This dissertation's research explored a new unit to teach the concepts of the ionic bond and dissolving of ionic compounds. Taber's electrostatic framework served as the framework for developing this unit. The electrostatic framework focuses more on the electrostatic attraction between ions within ionic solids. The molecular framework (business-as-usual) has the focus on an ion pair causing students to perceive two ions being linked together (Ben-Zvi, Eylon, & Siberstien, 1986, 1987; Boo & Watson, 2001; Coll & Treagust, 2002, 2003; Harrison & Treagust 2000; Othman, Treagust, & Chandrasegaran, 2008; Taber, 1994, 1997, 1998, 2002a; Taber, Tsaparlis, & Nakiboglu, 2012). In addition, the lessons were developed while keeping the different representations of Johnstone's triangle in mind and connecting these representations.

The curriculum unit was designed using literature to identify misconceptions and NGSS as the standards. Appendix A contains the basic 5-E lesson plans for this unit. Appendix B has the required worksheets used with this unit. The next chapter, *Methodology,* outlines the research plan, research setting and methods used for this study.

CHAPTER 3. METHODOLGY

Purpose of Study

The purpose of this research was to determine if a unit based on Taber's (1997) electrostatic framework by introducing ion formation using ionization energies and electron affinities, and balancing the ionic formula unit using crystals improves students' understanding of ionic compounds and dissociation of ionic compounds in aqueous solutions compared to students with a more molecular (business-as-usual) teaching method using Lewis Electron Dot Diagrams and conductivity. Additionally, how students' spatial skills changed for the new unit (electrostatic) compared to students using the business-as-usual teaching methods was investigated.

Research Questions

Research Question 1: How does the understanding of the ionic bond and dissolving of ionic compounds in water compare for students using a unit focused on an electrostatic framework to students utilizing a molecular framework (business-as-usual) related to their spatial ability and using the spatial ability as a covariant with treatment group?

Research Question 2: How do spatial visualization skills compare for students using an electrostatic framework and students focused on a molecular framework?

Research Null Hypothesis

Research Question 1 Null Hypothesis: There are no statistically significant differences for the gains in content using spatial skills as a mediating variable between students taught with the new electrostatic curriculum unit and students taught in the business-as-usual way.

Research Question Null Hypothesis: There are no statistically significant differences for the gains in spatial skills between students taught with the new electrostatic curriculum unit and students taught in the business-as-usual way.

Research Design

The overall design for this research utilized a concurrent parallel design (Criswell, & Plano Clark, 2007). Both the quantitative and qualitative data were gathered at the same time. This data was examined separately and together to explain differences between the experimental (new unit) and business-as-usual students. Table 8 explains the way each research question was addressed in terms of data collection and instrumentation, and data analysis. Appendix E contains the interview transcript used. This study had a quasi-experimental design with nonequivalent groups using a pretest-posttest design (Figure 8).

Students discuss ions in Integrated Science courses in the ninth or tenth grades depending upon the school or in their regular Biology course. Ions may be mentioned in Middle School Science courses as a type of particle (NGSS MS-PS-1: Develop models to describe the atomic composition of simple molecules and extended structures), but formation of ions and balancing of formula units are usually left to high school Chemistry courses. Periodic trends are covered in Chemistry courses. Dissociation equations may or may not be covered, but the dissolving process is mentioned in Chemistry courses.

For this study, experimental students covered the ionic bond and ionic compounds dissolving using a unit that uses crystals to teach the development of an ionic compound's formula unit. The experimental students are compared to students being taught to balance the formula unit using the more common criss-cross method. The criss-cross method takes the absolute value of charges for each ion and then using this or the lowest whole number multiple as the subscript for the other ion (Figure 9).

Table 8: Research Questions, Data Collection, Instrumentation and Analysis

Research Questions	Data Collection and Instrumentation	Data Analysis
How does the understanding of the ionic bond and dissolving of ionic compounds in water compare for students using a unit focused on an electrostatic framework to students utilizing a molecular framework (business-as-usual) related to their spatial ability and using the spatial ability as a covariant with treatment group?	• Pre- and post-test results for Chemical Bonding and Dissociation Diagnostic Assessment • Videotaped and Transcribed Interviews • Teaching Log • Researcher Log	• Multiple Linear Regression • Examination of Codes from Interview Videos, Teaching Logs, Observations, and Discussions
How do spatial visualization skills compare for students using an electrostatic framework and students focused on a molecular framework?	• Pre- and post-test results for Purdue Spatial Visualization-Rotation Test • Pre- and post-test results for Chemical Bonding and Dissociation Diagnostic Assessment (Part III) • Videotaped and Transcribed Interviews • Teaching Log • Researcher Log	• Multiple Linear Regression • Examination of Codes from Interview Videos, Teaching Logs, Observations, and Discussions

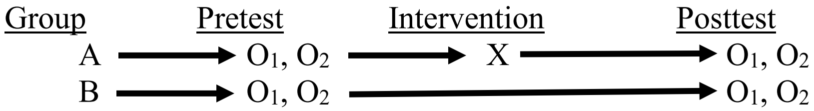


Figure 8. Experimental Design

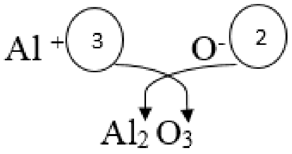


Figure 9. Example of the Criss-Cross Method

Research Setting.

This research study was performed in two suburban high schools located in the south central United States: Elm and Ash (all references to schools, teachers, and students are pseudonyms). Both schools were part of the same district. The demographics for the schools are from the previous year as the report card for 2017-2018 was not available at the time of defense. Elm's, the experimental school, report card recorded a membership of 1,868 students with 44.7% free and 4.0% reduced lunch. Ash's, the business-as-usual school, report card had a student body of 1,134 with 48.0% free and 4.4% reduced lunch. Two schools were chosen in an attempt to ensure that students did not discuss the study with each other.

A Chi-Square test was employed to compare the two schools based on gender. Assumptions for this test were checked. Random sampling was not done for this test as the two schools were assigned new unit (Elm =1) or to continue to teach as previous years (Ash = 0). Students could choose whether or not to participate in the study. Independence between observations was done as each student had only one entry on gender (male =0; female =1). The state report card did not specify binary or non-binary options for students. The expected frequency assumption was satisfied as 0 cells had an expected count less than 5. No association was found between gender and school ($\chi^2(1) = 0.742$, $p = 0.389$).

This study involved three experimental teachers (Harleyquin, BSB and Cleo) at Elm. Harleyquin had Bachelor Degrees in Chemistry and Biology. She also had Master Degrees in Chemistry and Education. Harleyquin had taught for 11 years. Her classroom layout comprised of a student table area and a lab area. The student table area was at the front of the room with three columns of tables able to sit two students per table. One column consisted of five tables, while the other two columns contained six tables each. The students sit with their backs to the lab area facing the whiteboard. Harleyquin's desk was on one side of the student area with a long lab bench next to the desk. The lab area had three long lab benches requiring students to stand. These benches had two identical sides with a divider separating the two sides. Several groups of students could use one side of the lab bench area.

BSB had a Bachelor Degree in Chemistry and a Masters Degree in Education. She had taught for six years. Her classroom had a main student area with counters and cabinets around three sides of the classroom. Each of the three sides has a sink. While this classroom setup did not have lab benches, there was some work area for the students besides their tables. The front of the classroom did not have counters and cabinets. The front had a whiteboard, an instructor's lab bench, and BSB's desk away from the lab bench. The tables for this classroom sit two students, and BSB had her tables set up such that two tables faced each other. A total of eight table groupings were in this classroom. These groupings were positioned at an angle around the room.

Cleo had a Bachelor Degree in Pharmaco-biological-chemistry and a Masters Degree in Chemistry. She had taught for 24 years and is a National Board Certified Teacher. Cleo's classroom setup was similar to Harleyquin's with a student table area and a lab area. Her tables also accommodated two students a piece. Cleo chose to arrange her tables such that two columns had two tables facing each other forming a group of four. Each of these columns had three sets of these table groups. The third column consisted of one two table grouping (four students) and two tables by themselves (each table could have 2 students). The students sat perpendicular to the whiteboard at the front of the classroom and parallel to the lab area. To one side of the classroom was an instructor's lab bench with Cleo's desk situated next to this lab bench at the end. Cleo's lab area was setup the same as Harleyquin's lab benches with three lab benches being able to handle several groups of students. A divider was in the middle of the lab bench separating the two sides.

Elm's teachers were given four hours of professional development before the unit began. Even though these teachers have been exposed to ion formation, balancing formula units and dissociation of ionic compounds in aqueous solutions, this unit presents the material in a new way with the focus on utilizing ionization energies, electron affinities and ionic crystals. The teachers were provided with copies of the lessons plus the associated worksheets, the sodium chloride lattice model and the water model kit after the professional development to familiarize themselves with the material. The researcher attended their classes in an attempt to mitigate this limitation and was answered questions to clarify the lessons. The researcher became a participant observer with the experimental students.

For Elm, seven classes participated in the study (*N* = 172). Students who did provide both consent and assent but did not take one of the Pre- or Post-Tests for the PSVT-Rot or the CBDDA were removed from this research (*N* =20). The final number of students involved in the quantitative analysis was (*N* =72). Both BSB and Harleyquin had three classes each participating in the study with Cleo only having one class. As Elm's teachers were implementing the lessons, this study's author was in their classrooms answering questions and assisting where needed as some classes had over 30 students.

This study had two control teachers at Ash. Rocky had Bachelor Degrees in Chemistry and Physical Science-Teaching with graduate hours in both Chemistry and Education. Rocky had been teaching 5.5 years. Rocky's classroom consisted of a student table area and a lab area. Each table could sit two students. Rocky had the tables arranged in groupings of two tables sitting four students maximum. The table groupings were arranged in three columns with each column consisting of three groupings. The groupings were perpendicular to the white board at the front of the classroom and parallel to the lab bench area. An instructor lab bench with her desk was to one side of the table area. The lab bench area consisted of three long lab benches requiring students to stand. A divider in the middle separated the two sides of the lab benches. Several groups of students could use one side of the lab bench area.

Trek had a Bachelor Degree in Chemistry, a Masters Degree in Soil Science and a Master Degree in Education. He had been teaching for 11 years. His classroom layout was similar to Rocky's consisting of a table area and lab bench area. He also had his tables arranged in two table groupings for four students. These groupings were placed into three columns for three groupings. These groupings were perpendicular to the white board at the front of the room and parallel to the lab bench area. Trek had an instructor's lab bench and his desk to one side of the room. The room had three lab benches with a divider in the middle and were able to handle several groups of students.

At Ash, the teachers (Trek and Rocky) were instructed to teach the concepts of ionic formula unit and dissolving as they had planned for the year which included labs about dissolving and explaining the concepts on the board. Four classes with each teacher having two classes participated in the study with a total number of 113 students. Ten students who provided consent and assent did not take all of the pre and post assessments were not included in the quantitative analysis. The final number of students included for the quantitative portion was 20. The control teachers administered the assessment before they started different types of bonding. They decided when to deliver the post-test since dissolving was not explained at the same time as balancing the formula unit of ionic compounds. After the study was completed, the control teachers were introduced to the unit being studied. By providing teachers with this information, they understood the research better and potentially incorporated all or parts of the new unit into their teaching.

Quantitative Analysis

Quantitative data was collected used two instruments. The Purdue Spatial Visualization-Rotation Test (PSVT-Rot; Bodner & Guay, 1997) tested students' spatial abilities. The Chemical Bonding and Dissociation Diagnostic Assessment (CBDDA) covered the difference among covalent and ionic bonding, balancing of ionic formula unit, and dissociation equations.

Dependent variables.

The students' post-test score for both the CBDDA and the PSVT-Rot (Bodner & Guay, 1997) were the dependent variables. The scores from these instruments were continuous variables. The CBDDA was piloted, because this assessment was developed from other instruments (Jang, 2003; McBroom, 2011; Tan & Treagust, 1999).

Independent variables.

The number of independent variables was based on the Research Question. Research Question 1 involved three independent variables and one covariant variable. The pre-test score on the CBDDA and spatial gains (post-test score minus pre-test score) were continuous variables. The teaching method for the ionic formula unit (0= Ash, 1 = Elm) was used as an independent variable classified as a categorical variable. The covariant variable was the treatment * spatial. For Research Question 2, two independent variables were used to predict the post-test score on the PSVT-Rot. The pre-test score on the spatial test was used as a continuous variable. Again, the teaching method for the ionic formula unit was a categorical variable.

Instrumentation.

From the literature, students with higher spatial skills perform better on chemistry tests including problems that do not require spatial skills (Bodner & McMillian, 1986). With this dissertation study, students had to visualize and utilize drawings to develop the formula unit from crystal unit cells. The PSVT-Rot (Bodner & Guay, 1997) was used as a pre- and post-test to check the impact of introducing this unit has on improving students' spatial skills.

For this research, a published instrument was not located covering the concepts of this curriculum unit. Taber (2002b) had a Truth about Ionic Bonding Diagnostic Instrument, but this instrument only had True-False questions. Students would have a fifty-fifty chance at picking the correct answer. Luxford (2013) developed the Bonding Representations Inventory using student interviews and Treagust's (1988) process for creating diagnostic instruments. Luxford's assessment includes covalent and metallic bonding. The ionic portion of the instrument was mainly for an ionic formula unit with a 1 cation to 1 anion ratio. Some of the figures used the sodium chloride ionic model from 3D Molecular Designs (n.d.) which was part of this research's curriculum unit causing an unfair advantage for Elm's group compared to the Ash's group.

Four different instruments were used as the basis for this research's assessment. The first instrument was the Chemical Bonding Diagnostic which included both covalent, metallic and ionic bonding. While these concepts all cover chemical bonding, only certain questions can be used with this unit for the questions that cover the macromolecule concept (Tan & Treagust, 1999). The first instrument was based on student interviews and Treagust's (1988) steps for developing a diagnostic instrument. From Jang's dissertation (2003), the second instrument was also called the Chemical Bonding Diagnostic and was based off of Tan and Treagust's instrument. Jang used one question from Peterson's (1986) instrument developed for his master's thesis. Jang conducted interviews of Korean high school students for developing his instrument. Even this instrument was not suitable for this research. Table 9 explains the reasons for not including some of the questions from this instrument.

Table 9: Questions not used from the Chemical Bonding Diagnostic Test

Question Number	Reason
1	Question describes the most important particle for chemical bonding with the reason being the electron's transfer creating a possible misconception due to covalent bonding and metallic bonding (sea of electrons).
5	Question deals with the type of bonds for diamonds and macromolecules. This information is not part of this research.
10	Question covers molecular shapes and is not part of this research's unit.
11	Question concerns the octet rule which is not part of the electrostatic framework.
14	Question covers coordination bonding and is not part of this research's unit.
15	Question covers metallic bonding and is not part of this research's unit.

Jang (2003)

McBroom's dissertation dealt with preservice teachers and their understanding of dissociation and precipitation reactions using videos. An instrument (no name) was developed to assess understanding of these reactions. Students were interviewed after the initial development of this inventory to check the questions purpose. Each question had 3 parts: identifying the process occurring in the video such as when solid potassium iodide is added to water, writing the dissociation/precipitation equation, and drawing a particulate representation of the process. McBroom identified thematic categories for the second and third part of this assessment (Tables 10 and 11). While the dissociation reactions are pertinent to this research, the precipitation portion is not part of this research and was eliminated. In addition, videos showing the process of dissociation for answering these questions was not used as dissociation was to be represented in a different method for the Elm group using water kit models with a sodium chloride lattice and a video. Ash's teachers exposed their students to dissolving while measuring conductivity to classify compounds as polar or ionic.

Table 10: Thematic Categories of Participants' Equations Representing Dissolution

Change of State
Creation of new compounds through combination of solid and water
Separation of H_2O into components
Separation of solid into incorrect or partially correct components
Separation of solid into correct components with correct charges

(McBroom, 2011)

Table 11: Thematic Categories of Participants' Drawings

Change of State
Creation of new compounds through combination of solid and water
Separation of H_2O into components
Separation of solid into incorrect or partially correct components
Separation of solid into correct components with correct charges
Separation of polyatomic ion into constituent elements
Macroscopic representation

(McBroom, 2011)

The CBDDA measured students understanding of ionic bond, ionic formula unit and dissociation of ionic compounds in aqueous solutions. The multiple choice part of the instrument covering content used a two-tier format. Treagust (2012) indicated that a two-tier test can have between 2-4 answer choices for tier one and 4 answer choices for tier two. The instrument chosen for this research has 2-3 answer options for tier one depending on the question and 4 answer options for tier two. While more answer 2-3 answer choices for tier one may give false positives, the purpose of this study was not to develop an instrument. Tier two require students to pick an option showing their justification for their tier one choice. For this study, the students were required to answer both tiers correctly to count towards their score.

> "When students are required to justify their choice, they have to consider data in all the options and explain why a certain option is better than the others. By including wise options, both as the best answer and distractors, we 'force' the students to consider specific matters and to express their position in writing" (Tamir, 1990, p. 565).

Distractors are used as part of tier two to ensure that students have to understand the material.

This instrument was piloted using a summer General Chemistry II course as these students had been exposed to both ionic and covalent compounds in General Chemistry I. In addition, they also had been introduced to the dissolving process. A copy of the final instrument after piloting study can be found in Appendix D. The instrument consists of three parts. The first part is demographics. The second part of the assessment contains two-tiered multiple choice questions with the second tier requesting the student to make a choice explaining their answer from the first part of the question. From Jang's dissertation, wording was changed from "The state of electron for an ionic bonding is" (p. 207) to "For forming ions, electrons will be." In addition, "The kind of bond" (p. 211) was replace with "The type of bond." The piloted instrument consisted of 11 two-tier questions, and the number was reduced to eight two-tier questions to obtain an acceptable Cronbach's alpha. As questions were removed, the researcher reflected upon whether or not the removal would affect the study. The first two-tier question removed covered Hydrogen Fluoride's (HF) Lewis Electron Dot Diagram. The figures from Jang's dissertation (2003) were copied using the snipping tool on a PC. The difference between these figures was subtle on the placement of a pair of electrons potentially causing confusion for the students. Lewis Electron Dot Diagrams are usually used in association with covalent compounds. Next, the two-tier question dealing with graphite and delocalized electrons was removed. While the General Chemistry students had been exposed to chemical bonding, the topic of delocalized electrons is not part of the curriculum unit and for this university was not covered until the second semester of General Chemistry. This question's topic was not going to be covered in the new curriculum unit. The last two-tier question removed was silicon carbide's melting and boiling point which is not covered until the second semester of General Chemistry at the University and also was not part of the new curriculum unit.

The second part of this instrument had students drawing the dissociation of ionic compounds in water. McBroom's (2011) dissertation was the source for the three questions used with this part of the assessment. In addition, she coded different misconceptions and correct responses for the equations representing dissolution (Table 10) and particulate diagrams (Table 11). Since students are to write a dissociation equation and draw a particulate diagram for the ionic compound dissolved in water, the primary researcher and another experienced Chemistry Lecturer developed rubrics for both the dissociation equations (Figure 10) and the particulate equations (Figure 11). The experienced Chemistry Lecturer has a doctorate in Chemistry and has been teaching General Chemistry for 32 years. These scoring rubrics were based on Arkwright's Generalized Rubric for Assess Students' Written Explanations (2014), which was adapted from Trundle, Atwood and Christopher's (2002) delineation of scoring levels by a biology tenured faculty member, a science education faculty member and Arkwright (2014). Both new rubrics were piloted using students from a summer semester section of a General Chemistry II course at a four-year university during the first week of the course.

Reliability. The CBDDA was developed from Jang's (2003) Chemical Bonding Diagnostic Test. Several of Jang's questions were from Tan and Treagust's (1999) Chemical Bonding Diagnostic Instrument. Jang reported Cronbach's alpha for his whole test as 0.74. Each of the questions used from Jang's test met the criteria of 0.7 or greater. Since the test has been modified with items eliminated that do not pertain to this research project, the new version was piloted to determine a new Cronbach's alpha which was used for measurement reliability (Cronbach, 1951). Cronbach's alpha was used with tests that have a range of answers not just a right or wrong answer. For internal consistency, questions that are similar should be compared to each other, but the decision on the way to split the test would have to be made for this comparison (McMillan, 2016). The researcher's over ten years of teaching Chemistry was also used to determine if any questions removed would affect the assessment's purpose.

Using the pilot data for this study with SPSS version 24, the Cronbach's alpha was .361 for the 11 two-tier questions. To increase the Cronbach's alpha, questions were removed after the content of these questions were analyzed as to whether the content was pertinent to ionic bonding. The questions removed dealt with silicon carbide's melting and boiling point which is not covered until the second semester of General Chemistry at the University. The Cronbach's alpha increased to .501. Next, the question concerning graphite and its ability to conduct electricity. While the students had been exposed to chemical bonding, the topic of delocalized electrons is not part of the curriculum unit and for this university was not covered until the second semester of General Chemistry. The

Cronbach's alpha increased to .588. The third question covered Hydrogen Fluoride's (HF) Lewis Electron Dot Diagram. The figures from Jang's dissertation (2003) were copied using the snipping tool on a PC. The difference between these figures was subtle on the placement of a pair of electrons potentially causing confusion for the students. After the removal of the three two-tier questions, a Cronbach's alpha of .644 was obtained.

For the dissociation equation and particulate diagram rubrics (Part 3 of the CBDDA), interrater reliability was performed with the experienced General Chemistry Lecturer who assisted with the development of the rubrics. After the first scenario about potassium iodide was individually scored, the two raters compared scores. The two raters discussed any inconsistencies and were able to agree on a final score. One of the main issues with scoring was to ensure the correct rubric was used for the correct question. Another issue had to do with the Conservation of Mass aspect of the dissociation rubric as one of the scorers did forget this aspect for some ratings. The 1 cation to 1 anion ratio was considered easy. In the end, the raters agreed that while this was the case for the potassium iodide other ionic compounds not with a different ratio will not be the case for other compounds. The raters then scored the second and third dissolving scenarios. Again, some discussion occurred due to using the wrong rubric. Also, the raters discussed the sphere of hydration and that students have to show the particles of water and not just a circle of water. Finally, the raters had to revisit relating the dissolving equation to the drawing aspect of the particulate diagram rubric. For the dissociation rubric, the only score not assigned was the 4 and this was mainly due to students not writing the phases of matter as part of the equation. All of the possible scores were obtained from the piloting study for the particulate diagrams. Overall, the two raters were able to come to agreement on scores for the piloting study.

4 points awarded - Students' dissociation equation has all of the following criteria:
A. For the product, ions are separated correctly. This point refers to the elements forming the ionic compound are separated correctly.
B. Each ion displays the correct charge for the dissociation equation.
C. The dissociation equation is balanced correctly implying that the student understands the Law of Conservation of Mass.
D. The correct physical state has been indicated for both the reactants and products of the dissociation equation.

3 points awarded - Students' dissociation equation has the following criteria:
A. For the product, ions are separated correctly. This point refers to the elements forming the ionic compound are separated correctly.
With **one** of the following criteria is missing:
B. Each ion displays the correct charge for the dissociation equation.
C. The dissociation equation is balanced correctly implying that the student understands the Law of Conservation of Mass.
D. The correct physical state has been indicated for both the reactants and products of the dissociation equation.

2 points awarded - Students' dissociation equation has the following criteria:
A. For the product, ions are separated correctly. This point refers to the elements forming the ionic compound are separated correctly.
With **two** of the following criteria is missing:
B. Each ion displays the correct charge for the dissociation equation.
C. The dissociation equation is balanced correctly implying that the student understands the Law of Conservation of Mass.
D. The correct physical state has been indicated for both the reactants and products of the dissociation equation.

1 point awarded - Students' dissociation equation definitely has the following criteria:
A. For the product, ions are separated correctly. This point refers to the elements forming the ionic compound are separated correctly.
None of the other criteria from the four point category are associated with the students' dissociation equation.

0 points awarded – None of the criteria listed in the four point category has been met.

0/NA points awarded – Student did not answer the question.

Figure 10. Dissociation Equation Rubric

4 points awarded - Students' particulate diagram has all of the following criteria:
A. Sphere of hydration is indicated around both ions.
B. More than 1 water molecule has to surround each ion
C. The water molecules are oriented correctly for each ion.
D. Correct ratio of cations: anions based upon the students' given dissociation equation.

3 points awarded - Students' particulate diagram has the either:
All of the following three criteria:
A. Sphere of hydration is indicated around both ions.
C. The water molecules are oriented correctly for each ion.
D. Correct ratio of cations: anions based upon the students' given dissociation equation.
OR
A. Sphere of hydration is indicated around both ions.
B. More than 1 water molecule has to surround each ion
AND one of the following is missing
C. The water molecules are oriented correctly for each ion.
D. Correct ratio of cations: anions based upon the students' given dissociation equation.

2 points awarded - Students' particulate diagram has the following criteria:
All of the following three criteria:
A. Sphere of hydration is indicated around both ions.
B. More than 1 water molecule has to surround each ion
OR
B. More than 1 water molecule has to surround each ion
AND one of the following is missing
C. The water molecules are oriented correctly for each ion.
D. Correct ratio of cations: anions based upon the students' given dissociation equation.

1 point awarded - Students' particulate diagram has the following criteria:
A. Sphere of hydration is indicated around both ions.
OR
C. The water molecules are oriented correctly for each ion.
OR
D. Correct ratio of cations: anions based upon the students' given dissociation equation.

0 points awarded – None of the criteria listed in the four point category has been met.

0/NA points awarded – Student did not answer the question.

Figure 11. Particulate Diagram Rubric

In addition, both Elm and Ash teachers took the test such that they understood the questions being asked of their students. As Elm's teachers were answering the questions, the researcher had to continually ask them not to discuss the questions among themselves which is the reason for not using these assessments as part of this study. Professional development was delivered to Elm's teachers participating in this study. To probe, students answers to CBDDA six Elm students and six Ash students were picked to be interviewed about their answers to both the two-tier portion, dissociation equations, and drawings. A combination of the spatial test and CBDDA was used to pick students. Two students were picked from the top 20%, two students from the middle 50%, and the final pair from the lower 20%. Students were not informed on how they scored on their test when they interviewed.

PSVT-Rot was developed to test spatial ability. The twenty question test was used for a variety of college chemistry courses. Bodner and Guay (1997) reports KR_{20} scores for 3 general chemistry sections of 0.80 (n = 42), 0.78 (n = 41) and 0.80 (n = 42). Wilhelm, Jackson, Sullivan and Wilhelm (2013) had a Cronbach's alpha of 0.79. PSVT-Rot has been used to test spatial abilities of both Middle School students and University students encompassing the typical age range for High School Students.

Validity. Since CBDDA has been developed from previous instruments, content validity for the questions can be answered using these previous studies. Jang (2003) outlined his development of the Chemical Bonding Diagnostic Test using the 10 steps from Treagust (1988) as did Tan and Treagust (1999). The Tan and Treagust version modified items from Peterson's test (Peterson, 1986). These questions are based off of literature research and interviews with students (Jang, 2003; Peterson, 1986; Tan & Treagust, 1999). Jang used his assessment with Grade 11 and 12 Korean students (2003). Tan and Treagust used their assessment with Secondary Four (15-16 year old) students (1999). McBroom originally developed her questions using literature as a basis. McBroom performed a pilot study analyzing and probing participants' responses in interviews. The participants were pre-service teachers (2011).

Bodner and Guay (1997) established the construct validity based on concurrent relationships for the PSVT-Rot by correlating the test with the Shephard-Metzler Test ($r = .61$, $p < .001$). This instrument has been used with chemical education research (Carter, LaRussa, & Bodner, 1987) and astronomical education research (Wilhelm, Jackson, Sullivan & Wilhelm, 2009).

Data Analysis Techniques

Quantitative Analysis.

The scores for CBDDA were a combination of the second and third parts of the instrument. The first part of the instrument was demographics collected, but not used as part of this research. For the second part of the instrument, a correct answer was scored when both tiers are answered correctly. The second part of the instrument was scored according to the rubric in Tables 10 and 11. For Research Question 1, the data from the instruments was analyzed using multiple regression with the spatial gains mediating the treatment.

CBDDA DV = $\beta_0 + \beta_1$*PreContent + β_2*Treatment + β_3*Spatial + β_4 * Treatment * Spatial + ε

CBDDA DV = Student's post-score on the Chemical Bonding and Dissociation Diagnostic Assessment

PreContent = Student's pre-score on the Chemical Bonding and Dissociation Diagnostic Assessment

Treatment = Student is part of the Ash or Elm group (0 = Ash [business-as-usual]; 1 = Elm [new unit])

Spatial = Student's gains (post-pre) on the PSVT-Rot

β_0 =Intercept if the student had a pre-score of 0, part of Ash and had 0 spatial gains

β_1 = slope for the pre-score on the Chemical Bonding and Dissociation Diagnostic Assessment

β_2 = slope for the treatment depending on whether the student is an Ash or Elm student

β_3 = slope for the spatial gains

β_4 = covariate slope of the spatial gains * treatment

ε = error

For Research Question 2, the results from PSVT-Rot were analyzed using multiple linear regression with the dependent variable referring to the Post-Test for the PSVT-Rot. The treatment group and Pre-Test Scores were the independent variables for the regression.

PostSpatial DV = $\beta_0 + \beta_1$*PreSpatial + β_2*Treatment + ε

PostSpatial DV = Student's post-score on the PSVT-Rot

PreSpatial = Student's pre-score on the PSVT-Rot

Treatment = Student is part of the Ash or Elm group (0 = Ash [business-as-usual]; 1 = Elm [new unit])

β_0 =Intercept if the student had a pre-score of 0, part of the control group and had 0 spatial gains

β_1 = slope for the pre-score on the PSVT-ROT

β_2 = slope for the treatment depending on whether the student is part of the control or experimental group

ε = error

For multiple linear regression, scatterplots were generated using SPSS software between each continuous dependent variable and the independent variable to check for an approximately linear relationship. From the Model Summary, the Adjusted R Square value indicated the percentage of variance that has been accounted for by the proposed model. The model's significance was checked using the p-value of the F statistic of the ANOVA table. The model was significant when the p-value is less than .05. When the model was significant, at least one of the predictors is significant indicating that one of the predictors explained the variation in the model. To test predictor significance, the p-value for each predictor was checked whether or not the value was less than .05. The Unstandardized Coefficients were used for the β (slope) values. For significant β values, the interpretation can be made for each one unit increase in predictor, the dependent variable increased by β. The intercept each model referred to the value if each of the independent variable was set to 0. For Research Question 1, the intercept referred to a student from the control group with a Pre-CBDDA value of 0 and PVST-Rot Gain of 0. For Research Question 2, the intercept referred to a control student who has a Pre-PVST-Rot of 0.

Qualitative Analysis.

Multiple sources may provide validity to the study by allowing the possibility of convergence to the same findings. Triangulation consists of at least three sources of evidence (Yin, 2011). Several pieces of evidence were analyzed to provide triangulation of data and are specified in Table 8 on page 58 of this dissertation including interviews, teachers' logs, part III of the CBDDA, and the researcher's log (observations plus discussions).

Interviews were performed of the students with students from both Ash (business-as-usual) and Elm (experimental) groups. A maximum of six students were picked from each group as this number should give an insight to students' knowledge. Students were chosen based on the pre-test scores with two students scoring from the lowest 25% of the group, two students from the upper 25% scores, and two with scores between these two groups. These interviews were performed after the pretests were administered but before the content was taught. Eleven out of the twelve students were interviewed after the post-test to check student thinking and understanding of the concepts. The twelfth student from the pre-interviews did not take the post-tests, but another student was chosen from the same range in the group. By analyzing student responses, differences between the two units and students' understanding will be determined. Appendix E contains the interview protocol.

Coding process.

Student interviews were transcribed from videotapes. From the first set of transcriptions, codes were developed for this study, and these codes followed themes of questions/answers. The teachers' logs were reviewed using this set of codes. The researcher's log and discussions were also analyzed with these codes. The final set of codes included: Ion Formation, Ionic Bond, Balancing Formula Unit, Dissolving, and Spatial.

Research Biases

I have taught a variety of Chemistry courses over the past 10 years including face-to-face and on-line courses. My experience has made me think about ways to explain the difference between the ionic bond and covalent bond. I have utilized the octet rule and have taught the criss-cross method. Students' questions from my classes has made me consider different ways to teach this material which helped me with the design of the new unit and I maybe biased towards the new unit. It is my attempt in the Qualitative portion of this dissertation to explain the differences between the two groups of students and be objective with this explanation. I was the one who recruited the teachers for this study from connections that I had developed over the years with working in a Department of Chemistry.

This chapter outlined the Research Questions with associated Research Null Hypothesis. This chapter also explained the research design and described the research setting. The initial models for the Quantitative portion of the study were explained including the dependent and independent variables. The chosen assessments employed in this study were detailed including a small pilot study for the CBDDA to validate the questions and the two rubrics (Figures 9 and 10) used with grading. For the Qualitative portion of the study, the data sources utilized and the coding process was described in this chapter. Finally, the biases of the researcher were mentioned to ensure that the reader will understand some development of the study and recruitment of individuals.

CHAPTER 4. QUANTATITVE ANALYSIS

The purpose of this study was to compare students' understanding for the ionic bond, ionic formula unit, and dissolving of ionic compounds between an experimental group using an electrostatic framework including examining unit cells of ionic compounds and a business-as-usual group using a molecular framework. This chapter covers the Quantitative Analysis portion to answer the two Research Questions:

Research Question 1: How does the understanding of the ionic bond and dissolving of ionic compounds in water compare for students using a unit focused on an electrostatic framework to students utilizing a molecular framework (business-as-usual) related to their spatial ability and using the spatial ability as a covariant with treatment group?

Research Question 2: How do spatial visualization skills compare for students using an electrostatic framework and students focused on a molecular framework?

Description of Sample

For the Quantitative Analysis of date, the sample contained students whose parents gave consent and the student gave assent. These students also had to take pre- and post-test for both the PSVT-Rot and CBDDA. If a student missed one of these four tests, they were removed from the sample. For Experimental students, out of 172 students only 72 students supplied proper documentation and testing representing 41.9% of the potential sample pool For Control students, out of 104 students only 20 students had proper documentation and testing representing 19.2% of the potential sample pool. The majority of these students were in their third year of High School.

Summary of the Results

For the data collected, SPSS Version 22 was used for analysis. The research hypothesis utilized multiple linear regression. Tables 12 – 13 summarized the results for the two research questions.

Table 12: Linear Model of predictors of Post CBDDA

	Unstandardized		Standardized	
	B	SE	B	*p*
Constant	2.326 (.173, 4.479)	1.083		.035
PreContent	.492 (-.036, 1.020)	.266	.187	.067
Con_Exp	3.523 (1.287, 5.758)	1.125	.317	.002
PVST_Gain	.041 (-.366, .448)	.205	.031	.841
Treat*PVST_Gain	-.176 (-6.95, .343)	.261	-.106	.502

95% confidence interval reported in parentheses

Table 13: Linear Model of predictors of Post Spatial

	Unstandardized		Standardized	
	B	SE	B	*p*
Constant	3.331	1.352		.016
PrePVST	.694 (.504, .884)	.096	.610	.000
Con_Exp	.243 (-1.465, 1.951)	.860	.024	.778

95% confidence interval reported in parentheses

Detailed Data Analysis for Research Question 1

Research Question 1: How does the understanding of the ionic bond and dissolving of ionic compounds in water compare for students using a unit focused on an electrostatic framework to students utilizing a molecular framework (business-as-usual) related to their spatial ability and using the spatial ability as a covariant with treatment group?

Content and Spatial.

Both the Elm and Ash students covered the similar content using different teaching methods, the pre- and post-CBDDA results were used for both groups with the pre-score as an independent variable and the post-score as the dependent variable for the model. The two different groups was part of the model such that the model could predict post-CBDDA scores for either group. The new curriculum incorporated integrated spatial activities. The gain in PVST-Rot scores was incorporated into the model. In addition, the pre-CBDDA score and PVST-Rot gains were combined into a covariant predictor to further study the relationship between spatial and content. This analysis is for the overall multiple linear regression equation without removing any variables that did not have significant slope values.

Assumptions of multiple linear regression.

Sample Size. According to Fields (2013), sample size should be approximately 10 - 15 cases of data should for each predictor. This model has four predictors resulting in a range from 40 to 60 cases of data. The sample size of 92 satisfies this assumption.

Continuous variables. For a linear regression analysis, at least one of the independent variables must be continuous. The dependent variable be categorized as a continuous variable.

Linear relationship. Each independent variables categorized as continuous must have a linear relationship with the dependent variable. Visual analysis of the appropriate scatter plots for the continuous independent variable with the dependent variable displayed a general linear relationship. There was a slight skewness to the residuals histogram (Figure 12), but since this skew was close to the middle, the linearity assumption was not changed.

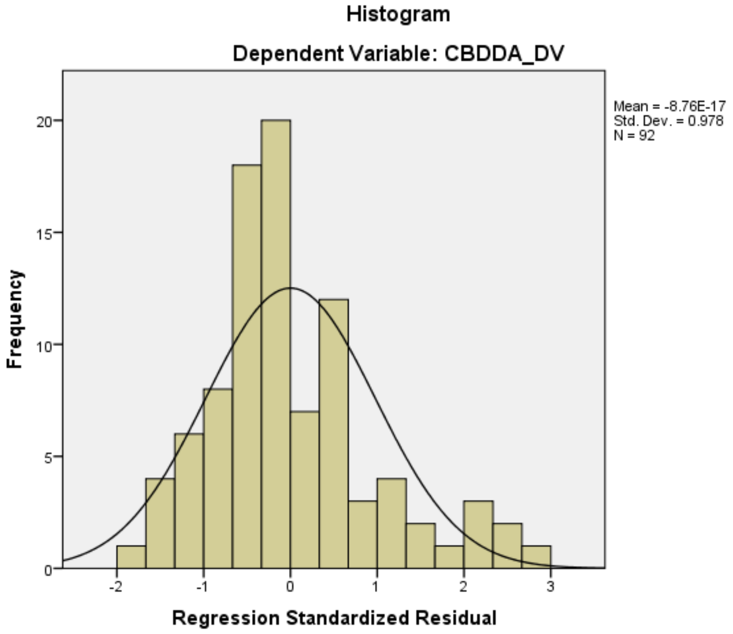


Figure 12.RQ1 Standardized Residual Distribution

Homoscedasticity. This assumption discusses the equal variance between pairs of variables. This assumption can be checked by visually inspecting the scatterplot of the residuals against the model's predicted value (Ho, 2006). After visual inspection, this assumption was met for the model (Figure 13).

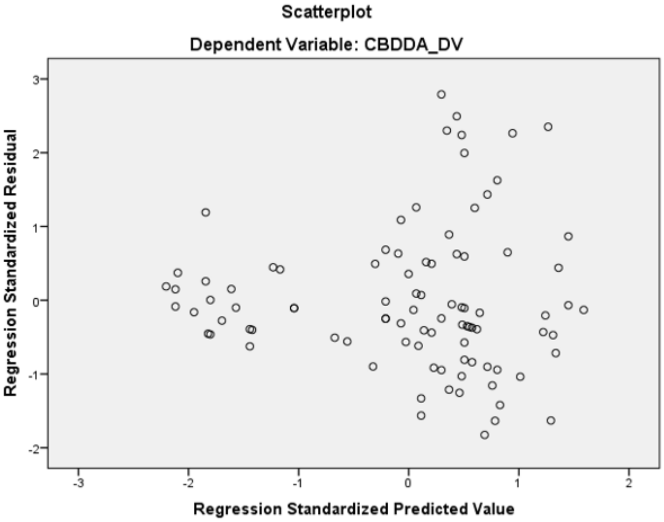


Figure 13. RQ1 Scatterplot - Homoscedasticity

Normality of the error distribution. With multiple regression, the assumption that the errors of prediction are normally distributed. The errors of prediction are the differences between the actual and predicted dependent scores. A normal P-P Plot of the standardized residuals (Figure 14) shows that this assumptions did have some violations but overall the differences does show a general trend.

Independence of random errors. With regression analysis, the assumption is made that the predicted value is not related to any other predictor. This assumption can be checked using the Durbin-Watson statistic. From Fields (2013), this value should be between one and three. For the suggested model, the Durbin-Watson value is 1.662 satisfying this assumption.

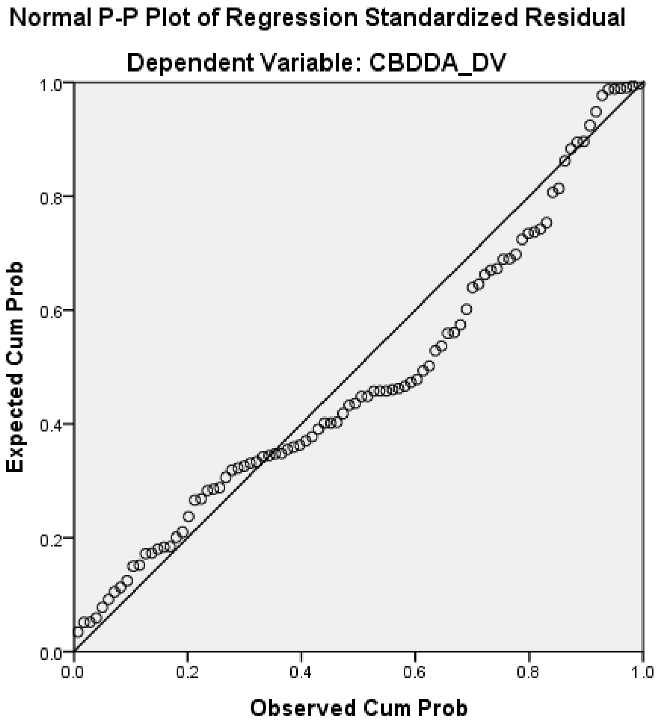


Figure 14. RQ1 Normal P-P Plot for Normality of the Error Distribution

Regression analysis.

The following is the multiple regression model with the spatial gains mediating the treatment:

CBDDAI DV = $\beta_0 + \beta_1$*PreContent + β_2*Treatment + β_3*Spatial + β_4 * Treatment * Spatial + ε

CBDDA DV = Student’s post-score on the Chemical Bonding and Dissociation Diagnostic Assessment

PreContent = Student’s pre-score on the Chemical Bonding and Dissociation Diagnostic Assessment

Treatment = Student is part of the Ash or Elm group (0 = Ash [business-as-usual]; 1 = Elm [new unit])

β_0 =Intercept if the student had a pre-score of 0, part of the control group and had 0 spatial gains

β_1 = slope for the pre-score on the Chemical Bonding and Dissociation Diagnostic Assessment

β_2 = slope for the treatment depending on whether the student is part of the control or experimental group

β_3 = slope for the spatial gains

β_4 = covariate slope of the spatial gains * treatment

ε = error

Research Question 1 Null Hypothesis: There are no statistically significant differences for the gains in content using spatial skills as a mediating variable between students taught with the new electrostatic curriculum unit and students taught in the business-as-usual way.

Multiple Regression was used to test a model of the influences that pre content score, spatial gains, treatment group, and using the treatment group as a mediating factor on spatial gains. Scatterplots were used to test the linearity of the independent variables with the dependent variable. Table 12 summarizes the results for the model. The treatment group and the model constant were the only independent variables that had a statistically significant slope ($p < .05$). According to Ho (2006) when VIF values are greater than 10, the multicollinearity should be investigated. The VIF values for this model were all less than 2.61.

The ANOVA table showed that the model was statistically significant explaining the post content score based on the model's predictors. The null hypothesis was rejected, F(4, 87) = 4.674, *p* < .05. Thus the model shows statistically evidence that it may predict the score on the post content test.

The Adjusted R Square for this model is .139 stating that 13.9% of the variance in the post content score has been accounted for by the model. Only the constant and the treatment group can be interpreted for this model as their slopes were the only statiscially significant slopes. To interpret the constant, a student who is in the control group with zero spatial gains and a zero score for the pre CBDDA, the increase in post CBDDA score is estimated to be 2.326 on average. For one unit increase in pre CBDDA score, the increase in post CBDDA score is estimated to be 0.492 on average holding all other variables in the model statistically constant. For a student in the treatment group, the increase in post CBDDA score is estimated to be 3.523 on average holding all other variables in the model statistically constant. The final model:

$\text{CBDDA DV} = 2.326 + 0.492*\text{PreContent} + 3.523*\text{Treatment} + \varepsilon$

While the curriculum unit has spatially integrated activities, the spatial gains does not appear to affect the post CBDDA score. Also the spatial gains mitigating the treatment group also do not appear to affect the post CBDDA score. The pre CBDDA score may not affect the post CBDDA score. The main influence for this model is the group that the student belongs indicating that the teaching of the content possibly has an effect on the post CBDDA score. Thus, the null hypothesis may be only rejected for the treatment type. Taber's electrostatic framework (1997) and the new curriculum unit may improve the students' scores on the CBDDA. A students' CBDDA post-score is independent of the spatial score and dependent on both the pre-score and the treatment group. Further analysis of the data and additional studies may provide more insight to the model.

Detailed Data Analysis for Research Question 2

Research Question 2: How do spatial visualization skills compare for students using an electrostatic framework and students focused on a molecular framework?

Assumptions of multiple linear regression.

Sample size. Again a sample size of 10-15 cases of data for each predictor should be collected (Fields, 2013). Since this model has 2 predictors, the sample size of 92 is greater than the 20-30 cases for this assumption.

Continuous variables. Only one of the independent variables needs to be continuous for the linear regression. The pre PVST score was the continuous variable for this model. The dependent variable has to be continuous for the regression, and the post PVST score was categorized as continuous. The treatment group was assigned as a categorical variable.

Linear relationship. The continuous independent variable must be linear with the dependent variable. The pre PVST score was found to be linear with the post PVST score after analyzing a scatter plot. The residuals histogram shows a normal distribution (Figure 15).

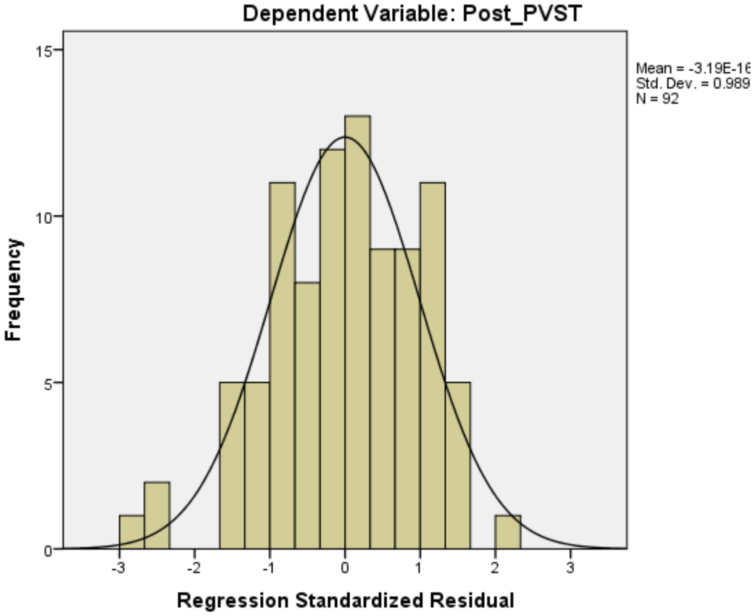


Figure 15. RQ2 Standardized Residual Distribution

Homoscedasticity. Equal variance between pairs of variables assumptions can be checked visually by inspecting the scatterplot of the residuals against the model's predicted value. Figure 16 shows that this assumption was met for the model.

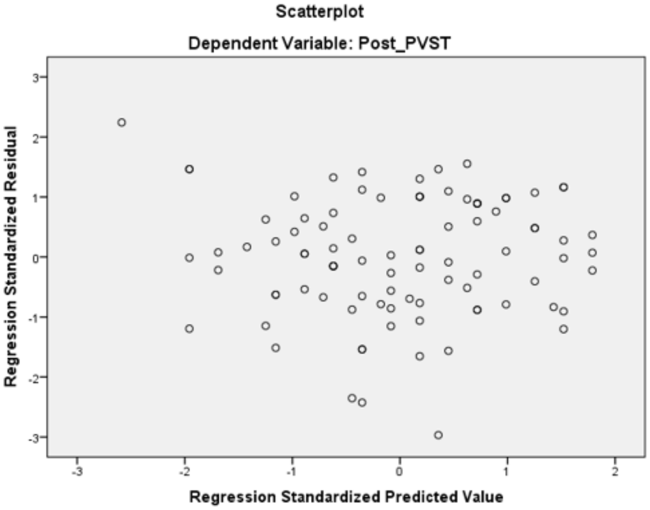


Figure 16. RQ2 Scatterplot - Homoscedasticity

Normality of random errors. Linear regression assumes that the errors of prediction are normally distributed with the errors of prediction being the differences between the actual and predicted dependent scores. The normal P-P plot in Figure 17 shows that this assumption was met for the model.

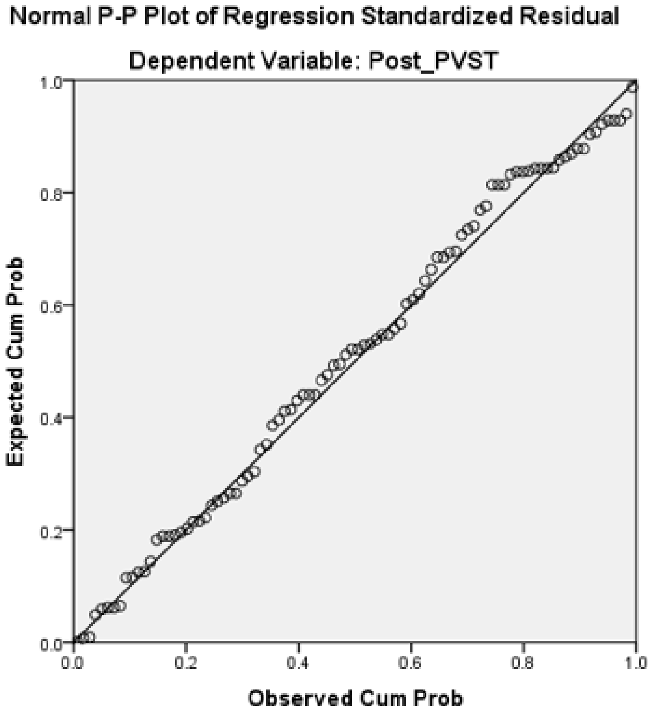


Figure 17. Normal P-P Plot for Normality of the Error Distribution

Independence of random errors. The assumption was made that the predicted value is not related to any other predictor using the Durbin-Watson statistic which should be between one and three according to Fields (2013). For this model, the Durbin-Watson statistic was found to be 1.705 meaning that this assumptions is met.

Regression analysis.

The treatment group and Pre-Test Scores are the independent variables for the regression.

PostSpatial DV = $\beta_0 + \beta_1$*PreSpatial + β_2*Treatment + ε

PostSpatial DV = Student's post-score on the PSVT-Rot

PreSpatial = Student's pre-score on the PSVT-Rot

Treatment = Student is part of the Ash or Elm group (0 = Ash [business-as-usual]; 1 = Elm [new unit])

β_0 =Intercept if the student had a pre-score of 0, part of the control group and had 0 spatial gains

β_1 = slope for the pre-score on the PSVT-ROT

β_2 = slope for the treatment depending on whether the student is part of the control or experimental group

ε = error

Research Question 2 Null Hypothesis: There are no statistically significant differences for the gains in spatial skills between students taught with the new electrostatic curriculum unit and students taught in the business-as-usual way.

Multiple linear regression was used to develop a model using the pre PVST score and the treatment group as the independent variables with the post PVST score as the dependent variable. A scatterplot was used to test the linearity of the pre PVST score with the post PVST score. Table 13 summarizes the results for this model. The pre PVST score slope and the regression model constant (intercept) were found to be significant (p <.05). The treatment group slope was not found to be significant. Multicollinearity has to be investigated for VIF values greater than 10 (Ho, 2006). This model's VIF values were one meaning no investigation was required.

The ANOVA table indicated that the model was statistically significant for explaining the post PVST score based on the predictors. The null hypothesis was rejected for Research Question 2, F(2,89) = 26.732, $p < .05$. The Adjusted R Square was .361 meaning that 36.1% of the variance in the post PVST score was accounted for by the model. Only the constant and pre PVST score slope were significant. For a student with a pre PVST score of 0, the post PVST score was 3.331 points. For a one unit increase in pre PVST score, the post PVST score increased by 0.694 points holding all other variables in the model statistically constant. The final model:

PostSpatial DV = 3.331 + 0.694*PreSpatial + ε

The null hypothesis was that there was no difference between the new curriculum unit (Elm) spatial scores and the business-as-usual (Ash) spatial scores. With the removal of the treatment variable from the final model, the post PVST score depends only on the pre PVST score. One limitation of this analysis is the difference in treatment group size with more than three Elm students to one Ash student participating in the study. Bodner and McMillen (1986) were able to correlate spatial ability to success in chemistry concepts. Harle and Towns (2010) also indicated that spatial ability is needed to learn chemical concepts. The teachers from Ash did have some spatial components to their lessons including using conductivity probes for to distinguish different types of bonding in compounds, writing Lewis Electron Dot Diagrams to demonstrate the electron transfer from cations to anions, and having students analyze molecular geometries for polarity. Further studies with a more even group size between the two treatments and a larger business-as-usual group may provide further insight with the model.

Summary of Findings

This study compares students' performance on the CBDDA (content) and PVST-Rot (spatial) tests between two treatment groups, new curriculum based on the electrostatic framework and business-as-usual. While the null hypothesis for both research questions was able to be rejected, not all the predictors for the model were proven to be significant. The approximate 3.2 Elm students to one Ash student may be a limitation of the models.

Research Question 1.

How does the understanding of the ionic bond and dissolving of ionic compounds in water compare for students using a unit focused on an electrostatic framework to students utilizing a molecular framework (business-as-usual)?

- Regression analysis showed some skewness to the data which may have affected the linearity of the independent variables to the dependent variable.
- Only pre CBDDA score, and the treatment group had significant slopes meaning that the higher post CBDDA score depended on both the pre CBDDA score and being in the experimental group.
- Spatial gains and spatial gains mitigated by the treatment group did not have statistically significant slopes. Spatial ability does not effect the model.
- $\text{CBDDA DV} = 2.326 + 0.492 \cdot \text{PreContent} + 3.523 \cdot \text{Treatment} + \varepsilon$
- Students' post-score on the CBDDA increase by 3.523 if they were an Elm student and by 0.492 for every one point increase on the pre-score.

Research Question 2.

How do spatial visualization skills compare for students using an electrostatic framework and students focused on a molecular framework?

- While the null hypothesis was able to be rejected, the final model only had the pre PVST-Rot score having a significant slope indicating that the treatment group did not matter.
- $\text{PostSpatial DV} = 3.331 + 0.694 * \text{PreSpatial} + \varepsilon$
- For every one point increase in pre-score for the PVST-Rot the post-score will increase by 0.694. This increase is not dependent on treatment group.

CHAPTER 5. QUALITATIVE ANALYSIS

Since two groups are being compared using different lessons, the data was not examined by only comparing the test scores for both the CBDDA and the PVST-Rot. This chapter covers the Qualitative Analysis portion to answer the two Research Questions:

Research Question 1: How does the understanding of the ionic bond and dissolving of ionic compounds in water compare for students using a unit focused on an electrostatic framework to students utilizing a molecular framework (business-as-usual)?

Research Question 2: How do spatial visualization skills compare for students using an electrostatic framework and students focused on a molecular framework?

In addition, issues with the new unit will be discussed, and what worked well for business-as-usual groups.

Data Sources

With Qualitative Analysis, multiple Data Sources are required for triangulation. According to Yin (2011): "In research, the principle pertains to the goal of seeking at least three ways of verifying or corroborating a particular event, description or fact being reported by a study" (p. 81). Multiple Data Sources were analyzed for both research questions:

- Pre/post interview with both Ash and Elm students about their answers to CBBD
- Ash and Elm teacher logs
- Ash and Elm classroom observations by the researcher
- Informal discussions with both Ash and Elm teachers about content and activities
- Drawings from the third portion of the CBBD assessment

- Dissociation Equations from the third portion of the CBBD assessment

Student Sample for Interviews.

Six students from both Ash and Elm were chosen to be interviewed. While all six Ash students were available for pre/post interviews, only five Elm students were available. One of the Elm students had stopped attending class such that the post interview was not possible. No reason was given for the student missing school. The researcher decided to interview another student who had similar pre test scores to determine if this student would discuss crystals.

The decision on which students were to be interviewed was based on both the pre-tests for the PVST-Rot and CBBD Part II scores. For each group, 2 of the students were chosen from the bottom 25%, from the middle 50% of the group and from the top 25% of the group. The decision of which student to pick for interviews was difficult as so many students scored poorly on the CBBD Part II which was expected since students probably had not covered the majority of concepts in previous science classes. A review of Part III of CBBD was not used as a review of students' drawings showed a lack of understanding for the particulate level of the dissolving process for the pre-tests. The student code was developed by the researcher for students to remain anonymous and will not be explained in this dissertation. To help distinguish between students, the number assigned to them has been referenced in the explanations.

Coding.

The interviews were transcribed by the researcher using no qualitative analysis program. After both pre and post interviews were transcribed, major themes of the CBBD assessment were determined to develop a set of codes: Ions, Ionic Bond, Balancing Formula Unit/Ionic compound, Dissolving, and Spatial. Different colored pens were used to indicate the codes on hardcopies of the interview transcripts which had any student names redacted. The Spatial code was tied with the other codes depending on the students' answer, researcher log or the teachers' log. The researcher also clustered the interviews by group (Ash or Elm) and by instance (pre or post). The researcher then took these clusters and compared their explanations to the questions between students while reviewing their PVST-Rot score for the Spatial code to answer Research Question 2. For example, one student discussed drawing out the solution for whether or not 2 elements with different electron configurations would form an ionic compound. The researcher did not ask the students why they changed any of their answers from their pre- to post-interview.

These codes were also used to analyze the following: the lesson logs provided by the Ash teachers; the lesson plans for the experimental unit were analyzed; observations by the researcher; and discussions with both sets of teachers. After reviewing the logs, the Ash teacher logs (Rocky and Trek) were identical and be referred as one item. When the logs were given, the researcher requested that the teachers to describe their lessons and any issues. Rocky did mention that the two teachers cover the topics in very similar ways and attempt to stay on the same schedule.

Research Question 1

To answer this Research Question, all of the codes except Spatial are discussed as this question focuses on the content between the two types of lessons. If the Spatial code is also related to the excerpt, discussion of this aspect has been discussed with the Research Question 2 section of this Chapter. Each code (Ion Formation, Ionic Bond, Balancing

Formula Unit, and Dissolving) has been discussed individually. If the evidence was coded into at least one additional code, the extra code may be mentioned if pertinent, but not thoroughly discussed as the focus of each section was one code. Different pieces evidence was used to examine each code.

Ion Formation Code.

This code was developed to include ion formation and ion usage. Ions are formed when electrons are transferred (added or removed). It is the electrostatic attraction between ions that form the ionic bond. While ions are formed when an ionic compound is dissolved in water increasing the conductivity of distilled water, this section focuses on the forming of ions and electrons. Ions in water was coded as dissolving and discussed in the Dissolving section of this chapter. From Part II of CBDDA, Question 3 was coded Ion Formation. Question 3 of the CBDDA as this question discusses ion formation in terms of electrons being shared, transferred or destroyed.

Ash Ion Formation. The teachers from Ash covered this topic by relating the position of an element on the periodic table with the number of valence (outer shell) electrons and then defining the octet rule (elements want to have a full outer also known as valence shell). They showed that to form ions electrons are transferred with Lewis Dot structures (Figure 18) with balancing of the formula unit focusing on the symbolics and the sub-micro (by focusing on the electrons).

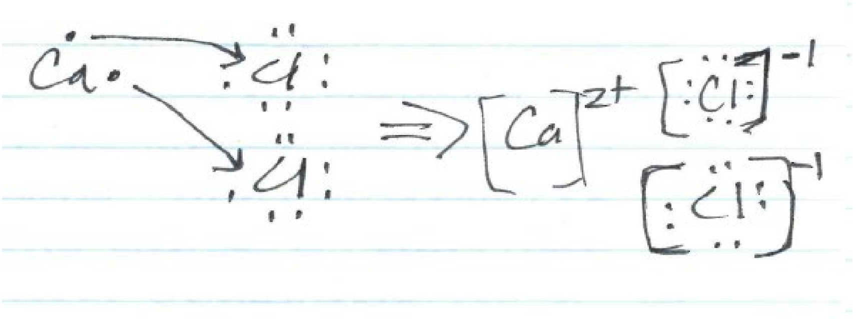


Figure 18. Ash Teacher showing the electron transfer to form ions and then an ionic compound.

In their pre-interviews, two of the students (High Spatial – 520801, and Low Spatial – 510601) chose share electrons in their pre-interviews. The Low Spatial student (510601) stated they guessed while the High Spatial thought they may be confused with a covalent. The other four students chose transfer electrons. None of the students were able to provide an explanation of their choice. Prior knowledge from courses, experiences, or reading influenced some students' answers. A Medium Spatial student (520901) mentioned learning transfer of electrons in a previous Biology course with "ions give and take".

All of the students chose transfer electrons for their post-interviews, but their explanations did not refer to ionization energy or electron affinities. A High Spatial student (521801) explained transfer for forming ions: "most nonmetals have a higher amount of valence electrons and umm so that don't need that many to become umm full. So they just transfer them to get it bigger." Other explanations included Newton's Law (Medium Spatial – 520901) to "you are talking about an ionic bond and therefor transferring of ions" (High Spatial -520801). From the teachers' logs, the transfer of ions was reinforced with balancing of the formula unit (Figure 18).

From their pre-interviews, a High Spatial student (520801) and Low Spatial student (510601) answered electrons were shared. Both High Spatial students (520801 and 521801) mentioned covalent bonds with their answers and 520801 stated the reason they answered sharing: "I probably got it confused with a covalent bond. And ummm it it's differernt… it's hard to say that word.. differeniate between the two, but that is probably why I chose that answer." The Low Spatial student (510601) could not explain their reasoning for choosing sharing.

Differences was seen in the students' explanations between the spatial groups with the Low Spatial students not providing much of a reason beyond "pulling." A Medium Spatial student discussed their reasoning to be linked to the lattice structure: "Because with the ionic bond it's that umm the continuous pattern and it transfers to make the bond stronger so it can make that continuous pattern." There was still some misconceptions with a High Spatial student when they thought ionic bonds were formed between two nonmetals.

Elm Ion Formation. For Elm students, ion formation was covered in Lesson 2 of the unit. The students modeled electron configurations using the Bohr Model which focuses on electron shells and not quantum numbers. NGSS does not mention quantum numbers, but the HS-PS1-1 Performance Expectation discusses the patterns of electrons based on the outermost shell. Students would model an atom of a main group element (Figure 19 chorine atom) and then model the ion for the element (Figure 20 chloride ion). Sodium and potassium were modeled to demonstrate that elements from the same column of the periodic table would have the same outer shell configuration for an atom and would have the same process add or remove to form the ion for the respective element.

After this one example, students were asked to predict the charge for the other elements in the same column of the periodic table. This part of the activity had students focusing on symbolics and sub-micro (an atom's different sub-atomic particle) of Johnstone's triangle.

Lesson 2 also had the students locating values and drawing graphs of the periodic trends for several properties including the first ionization energy, and electron affinity. Both ionization energy and electron affinity were explained in the worksheet for the students to read. After the electron affinity graphs, students were asked to the number of electrons added to Group VA, VIA and VIIA of the periodic table such that they would have the same electron configuration as Group VIIIA. Then the students were to examine a table of Ionization Energies to determine where the first largest jump occurred. For example, Sodium has a First Ionization Energy value of 495.9 kJ/mol, a Second Ionization Energy value of 4,560 kJ/mol (Chang & Goldsby, 2014) which means a sodium atom will form a +1 ion but not a +2 ion. From both the teacher logs and researcher observations, students had trouble analyzing the table of Ionization energies because each Ionization energy has a jump. Magnesium has a First Ionization Energy of 738.1 kJ/mol, a Second Ionization Energy of 1,450 kJ/mol, and a Third Ionization Energy of 7,730 kJ/mol (Chang & Goldsby, 2014). Students thought that the first increase would cause magnesium to have a +1 charge instead of looking for a several thousand kJ/mol jump such as between the Second and Third Ionization energies. The researcher had to help several groups in Harleyquin's class to understand the jump size had to be several thousand.

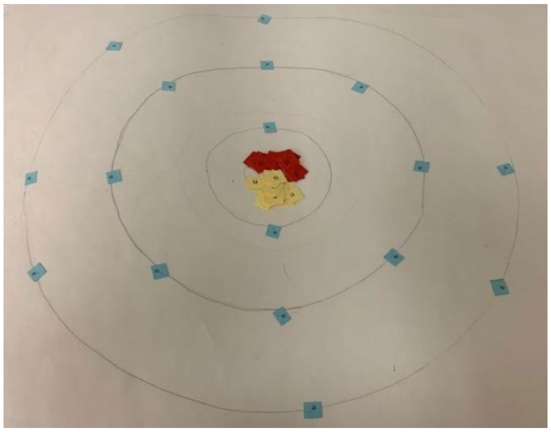


Figure 19. Lesson 2 Chlorine Example.

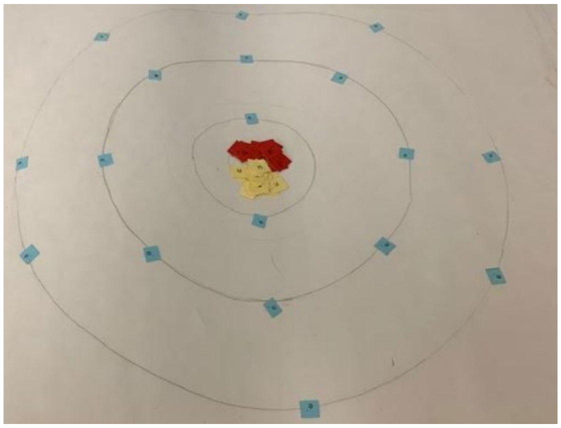


Figure 20. Lesson 2 Chloride Example.

Four of the Elm students chose transferred electrons in their pre-interviews with a Medium Spatial student (232001) mentioning "have to do with electronegativity like if they find uhhh fill their…fill their valence electrons." A High Spatial student (231001) relating the transfer of electrons to energy: "energy is usually transferred. And sharing would make it like bond kind of thing so I thought it would be transferred." The two students answering sharing (Medium Spatial – 271701 and Low Spatial – 370401) thought they remembered this fact from prior knowledge but were not specific about when they learned about sharing.

With the post-interviews, three of the students answered transferred with the post-interview High Spatial student (441501) providing the best explanation: "An ion is a particle with a charge and to have a charge you have to take one away it is positive and you add one it is negative." When asked what one was, the student said electron. A Medium Spatial student (232001) answered transferred explaining "when the ions can reach and have 8. 8 valence electrons." This student was referring to the octet rule. None of the students mentioned Ionization Energy or Electron Affinity in their post-interview answers. The two students relying on their previous knowledge about sharing from the pre-interview answered sharing in their post-interviews with both referring to the electrons "balancing" and "equilibrium" for forming a compound.

The trend between the Spatial groups was evident. Both High Spatial students (441501 and 231001) and a Medium Spatial student (232001) answered transferred for the post-test. As previously stated, the High Spatial student (441501) explanation concerned developing a charge by gain/loss of electrons, and the Medium Spatial student (232001) discussed the octet rule. While the Low Spatial students explanations were not as in-depth: "because they are not destroyed and they share them together" (361401).

Ionic Bond Code.

The ionic bond can be defined as the bond formed due to the electrostatic attractions between oppositely charged ions. While the CBDDA did not directly ask for the definition of the ionic bond, the students were asked this question at the start of their interviews and at the end just in case the assessment caused them to remember concepts leading them to change their definition. Metals have a tendency to lose electrons to form cations, positive ions, while nonmetals gain electrons forming anions, negative ions. Ionic compounds exist in a crystal lattice in their solid form. Due to the strong electrostatic attractions between oppositely charged ions, ionic compounds exist as solids at room temperature because they have a high melting point. These physical properties were also coded as ionic bond. While some ionic compounds can dissolve in water appreciably, it was determined to focus most of those interactions in the Dissolving code except for the conductivity activity by Ash as the teachers used conductivity results to classify bond type. The definition of an ionic bond and the physical properties of an ionic compound can be classified into the sub-micro aspect of Johnstone's triangle because the students have to visualize the particles and the attractions between particles.

From the CBDDA, Question 11 was identified with this code. Question 11 asked if given two elements would the resulting compound being ionic. Students had to realize that one element was a metal and the other element was a nonmetal. With magnesium and oxygen being able to form ions, a compound resulting from the two would be classified as ionic especially when the electronegativities (magnesium: 1.2; oxygen: 3.5) and the electronegativity difference (2.3) are taken into account. The resulting solid ionic compound has a high melting point due to the crystal lattice formed would have strong forces and would have different physical properties than the individual elements.

Ash Ionic Bond. In their logs, Ash teachers stated that they defined the octet rule and ionic bonds on the same day. The teachers did not state if they actually used the terminology of electrostatic attraction as part of their ionic bond definition. The researcher did observe students playing an card activity where students matched the type of bond with a description. In addition, the teachers had students hypothesize whether or not samples would conduct electricity when dissolved in water and then measure the conductivity of samples dissolved in water to identify the bond type. This activity represents the macro vertex (samples and measuring conductivity) and the sub-micro (students having to visualize the particles in solution).

The students from Ash did not provide the electrostatic definition in their pre- and post-interviews with some students discussing sharing of electrons and transferring electrons. A Low Spatial student (512001) mentioned that an ionic bond "..when two ions they like come together." A Low Spatial student (510601) stated "It's like when two atoms like combine together for form an element…. Pretty much like two atoms form together." In the post-interviews, a High Spatial student (521801) defined an ionic bond as "when two elements come together and they transfer their electrons." None of the students referred to the conductivity activity they had performed in class with their definition of an ionic bond.

For Question 11, fifty percent of the students answered True for the pre-test and post-test. A Low Spatial student (512001) changed their answer from True to False, and a Medium Spatial student (511201) changed their answer from False to True between the two tests. Students focused more on the individual elements rather than the resulting compound in their explanations (pre- and post-interview). During the pre-interviews for Question 11, both High Spatial students (520801 and 521801) and a Medium Spatial student (520901) mentioned oxygen and fire/flammable. These 3 students' in their post-interviews as they again discuss oxygen and fire. In their post-interview, the Medium

Spatial student (520901) did not realize that the question was referring to the resulting compound (I = interviewer; S = student):

> I: Number 11 the compound formed between magnesium and oxygen can be used as a heat resistant material to line the walls of furnaces. You said False for that.
>
> S: Cause it's like oxygen really flammable.
>
> I: Okay.
>
> S: Cause it doesn't say that they were bonded together at all. Oxygen is flammable.

Only one Medium Spatial student (5112010) discussed that ionic bonds are strong which could make a heat-resistant material. This student thought about the resulting compound instead of the individual elements forming the compound.

All of the spatial groups discussed the definition of an ionic bond. "An ionic bond would have to be with two molecules that would share electron that umm. They don't share actually. They uhhh like give it away take it." (pre-interview, High Spatial Student – 5120801) than " they give up like electrons and all that to other atoms, I guess." (pre-interview Low Spatial Student – 510601). Both of these responses do not mention electrostatic attractions. No trends of distinction could be made between these groups as all had some misconceptions such as the molecules and transfer of electrons.

For Question 11, no specific trends emerged between the different spatial groups. Five out of six students considered the elements and not the compound. These students were not visualizing the particles correctly meaning their sub-micro representation from Johnstone's triangle was incorrect. Only one Medium Spatial student discussed the resulting compound with (S = student; I = Interviewer):

> S: I think I looked on the periodic table so I could see like where each one was to see if it made an ionic bond and I know those are stronger so I feel like it would be heat resistant.
>
> I: What do you think a lattice is?
>
> S: A lattice is like the continuous pattern like I keep saying. Like when you look at some gardens, they have that lattice behind to keep it from going which way it wants, the structure.

Elm Ionic Bond. Ionic bond was discussed in Lesson 4 in terms of electronegativity difference between 2 elements. It was stressed that this difference ranges may not always be set but have some overlap between polar covalent and ionic. Coulomb's Law was also discussed in this lesson. Students had to answer questions based on increasing the charge and then increasing the distance between 2 particles. The symbolics region of Johnstone's triangle was the focus of this code because of the symbols involved with determining electronegativity difference between 2 elements to classify the bond.

In the pre- and post-interviews, Elm students provided a variety answers but none of these were the electrostatic attraction. The High Spatial student (231001) described an ionic bond in their pre-interview using knowledge from a previous course as:

> I think an ionic bond is if it's the right.. the one that I'm thinking about I think it's when umm like we always described it as like a clap. (*Student physically claps)* Like two molecules would come together clap but then they leave each other. It's like one whichever one was more electronegative would steal the electron from the other one.

For this student's post-interview, they define the ionic bond as "Based on what I wrote it's kind of like ionic like the ions are coming together so equalize them making them the way they were before." The equalizing referencing to balancing the formula unit.

For Question 11, two of the students answered True (Low Spatial student – 361401; High Spatial no post-interview student). The second Low Spatial student (370401) changed their answer during the interview to False due to "Flammability". The remaining students answered False but did not provide an explanation for their answer. All of the post-interviewed Elm students answered True but they were not able to provide an explanation that ionic compounds have high melting points. A Low Spatial student (370401) referenced it a metal and nonmetal being a "plausible material" for lining furnaces.

For the Ionic Bond code, there was not a distinct trend between the spatial groups. Each group struggled with defining the ionic bond. In the post-interviews for Question 11, students did not provide much of any explanation for their answers.

Balancing Formula Unit.

Since ionic compounds exist as solid crystals, the formula unit for an ionic compound is the lowest whole number ratio of cations to anions in the unit cell (the smallest repeating unit of the crystal), but the crystal itself will have multitude of cations and anions with the ratio given by the formula unit. On the other hand, a covalent compound exists as discrete entities called molecules where the chemical formula represents the exact number of atoms from each element composed in the molecule. From Part II of the CBDDA, Question 9, Question 17, and Question 18 were assigned this code. These Questions represent the symbolics region of Johnstone's triangle as symbols are being used to balance the formula unit. The electron configuration characterizes the sub-micro representation as students have to understand electron configuration and the different shells utilized for the given configurations. Question 9 required students to examine electron configurations for 2 element s and realize that one is a metal and the second is nonmetal which could form the ionic compound CE_2. Question 17 and 18 can be connected together as Question 18 has different drawings for Question 17 answers. Question 17 specified the number of electrons in the outermost shell and students had to realize that the formula unit possible would form an ionic compound. The exact formula unit was not given in Question 17's statement like the possible formula unit was for Question 9. Question 18 was the second tier of this question requiring students to pick the correct diagram representation for their answer to Question 17. While the dissociation equations from Part III of the CBDDA involved the students separating a formula unit to the separate component ions, these equations involve a representation of the dissolving process and will be discussed with the Dissolving code as the formula unit was given for each dissolving scenario.

Ash Balancing Formula Unit. From Ash's teacher logs, balancing the formula unit was accomplished using Lewis Electron Dot Diagrams showing the transferring of electrons between a metal and nonmetal (Figure 18). Their log example involved a 1 cation to 2 anion transfer. According to the logs, several pairs of elements were done using this type of diagrams, and students took a quiz that had questions for this concept. An issue with this teaching method is that the show of the transfer of electrons can be done for main group elements, but transition elements can transfer different number of electrons forming different ions such as lead (II) ion and lead (IV) ion. Rocky's and

Trek's logs indicated that they focused on the main group elements and not transition elements.

For Question 9, Ash students said in their pre-interviews that they guessed with a Medium Spatial student (520901) stating "I have no clue what half of those words meant so I guessed." For the post-interviews, only 2 answered True. A High Spatial student (521801) explained their answer by filling the outer shells (octet rule):

> I said it was True because I figured that umm since element C has 2 and 8 that means both of those shells are full and element E has 2 and 7 so it only needs one more to become full. So I figured that umm element C would lose 1 to give to E so that way E could be full.

From the teachers' log, while the discussed main group electron configuration for the valence shells, students were not exposed to this type of notation making this question difficult due to the more complex electron configurations for element C. The High Spatial Student (521801) attempted to draw their answer (Figure 21) to determine if they balance out but they said that "they wouldn't fit all together to make CE_2."

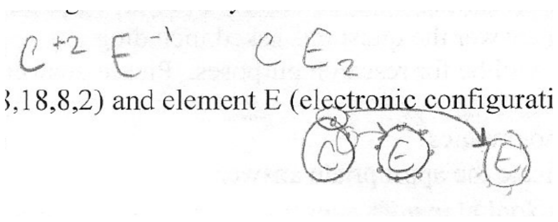


Figure 21. Student's (520801) drawing for Question 9 of CBDDA

For the pre-tests, 4 students answered ionic on Question 17. A Medium Spatial student (520901) explained their ionic answer: "It should be ionic because A has less than 4 so it needs to move over to B." This student had mentioned that they remembered some concepts from Biology that they had the previous year. A Low Spatial student (512001) answered covalent "because of the examples down below." Referring to Question 18.

For the post-test, the same 4 students answered ionic with a Low Spatial student changing their answer during the interview as they reviewed their assessment, and when asked about the change: "Because like it.. so they're not the same elements because they all have different electrons. I feel like its two different elements combining make it ionic." The octet rule was referenced by both of the Medium Spatial students (511201 and 520901). The High Spatial student (520801) who drew on Question 9 also answered this question based on their drawing (Figure 22). "It worked for ionic and covalent didn't seem reasonable I guess." The electron configuration was simpler for the two elements involved in this question compared to Question 9.

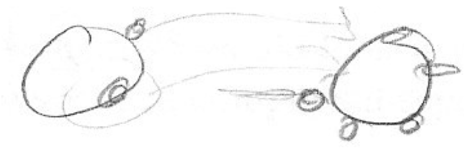


Figure 22. Student's (520801) drawing for Question 17 of CBDDA

For Question 18 on their pre-tests, 4 of the students chose B (both Low Spatial students and both Medium Spatial students). Ash students were not confident in their answers offering no explanations except for the Low Spatial student discussed "the xxs on the outside and … the element A was losing 2" even though they had chosen covalent on Question 17. The High Spatial student (520801) answered C but "It was hard for me to understand that umm the diagrams. I've never had…I don't think I didn't know how to read them."

Three students answsered this question correctly. 2 Medium Spatial students (511201 and 510901) answered C due to the [] around the elements and their familiarity with the brackets from class (Figure 18). The Medium Spatial student (511201) also mentioned: “it has the uhhh 2+ and 3- which is how many its added or gained or subtracted.” The High Spatial student (520801) chose C because “it helped to represent what I drew out the ionic bond between the two maybe.” This student also chose C over B because of the brackets. They had seen the brackets from the class activities. The second High Spatial student (51801) answered D on their scantron but decided to go with C because their elements were not connected. Choice C was the correct answer for this Question. The other students did not provide an explanation for answering B.

The main trend between Spatial groups was the High Spatial student (520801) drawing out their answers on their assessment for balancing. None of the other students discussed balancing this way. In addition, the High Spatial student (520801) and Medium Spatial students (511201 and 510901) reviewed the answers for Question 18 on their post-test and chose a diagram that was familiar to them from their class activities (Figure 18).

Elm Balancing Formula Unit. For the new unit, students were to learn about balancing the formula unit in Lesson 3 and they were to connect this information with the ion formation activity in Lesson 2. Lesson three had students building models of simple unit cells (Figure 23), a face-centered unit cells (Figure 24) and a body centered unit cells (Figure 25) using marshmallows and toothpicks. Students were to analyze these to determine the fraction of marshmallow that was part of one of the unit cells for each model. For example, a corner marshmallow belongs to 8 unit cells and thus have 1/8th of each corner belongs to one unit cell. A marshmallow that is in the face is shared by 2 unit cells and half of the marshmallow can be assigned to one unit cell. For a body-centered unit cell, the marshmallow in the middle of the body will belong only to 1 unit cell. In her teaching log, BSB discussed some students had issues visualizing the fraction of the marshmallow for the unit cells that they built. The students then watched a video covering this information with animations. The hyperlink is in the Lesson 3 5E instructions (Appendix A) Next, the students applied their knowledge about unit cells to derive the number for each cation and anion for several ionic compound unit cells which were printed in color for students to distinguish between cations and anions as the figures had a key to assist with identification. Then students determined the lowest whole number ratio of cations to anions. From Lesson 2, students were to apply their knowledge about the charges for main group elements to relate the charges to the lowest whole number ratio, but from BSB's teaching log some students only wanted to put + or – without a number such that O would just be – and not 2-. Students also were informed the meaning of Roman numerals for transition metal cations. Harleyquin stated in her log that she liked the unit cell activity for ionic compounds as it made more sense and to able to refer to it with the criss-cross method. Lesson 4 added polyatomic ions as the extension portion of the 5E and relied on the students remembering charges for main group elements. Calcium nitrate was used as an example to explain polyatomic ions to students and the way to write a formula unit when more than 1 polyatomic ion is involved. This code involved both the sub-micro (building and analyzing unit cells) and symbolics (extending their knowledge to balancing other compounds).

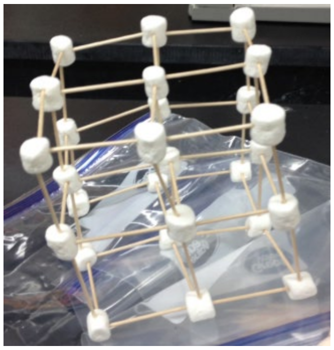


Figure 23. Student example of simple unit cells

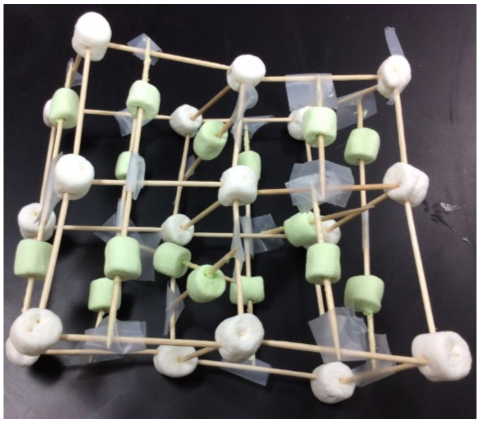


Figure 24. Student example of face-centered unit cell

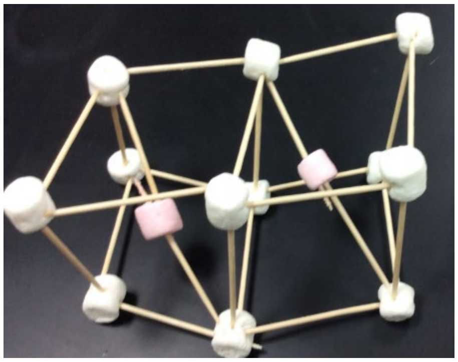


Figure 25. Student example of body-centered unit cell

For Question 9, 4 students (both Low Spatial – 361401 and 370401; 1 Medium Spatial -271701; 1 High Spatial - 231001) in their pre-interviews answered true meaning the compound would be ionic. The Low Spatial (361401) student explained their answer "cause they're coming together." The remainder of the students were not able to offer an explanation of their choice.

For their post-interviews with Question 9, 3 of the students (both High Spatial - 4410501 and 2331001; 1 Low Spatial – 361401) answered True meaning that an ionic compound can be formed from the given electron configuration. As the High Spatial student (4410501) stated: "because like this one has 7 valence electrons. Element C would have 2. So there would have to be 2 element Es for one to grab each one." The students who chose False did not provide an explanation.

For Question 17, 4 students (both High Spatial – 233201 and 231001; both Medium Spatial 232001 and 271701) answered ionic on their pre-tests but they were not able to explain their choice. The Low Spatial student (370401) answered covalent because "I was assuming they will share electrons which I think if I'm not mistake is uhh refers to covalent bonds."

With their post-test answers, students struggled to explain their choices for Question 17 with most not providing an explanation. 4 of the students (High Spatial – 441501; both Medium Spatial – 271701 and 232001; a Low Spatial student – 361401) answered ionic, the correct answer. The post-interview only High Spatial student (441501) thought ionic "cause I thought the electrons would have to be transferred." Ions are formed due to the transfer of electrons. On the other hand, the Low Spatial student (361401) answered ionic: "Because it's sharing electrons." The 2 students answering covalent did not provide explanations. Electron configurations similar to Questions 9 and 17 were not part of the new unit.

Question 18 had 4 of the students choosing B for their pre-test answer with only the High Spatial student stating they "were familiar with that model." None of the other 3 students provided an explanation. A Medium Spatial student (232001) chose A due to "xxs." A Low Spatial Student (370401) chose C (the correct answer) because of sharing. These pre-test answers show students thinking about their previous experiences.

For the post-test, Question 18 had 3 students (both High Spatial – 441501 and 231001; Low Spatial 370401) pick D which is a covalent representation. The Low Spatial student (370401) chose this answer "because that looks like overlapping which would be sharing their electrons when they react." Two students (Medium Spatial – 271701; Low Spatial 361401) chose B with the Medium Spatial student mentioning "It looked like something I had seen before. The 1 student (Medium Spatial- 232001) who chose the correct answer, C, stated that they had guess on this question. Students chose answers based on familiarity (seen before) and understanding of overlapping for structures. They did not relate the brackets back to ion formation, and brackets with Lewis Electron Dot Diagrams were not used with Elm as much as Ash.

The main difference between the Spatial groups for the Balancing Formula Unit Code was found for Question 9 for the post-interviews. The electron notation used in Question 9 was not covered in the unit. Carter, LaRussa, and Bodner (1987) found that students' spatial skills correlated for areas requiring problem-solving skills such as stoichiometry problems. The two High Spatial students both used math to determine that the formula would be correct based on the valence electrons and the resulting compound would be ionic. The other Spatial groups did not use math and provided explanations like: "I said it's false cause I looked at the configuration and just figured basically" (Low Spatial – 370401).

Dissolving Code.

For this study, the different solubilities and the solubility rules for ionic compounds in water was not discussed. Several ionic compounds can be dissolved in water such as sodium chloride while other ionic compounds such as silver chloride do not dissolve appreciably and are considered insoluble. The dissolving process connects all 3 vertices of Johnstone's triangle as a person can watch a solid disappear in water (macro), and represent the dissolving process by writing dissociation equations (symbolics) and/or drawing particle diagrams (sub-micro). Part III of the CBDDA was the main portion of the assessment dealing with dissolving, and the compounds for this part were all soluble in water.

Ionic compounds form a crystal lattice due to the electrostatic attraction between positive and negative ions. Water is a polar covalent compound meaning the covalent bonds within the water molecule do not equally share the electrons in the bond. In addition, the oxygen in water has two lone pairs of electrons causing the electron cloud to be denser around the oxygen giving it a negative pole than the two hydrogens creating a positive pole (Figure 26). When an ionic compound such as sodium chloride dissolves in water, the cation, sodium ion, is surrounded by the oxygen portion (negative) of water while the anion, chloride ion, is surrounded by the hydrogen portion (positive) of water. Each of these ions has a sphere of hydration formed as water molecules are surrounding the ions from every angle.

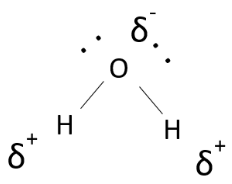


Figure 26. Water molecule – Polar covalent compound.

Question 15 involved water and classifying the bond type (polar covalent). This question was classified as Dissolving because the students had to differentiate between bond types and realize covalent compounds can have portions where the electron cloud is denser than other parts. The dissolving process can be represented using dissociation equations and particulate diagrams. Part III of the CBDDA contained both of these representations and were evaluated using the rubrics (Figures 9 and 10) discussed in Chapter 3 of this dissertation. Students were also probed about their answers for the first part of each dissolving scenario as they should have realized each compound was ionic and would separate into its individual component ions. Students were also asked to explain why one substance dissolved in water and another substance does not dissolve in water.

Ash Dissolving. While their logs did not discuss polyatomic ions or transition metal ions, the researcher saw precipitation reactions being covered using both polyatomic ions and transition metal ions. The timing of this visit was close to when students were being interviewed. No students changed their answers in their interview to Part III based on the precipitation reactions.

Ash teacher logs indicated that they used conductivity probes to determine the difference between ionic and covalent compounds for everyday samples. To do this type of activity, the ionic compounds had to be dissolved in water (preferably distilled). Rocky stated that she explain dissolving as water coming in between the ions and separating them. Some of her students did refer back to this definition to explain either their dissociation equations and/or their particulate diagrams. Ash students used a PhET molecular geometry simulation to relate molecular symmetry, electronegativity, and polarity. This activity reinforces the unequal sharing of electrons by water which would be useful to explain the dissolving process for soluble ionic compounds.

For the pre-interviews, 5 of the students answered polar, but none of the students could explain their choice. As the Medium Spatial student who chose nonpolar stated, "Cause I know it covalent, but I don't know if polar or nonpolar." All 6 students answered polar covalent. A Low Spatial student's (512001) explanation incorporated an ion: "because of the oxygen gains the two electrons to be the oxide ion, O^{2}". The student confused ionic and covalent. While students did not mention electronegative, a Medium Spatial student (511201) discussed the lone pair of electrons on the oxygen using a metaphor (S = student; I = interviewer):

> S: Cause when you draw it out it has the H and it has the 2 Os behind it has the little aliens on it which makes it.
>
> I: What do you mean by aliens?
>
> S: The two extra we forgot what they are called. *(Student made hand motions to show the two above what would be the O)* But I know what they are. They are just extra instead of being two complete pairs. They're like extra that makes it polar.

In their pre-interviews, Ash students guessed on the multiple-choice questions for Part III. They would also answer differently for the three scenarios such as split into individual molecules for potassium iodide and melt into the liquid phase for sodium hydroxide (Low Spatial student – 512001). For the post-interview, only one Medium Spatial student (511201) answered all three multiple choice questions ions, because "… I know water likes to tear things apart."

A High Spatial student (520801) answered separate into its component ions for potassium iodide and lead (II) nitrate, but they answered separate into its individual molecules for sodium hydroxide: "I did that because of the polarity of the water. I did that. Maybe like… I'm not sure if this is right. This is what I wrote I said the electronegativity helps to separate the hydroxide."

Ash students guessed for the dissociation equations for their pre-tests, but a High Spatial student (520801) attempted to utilize their previous knowledge:

> S: I knew kind of how to write out a chemical formula like. {*Student moves hands back and forth potentially indicating the transition from reactants to products]*
>
> I: Where did you learn that?
>
> S: Biology
>
> I: Biology
>
> S: Mainly from like photosynthesis…

During the post-interviews, students had a variety of answers. A High Spatial student (520801) thought that the reaction was a double displacement with both the potassium iodide and lead (II) nitrate reacting with water for each scenario. A Low Spatial student

(510601) had the compounds split into the individual elements and they used coefficients to balance the number of elements on the product side from the compound's formula for lead (II) nitrate. The other Low Spatial student (512001) wrote a second subscript for the nitrate ion, $NO_{3\,2}$ instead of using a coefficient in front of the ion.

Using the rubric in Figure 10, an individual dissociation equation can earn a score ranging from 0 to 4. After summing all the dissociation scores for a student, the maximum score possible would be 12, and the minimum would be 0. For all 3 equation summed scores, Ash's pre-test scores ranged from 0 to 2 with an average of 0.087 with only the High Spatial student (520801) achieving a total of 2. This student was interviewed for this research. The post-test scores ranged from 0 to 5 with an average of 0.739. Students admitted to guessing on dissociation equations in their pre- and post-interviews. Figure 27 contains examples for dissociation scoring.

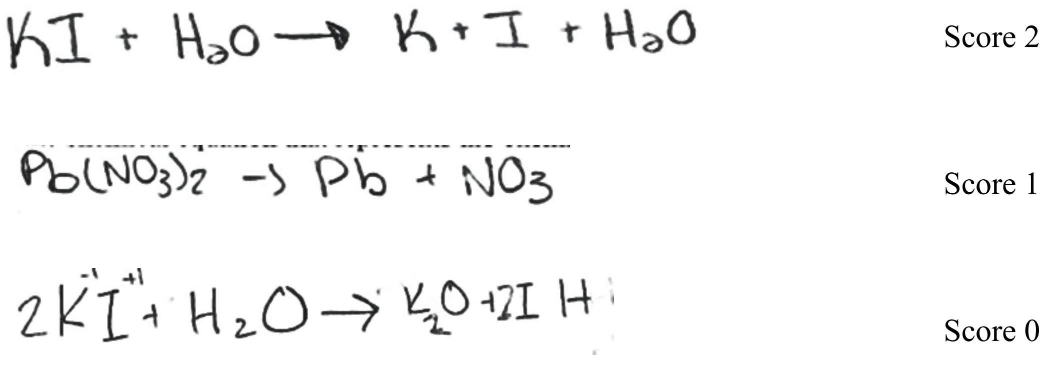


Figure 27. Ash post-test dissociation equations examples

The pre-test drawings were dots for most of the students interviewed, and they said their drawings were guesses. One High Spatial student (521801) did explain that their first drawing in the pre-interview was the compound initially and then separate apart in water. They explained that water was "Mickey Mouse molecules" per Rocky because water has ears. For the post-interviews, the students still stated that they were guessing and drawing how they would split per the dissociation equation with Medium Spatial student (511201) discussed drawing "like instead of doing them like bunny ears, I did them on the bottom because whenever we would draw them in class." A Low Spatial student (510601) mentioned that their drawing: "I just kind of showed them how they would kind of look roughly in like a beaker. Like if.. it said look in a microscope. You would see them kind of close together but they wouldn't be really combined."

Ash students referred to water in a certain orientation. The particulate diagrams were scored using the rubric in Figure 11. After summing all the scores for all 3 particulate diagrams, Ash students had pre-test scores ranging from 0 to 1 with an average of 0.043, and their post-test scores ranged from 0 to 7 with an average of 0.696. The highest score by an Ash student on a particle drawing was a 3. Figure 28 has examples of Ash particle diagrams scores.

For Dissolving, while the High Spatial student (520801) scored the highest for their dissociation equation. All students struggled with writing these equations. In addition, the particle diagrams were also difficult for these students. All of the students' explanations in the post-interview showed all groups were thinking deeply such as from a Low Spatial student's (510601) explanation for answering split into its atoms for lead (II) nitrate dissolving scenario:

> Cause like so NO_3 you know that's how many atoms are in that but then you have to multiply it by the 2. So NO_3 6. Oxygen is 6. I guess the oxygen would be

> the one with 6. So they would kind of break apart: Pb and the N wouldn't be combined into that one. Because they wouldn't be together.

While this explanation is incorrect, they were able to explain their answer. Only one student (Medium Spatial student 511201) provided the correct answer to all three multiple choice questions for the dissolving scenarios.

Score 3

Score 2

Score 1

Score 0

Figure 28. Ash post-test particulate diagram examples

Elm Dissolving. Lessons 1, 4 and 5 of the new unit are associated with the dissolving process. The phenomenon investigated in Lesson 1 was the difference between the conductivity of solid sodium chloride and dissolved in distilled water. Lesson 4 had students calculate the electronegativity difference between two elements to identify bond type. Students then drew Lewis Electron Dot Diagrams for methane, CH4, and water, H2O, comparing these two covalent compounds to distinguish between nonpolar (methane) and polar (water). Lesson 5 revisits water's Lewis Electron Dot Diagram. Students then use a portion of the sodium chloride lattice and a cup of water molecules from 3D Molecular Designs (n.d.). Students investigate which portion of water is attracted to the positive sodium ion and attracted to the negative chloride ion. These models refers to the sub-micro aspect of the Johnstone's triangle. The dissolution of an ionic salt video from Vischem (CADRE Design Pty Ltd & Tasker, R., 2010) can be using the following steps:

1. Access the website: http://vischem.com.au/
2. Click on the Online Resources menu at the top of the screen.
3. Scroll down til the Scootle site link is viewed. This link is above the "Types of Vischem Resources" title.
4. Another window will open with a variety of videos. Note these videos are not in numeric order.
5. Scroll down to the video title - M008653 VisChem topic 2: dissolution of an ionic salt
6. Click the title and another window will open. Click on the video which is about middle of the webpage and starts off as a blue screen with fish.

This video discussed the dissolving of sodium chloride by mixing salt with water (macro – Johnstone's triangle) and then had animation for dissolving sodium chloride at the particle level (sub-micro – Johnstone's triangle). Dissociation equations were also explained using this video (symbolics – Johnstone's triangle). Students mixed the sodium ions and negative ions rebuilding the sodium lattice. Students were to realize that a sodium ion is not linked to a specific chloride ion. Next, students were to classify different situations based on the conductivity that they had measured in Lesson 1 (solid sodium chloride, distilled water, and the solution of sodium chloride dissolved in water) as nonelectrolyte (low conductivity value < 50 μS/cm) or electrolyte (conductivity value > 50 μS/cm). Students were to apply their knowledge from the video and previous lessons to write dissociation equations and particulate diagrams. From Harleyquin's teaching logs, students did better on the dissociation equations than the drawing the diagrams. BSB and Cleo also stated in their teaching logs that students have a difficult time visualizing the particle level, sub-micro representation part of Johnstone's triangle (Figure 3; Johnstone, 1991).

For Question 15, 3 students (both High Spatial – 233201 and 231001; Medium 232001) in their pre-interviews answered covalent when asked about the type of bonding in water, but no one mentioned polar or nonpolar. With their post-interviews, only 3 students (both High Spatial -441501 and 231001; Low Spatial – 361401) answered the question correctly with polar covalent, but the Low Spatial changed their answer to nonpolar covalent "cause it's water." The High Spatial student's explanation highlighted the unequal sharing but mentioned energy instead of electrons:

> Oxygen has a higher electronegativity so umm when it covalently bond. It will covalently bond with the hydrogens in order to gets to its 8. Like electrons and fulfill its circle thing. And its polar because umm the electrons are going.. the energy more towards oxygen because it wants to have those and hydrogen is kind of like giving them up. So there would be a pole of energy on the oxygen.

A Medium Spatial student (232001) change their answer from ionic to polar covalent based on what they learned after the assessment but was not specific about the activity causing this change.

For Part III multiple choice questions, Elm students in their pre-interviews stated that they guessed for these questions and no students were consistent for all three questions. A High Spatial student (231001) answered separates into ions for both potassium iodide and lead (II) nitrate but melts for sodium hydroxide. The other students changed answers for the questions with several students choosing melting. For the post-interview, the High Spatial student (231001) was the only student answering separates into its component ions for all three scenarios with the following explanation for potassium iodide:

> I went with water would uhh want to bond to each of the ions and it would separate them in the water. Cause if the water surrounded the potassium and the io.. I can't talk.. Yeah if it surrounded the potassium and iodide then they wouldn't be able to combine and create new bonds.

A Medium Spatial student (232001) chose separates into ions for potassium iodide and sodium hydroxide scenarios. They related the dissolving of potassium iodide due to different solubilities of the elements which is incorrect, and they said they guessed for the sodium hydroxide. A Low Spatial student (361401) stated that potassium iodide splits into molecules because they are both metals which is also incorrect. The other students were not able to explain their choices for molecules or melting. None of the interviewed students chose separates into atoms.

The dissociation equations were rated using the rubric from Figure 10. One Low Spatial student (370401) commented for the potassium iodide combining with water: “That’s how I have seen it before.” They did not elaborate when or where. A Medium Spatial student (271701) incorrectly separated the lead chemical formula into P and b displaying a misunderstanding of element symbols. The other students stated that they guessed on this portion of the assessment in their pre-interviews. For their post-interview, a High Spatial student (231001) discussed the polyatomic ions not separating describing as: “like a whole thing cause the nitrate is the nitrogen and oxygen created its own thing that wouldn’t be broken apart.”

For the dissociation equations, the rubric from Figure 10 was used and a max score of 12 was possible. For the summed scores, Elm’s pre-test summed scores ranged from 0 to 5 with an average of 0.886, and the post-test summed scores ranged from 0 to 11 with an average of 2.48. Even though an Elm student was able to score 11, the average of the summed scores indicate that most students still did not understand dissociation equations.

$NaOH_{(s)} \rightarrow Na^{+}(aq) + OH^{-}(aq)$	Score 4
$Pb(NO_3)_{2(s)} \rightarrow Pb^{2+}(aq) + NO_3^{-2}(aq)$	Score 3
$KI \rightarrow K + I$	Score 2
$Pb(NO_3)_2 \xrightarrow{H_2O} Pb_2 + NO_3$	Score 1
$KI + H_2O \rightarrow K(H_2O)_6 + I(H_2O)_6$	Score 0

Figure 29. Elm post-test dissociation equations examples

Part III drawings for Elm were scored using the same rubric as Ash (Figure 11). The particulate drawings for the pre-interviews were dots/circles showing the molecules separating, but the students did state that these drawings were guesses. In their post-interview, a Low Spatial student (361401) stated that their drawing is showing how the formulas are separating in water. A Medium Spatial student (232001) mentioned potassium and iodide referring them to as cation and anion with their dissociation equations and then for their particle diagram: "I just showed the iodine and potassium together. And like when put them in water they.. they come apart."

The Elm particle diagrams were scored using the rubric in Figure 11 with a potential max score of 12. A High Spatial student (231001) and the no pre-interview High Spatial student (441501) from Elm discussed the portions of water attracted to the different parts of water. Elm students' pre-test scores ranged from 0 to 6 with an average of 0.278, and their post-test scores ranged from 0 to 12 with an average of 2.722. Only one student scored a 4 on all of their drawings.

For Part III of the CBDDA, differences between Spatial groups was noticed. Only a High Spatial student (231001) answered all of the multiple choice questions correctly for each dissolving scenario. In addition this student did not have the polyatomic ions splitting for their dissociation equations and drawings. The post-only High Spatial student (441501) drawing did show the attractions between water and the ions. A Low Spatial student (361401) only wrote the formulas for their dissociation equations and did not attempt to separate the formulas into the ions or elements unlike the second Low Spatial student (370401) and both Medium Spatial students (271701 and 232001). Thus, the High Spatial group provided more details and correct ion separation compared to the Medium and Low Spatial groups.

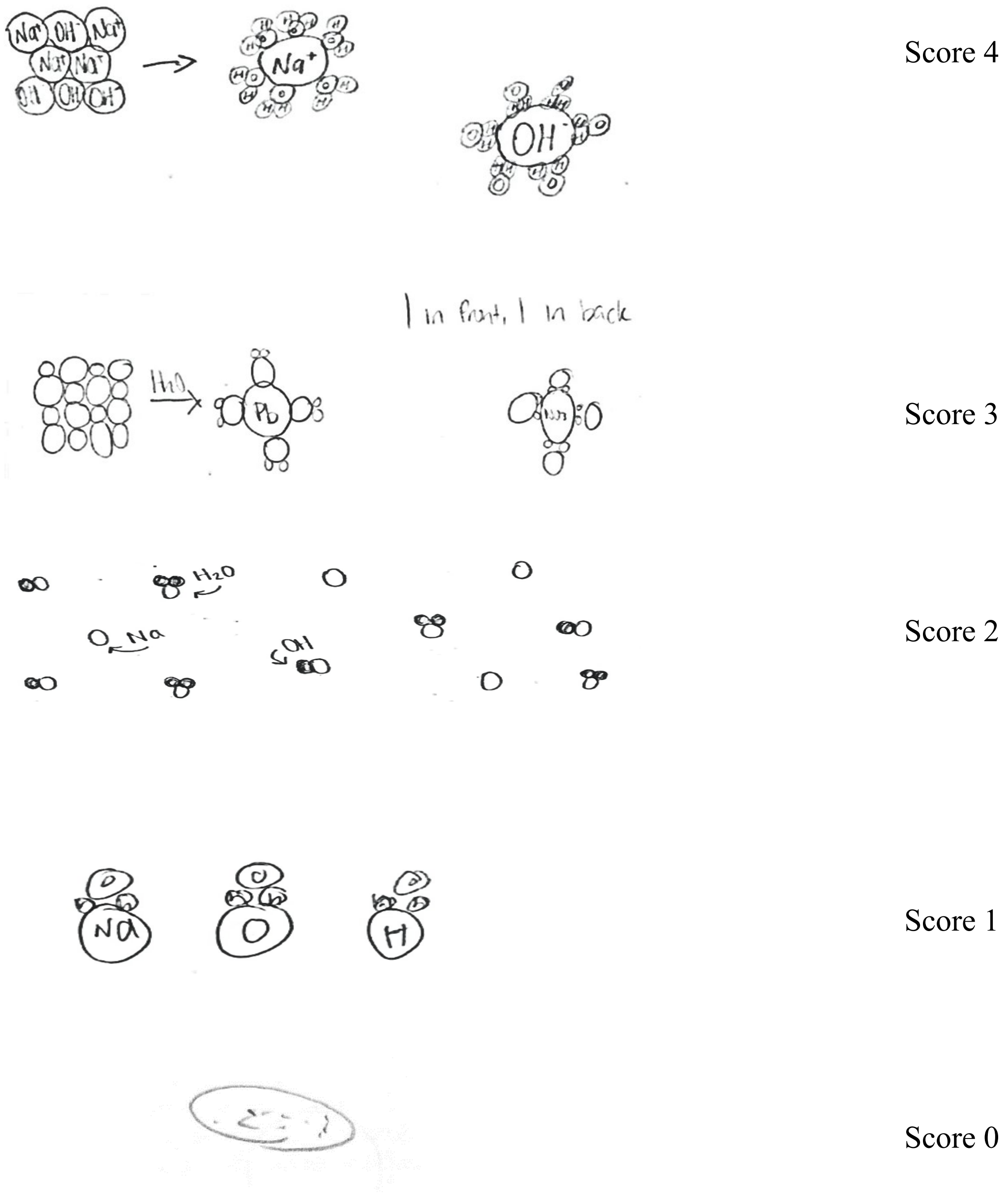


Figure 30. Elm post-test particulate diagram examples

Molecular versus Electrostatic Framework.

As the codes have compared the way the two schools taught the ionic bond and concepts related to it, this Research Question refers to the two frameworks that Taber (1997) compared (Table 1). The Role of Molecules status refers to ion pairs for the molecular framework. When Ash covered balancing the formula unit, they showed the transfer of electrons between cations and anions which can lead to the ions act as a molecule (Figure 18). This ion pair is a misconception for the formula unit and ionic compounds explored in literature (Ben-Zvi, Eylon, & Siberstien, 1986, 1987;. Boo & Watson, 2001; Coll & Treagust, 2002, 2003; Harrison & Treagust 2000; Othman, Treagust, & Chandrasegaran, 2008; Taber, 1994, 1997, 1998, 2002a; Taber, Tsaparlis, & Nakiboglu, 2012). Several games/activities in literature (Chimineo, 2000; Chimeno, et al., 2006; Kavak, 2012; Logerwell, & Sterling, 2007; Ruddick, & Parrill, 2012; Wirtz, et al., 2006), such also promote the ion-pair idea as Harrison and Treagust (2000) discussed that these games/activities serve as an analogy for balancing the formula unit. The electrostatic framework does not discuss ion pairs as part of ionic structures. In Lesson 2, Elm utilized ionic compound unit cells showing that cations and anions exist as part of a lattice with no set pairs of ions, but ions are part of a large structure. Students started this analysis by building their own unit cells (Figures 22, 23 and 24). From the researcher observations, students did have issues building and analyzing these cells which the teachers' logs also mentioned. The lack of prior configuration was addressed in Lesson 5. Part of the activity had students mix up the ions and rebuild the lattice. Then they were asked: When the lattice was assembled the second time, was every sodium ion connected with the exact same chloride ions from when you first assembled the lattice? From teacher conversations, the students appeared to understand that the ions are not paired together.

The Focus conjecture was evident for both schools. With molecular, the focus is more on the electronic configuration. Ash started with exploring electron configuration and the periodic table. They related ion formation with the octet rule. Ash utilized the electron transfer for forming ions and balancing the formula unit (Figure 18). Ben-Zvi, et al. (1986) and Taber (1994) found for textbooks and teaching resources. For the electrostatic framework, the lattice was explored initially in Lesson 3 by building different types of unit cells and analyzing ionic compound unit cells. The students then explored the lattice utilizing models and simulating the dissolving process of a sodium chloride lattice. Elm teachers' logs stated that the students did not have issues with the models in Lesson 5. While both the dissociation scores for Elm students increased from a pre-test average of 0.886 to a post-test average of 2.48 and particulate diagrams from a pre-test average 0.696 to a post-test average 2.722, the students' interviews did not relate to the dissolving process except for the no pre-interview High spatial student (441501) and the second High Spatial student (231001), because they both mentioned the different parts of water being attracted to different ion charges. For Question 5 of the CBDDA concerning the physical state of an ionic compound at room temperature, a Medium Spatial student (511201) mentioned a continuous pattern as part of their reasoning for choosing solid. Ash teachers may have had some of their activities linking to the electrostatic framework when they used a card activity to explore the differences between bonding types (metallic, ionic, and covalent).

The Valency conjecture status from Taber's comparison of the molecular and electrostatic frameworks refer to the number of bonds which can also be related to the way students learn about ion formation. Ash focused on the periodic table and the octet rule for ion formation. This strategy can cause students to link two oppositely-charged ions together with the potential of bond formation. Literature has shown that the octet rule has been a main focus for students' understanding of ion formation (Coll & Taylor, 2001; Coll & Treagust, 2003; Robinson, 1998; Taber, 1994, 1997, 1998, 2002a; Tan & Treagust, 2009; Waldrip & Prain, 2012). Covalent bonds (sharing of electrons) has been mistaken for ionic bonding which means that students confuse the sharing of electrons and the transfer of electrons for forming ions and thus the attractions between ions (Coll & Taylor, 2001; Coll & Treagust, 2002, 2003; Luxford & Bretz, 2013; Robinson, 1998; Taber, 1994, 1997, 1998, 2002a). All of the Ash interviewed students were able to answer Question 3 correctly in the post-interview about electrons being transferred to form ions with some students mentioning the octet rule concept in their interviews, but they had focused on this concept in several different activities besides ion formation. The electrostatic framework concentrated on the number of bonds depending on the coordination number. While the coordination was not explicitly covered in the new unit, the students were exposed to the fact that cations are not linked only to the number of anions to balance the formula unit using the unit cells of ionic compounds and dissolving plus reforming an ionic lattice using the magnetic models of sodium chloride plus water.

For the History conjecture, Ash had shown the electron transfer for the balancing of the formula unit (Figure 18) which was discussed with the Role of Molecules status for the molecular framework. The electrostatic framework has electrostatic forces being dependent upon charge magnitudes and separation (Columb's law). No mention of Columb's law was made in the teachers' logs. Ash students did not describe charge and distance in their pre- and post-interviews. For Elm, Columb's law was part of Lesson 4 with student having to exploring the equation for different charges and different distances between ions. Columb's law is part of the NGSS in HS-PS2-4 addressing electrostatic forces between distant objects (NGSS Lead States, 2013). Students have a tendency to think ionic bonds as weak (Coll & Taylor) which Question 5 showed that some students thought that ionic compounds are liquids or gases at room temperature. Question 11 should also have given an indication of the strength of ionic compounds due to a high melting point such that magnesium oxide can be used to line the walls of a furnace. Unfortunately, some students from both schools did not think that the resulting ionic compound formed from magnesium and oxygen would have different physical properties than the individual elements as oxygen and flammability was mentioned. In addition, the mixing of the sodium chloride ions to reform a new lattice activity in Lesson 5 addressed that electrostatic forces do not depend upon a prior configuration.

The 'Just forces' conjecture for the molecular framework limits an ionic bond being between the ions within one formula unit. These ions may be attracted to other ions but no bond formed. Figure 18 again shows the balancing of a formula unit which potentially could restrict Ash students' thinking to the ion-pair. Even though some of the students mentioned a continuous pattern for an ionic compound they were not able to explain this continuous pattern. For the electrostatic framework and Elm, students' did not mention electrostatic forces with their definitions of an ionic compound even after experiencing unit cells for different ionic compounds. Students from both Ash and Elm struggled with the concept of ionic bonds and vocabulary associated with different bond types such as molecules.

Research Question 2

This Research Question explores overall Spatial differences between Ash and Elm. Subcategories such as spatial visualization, spatial orientation or spatial relation as discussed by Gilbert (2005) were not coded and analyzed for this study. The code Spatial was used to answer this Research Question with the data sources of teachers' log about activities, Part III of the CBDDA (dissociation equations and particulate diagrams), students' interviews, and researcher observations. For this Research Question, the content aspect of examples was utilized to explain the spatial aspects of the material, but this does not mean students always visualize the material in this way.

Spatial Code.

Particulate Diagrams require students to be able to visualize elements/ions/compounds at the atomic/molecular/ionic level and processes such as dissolving. Students basically draw their thinking. These diagrams represent the sub-micro aspect of Johnstone's triangle (1991). Lewis Electron Dot Diagrams are another way to represent elements/ions/compounds. These diagrams intersect the symbolics and sub-micro representations of Johnstone's triangle. Element symbols are utilized to represent the atoms/ions for a specific element. Valence (outer shell) electrons are depicted as dots. These dots can be used to indicate bonds between atoms, the transfer of electrons to form ions, and lone pairs of electrons (extra electrons not involved in bonds).

Ash Spatial. The teachers from Ash covered several concepts utilizing activities requiring students to visualize but not every activity had a spatial aspect. Students learn to correlate valence electrons for a main group element with their position on the periodic table. With defining the octet rule, the teachers showed the way main group elements can obtain an octet by losing or gaining electrons using Lewis Electron Dot Diagrams. The Ash students interviewed answered Question 3 about forming ions correctly with transferring on the CBDDA, but they could not explain why this transfer. Some students did mention the octet rule in their interviews. Next, students drew Lewis Electron Dot Diagrams for ionic bonds. Figure 18 shows an example of these diagrams. A High Spatial student (520801) employed this concept in attempt to solve Question 9 (Figure 21) and Question 17 (Figure 22). Ash teachers covered developing Lewis Electron Dot Diagrams for covalent compounds by illustrating the steps and then spending the next 2 days practicing this subject. Then taking a quiz about Lewis Electron Dot Diagrams for ionic and covalent compounds.

Student then explored different substances' conductivity to classify compounds. While Rocky mentioned that water acts as a curtain to separate ions, the exact dissolving process (macro and sub-micro for Johnstone's triangle) was not covered in their classes. By not covering the dissolving process, no Ash student received a score of 4 on the particulate diagrams from Part III of CBDDA. Rocky's explanation of water separating the ions had students visualizing the particles in water which can be related to the sub-micro representation of Johnstone's triangle. The last activity utilized a pHet molecular geometry simulator relating structure symmetry, electronegativity, and polarity of a compound. In their post-interviews, Ash students answered Question 15 of CBDDA polar covalent for the bonding within a water molecule, but their explanation in their interviews did not include electronegativity.

The 3 particulate diagrams of Part III of CBDDA were scored using the rubric from Figure 11. These scores were summed. The minimum sum would be 0 and the maximum sum would be 12. Ash students' pre-test of the 3 diagrams summed had an average of 0.043 with a range of scores from 0 to 1. The post-test summed scores had an average of 0.696 with a score range of 0 to 7, but no student obtained a score of 4 for any of the 3 diagrams for their post-test.

Elm Spatial. The new unit's activities were designed to make students to visualize from Lesson 1 with students having to draw sugar and table salt (sodium chloride) dissolving in water. Students had trouble drawing their ideas. They asked their teachers if their drawings were correct and for the correct answers. For Lesson 2, students had to model elements and ions using posterboard and squares representing protons/neutrons/electrons. Students also graphed periodic trends. They were to analyze ionization energies for cation formations. Students had a difficult time grasping that they were supposed to be looking for large jumps in the ionization. Lesson 3 had students building crystals. Students spent 2 days building crystals and were to analyze ionic compounds unit cells to develop the appropriate formula unit. From the researcher observation and discussions with Elm's teachers, students struggled with analyzing the unit cells and needed help. After the study was completed the teachers taught the criss-cross method for balancing formula units. Harleyquin in discussion with the researcher that students asked why they were not taught this way and she explained that this was a shortcut of what they were doing with the unit cells. Lesson 4 introduced students to Lewis Electron Dot Diagram for polar and nonpolar covalent compounds. This activity had student review water as a polar covalent compound which was revisited in Lesson 5. Students then modeled the dissolving process for sodium chloride using models containing magnets such that the opposite poles of magnets have the negative portion of water (oxygen) attracted to the sodium ion and the positive portion of water (hydrogen) attracted to the chloride ion. Even with these visual activities, the score for the PVST-Rot decreased for Elm.

Part III of CBDDA had 3 diagrams using Figure 11 to score. Elm's students were summed such that the minimum of 0 to the maximum of 12. For the particulate diagrams, Elm's students showed a range of scores from 0 to 6 for their pre-test scores and from 0 to 12 with their post-test scores. The average for pre-test particulate diagrams was 0.278 and the post-test particle diagram average increased to 2.722. Elm students were able to score 4 on their particulate diagrams (Figure 30).

Summary of Findings

For Research Question 1, explored the different codes developed from the data sources collected with this study. These codes were explained in terms of ionic compounds and/or the dissolving process for ionic compounds. Students did mistake covalent bond theory (sharing of electrons) with ionic bond theory similar to the literature (Coll & Taylor, 2001; Coll & Treagust, 2002, 2003; Luxford & Bretz, 2013; Robinson, 1998; Taber, 1994, 1997, 1998, 2002a). The octet rule was a focus for Ash's ion formation while Elm focused on ionization energy for cation formation. The octet rule was further emphasized in Ash due to the drawing of Lewis Electron Dot Diagrams for covalent compounds (symbolics). In the post-interviews, some students from both schools mentioned the octet rule. Unfortunately, Elm students did not refer to their lessons with their explanations in the post-interviews. Some of this may be due to the CBDDA being the only assessment that Elm students were given, while Ash had a quiz and a separate assessment as part of their unit. Thus, Ash students may have studied the material more.

The dissolving aspect of the CBDDA did favor Elm students because they did cover this with Lesson 1 and 5. For the multiple choice question portion for Part III of the CBDDA, only 1 Ash Medium Spatial student (511201) and 1 Elm High Spatial student (231001) answered separates into its component ions for all 3 scenarios. In the post-interviews, students may have chosen molecules due to not understanding the definition of molecule. This definition was not covered in the Lessons of the new unit, and the teaching logs for Ash does not mention making the distinction between ions and molecules. Some students from both schools chose melting with their pre- and post-test. These students were unable to explain why they thought melting was correct except some related the hydroxide ion with water due to the similarities in the chemical formula (H_2O and OH^-). Students confuse dissolving with melting as they do not understand the distinction between the two processes (Adadan & Savasci, 2012; Ebenezer, 2001; Ebenezer & Erickson, 1996; Othman, Treagust & Chandrasegaran, 2008; Smith & Nakhleh, 2011).

Naah and Sanger (2012) discussed issues with the dissociation equations and the fact that these equations represent the dissolving process which can be classified as a physical change because the ionic compound can be recovered by evaporating water. Students from both Ash and Elm made some of the same errors with as the students from Naah and Sanger's (2012) study such as water reacting, missing/incorrect charges, and splitting the polyatomic ions. No students from Ash received a Score better than a 2 on their post-test dissociation equations using the dissociation rubric in Figure 10. While some students from Elm received Scores of 3 and 4, the low post-test average of 2.48 for the sum of all 3 dissociation scores indicates that the majority of Elm students did not do well on these equations.

Students also had issues with drawing the particulate diagrams. No Ash student scored a 4 on their diagrams. While some of Elm students did score 4 on their diagrams, again the low post-test average of 2.722 indicates that students still struggled with these drawings. Students' struggles with particulate diagrams had been previously studied (Ebenezer, 2001, Kelly & Jones, 2007,2008; McBroom, 2011; Naah & Sanger, 2012).

To answer Research Question 2, both Ash and Elm had activities that helped to develop their spatial skills. The researcher was surprised as the Ash teaching logs were reviewed for activities which required students to visualize and apply knowledge including having students draw the transfer of electrons to form an ionic compound. A High Spatial student (520801) from Ash utilized their knowledge to answer Question 9 and Question 17 by attempting to draw the transfer of electrons. In addition, Ash students covered covalent compound formations by having to draw Lewis Electron Dot Diagrams and utilizing pHet for molecular geometries and polarity of compounds. These different representations for covalent compounds agree with Kozma et al. (2000) findings that chemists need the skills to move between different representations to explain concepts. The new unit employed at Elm also attempted to utilize different representations with the building plus analyzing unit cells, Lewis Electron Dot Diagrams, graphing of periodic trends, modeling ion formation using the Bohr theory, and exploring the dissolving process with 3D Molecular Designs water kit plus sodium chloride lattice. Literature has found that students who can draw and visualize models perform better on chemistry exams (Harle & Towns, 2010; Pribyl & Bodner, 1987). None of the Elm students mentioned in their interviews any of the modeling that was done to improve their spatial skills. The Elm teachers also mentioned in their teaching logs that they were amazed by students having issues visualizing the fraction of the marshmallow for a unit cell, deriving a formula unit from an ionic compound's unit cell, and drawing dissolving particulate diagrams.

Ash students did not do as well as Elm students on Part III of the CBDDA which required them to be able to write a dissociation equation for a scenario and draw a particle diagram. During the pilot study with a University General Chemistry II course, the experienced Chemistry lecturer and the researcher discussed issues that the General Chemistry students had with the dissociation equations and particulate diagrams. Copolo and Hounshell (1995) discussed that students can be confused by the different representations in chemistry. During their interviews, several students from both schools did indicate that they were guessing for dissociation equations and their drawings. This study confirmed that students are not able to apply representations to explain concepts such as dissolving (Ben-Zvi, et al., 1986; Nakhleh & Mitchell, 1993; Treagust, et al., 2003). Students struggled with explaining their drawings and the teachers were surprised at the different student drawings as the CBDDA was collected. Literature confirms this challenge of having students represent chemical concepts using particle drawings (Davidowitz, et al., 2010; Kern et al., 2010; Nyachwaya et al., 2011; Naah & Sanger, 2013; Sanger 2005).

CHAPTER 6. DISCUSSION

The purpose of this study was to compare students' understanding for the ionic bond, ionic formula unit, and dissolving of ionic compounds between students who utilized a new unit based on Taber's (1997) electrostatic framework and students using a more molecular framework. In addition, students' spatial skills between the two groups were compared as the new unit utilized different activities especially with balancing the formula unit for an ionic compound (exploring crystal unit cells) compared to Lewis Electron Dot Diagrams and the criss-cross method. As part of the development for the new unit, a review of Performance Expectations (PE) of the Next Generation Science Standards (NGSS; NGSS Lead States, 2013) was performed for Ionic Bonding (Table 4), Structure and Properties of Matter (Table 5), and Chemical Reactions (Table 6). A final learning progression (Figure 6) was developed, and the High School PE were considered with the development of the 5 lessons for the new unit. In Appendix C, Table 14 lists the lessons with the appropriate PEs. The new unit utilized Johnstone's triangle with designing the activities. Macro representation was covered with the initial phenomenon of the dissolving and measuring conductivity. Sub-micro was covered with modeling the electron shells with Bohr theory, the unit cells, the water plus sodium chloride magnetic models, and the particle diagrams. The symbolics representation was covered with the ion formation, balancing formula units from the unit cells, and dissociation equations.

A concurrent parallel design (Criswell, & Plano Clark, 2007) was utilized with this study. The quantitative and qualitative data was gathered simultaneously. The quantitative data involved pre/post-test scores from the CBDDA and the PVST-Rot (Bodner & Guay, 1997). The qualitative data included pre/post-interviews with students of varying Spatial skills (2 Low, 2 Medium, and 2 High) from each school. Classroom observations and teacher discussions were also utilized. Finally, teacher logs for both schools was another data source, and these logs covered the activities covering the topic of ionic bond, ionic compounds, and dissolving of ionic compounds. This chapter examines the results for qualitative and quantitative data for each of the Research Questions. Johnstone's triangle was used as the conceptual framework to analyze answers and activities. Limitations and potential future research will be discussed in this chapter.

Discussion of Research Question 1

Research Question 1: How does the understanding of the ionic bond and dissolving of ionic compounds in water compare for students using a unit focused on an electrostatic framework to students utilizing a molecular framework (business-as-usual) related to their spatial ability and using the spatial ability as a covariant with treatment group?

The quantitative and qualitative results for the content helped explore students' understanding of the ionic bond, balancing the formula unit, and dissolving ionic compounds between the two groups. Johnstone's triangle was the conceptual framework used to analyze the activiites and interview answers. The findings did show some differences between the two groups understanding and where each group excelled with certain concepts. While initially, the thought that the Elm students with the new unit would do better with the concepts than Ash students with the business-as-usual methods, Ash students did show that they did understand and apply some of the techniques to answer questions.

The multiple linear regression model to predict the post-test score for the CBDDA found both the student's pre-test score and the treatment group (new unit-Elm versus business-as-usual-Ash) to be significantly different. Two of the independent variables (gains in spatial skills and a covariate of spatial gains * treatment group) were not found to be significant for this model. Thus, the post-test score was not dependent on the spatial score but only on the pre-test score and if they were in the new unit group or business-as-usual group. For one unit increase in pre CBDDA score, the increase in post CBDDA score is estimated to be 0.492 on average holding all other variables in the model statistically constant. For a student in the treatment group, the increase in post CBDDA score is estimated to be 3.523 on average holding all other variables in the model statistically constant. This model indicates that a student being in the new unit has the potential to increase their score over a student in the business-as-usual group.

Six students from each school were interviewed with 2 students scoring in the top 25% on PVST-Rot scores, 2 in the middle 50% PVST-Rot scores, and bottom 25% on PVST-Rot scores. An extra student was added to Elm because one of the High Spatial students ceased attending. No reason was given to the researcher for this student's lack of attendance. Six students were interviewed for pre and post for each school

Students from both groups (3 out 6 Ash students; 2 out of 7 Elm students) did refer to information from previous courses. Biology was the main course mentioned by the 3 Ash students and 1 Elm student. One Ash student referred to their Freshmen year course. Reviews of other Science courses taken by students was not part of this study, but several Chemistry topics are included in Biology courses to cover topics such as ion pumps, photosynthesis, and metabolism. This previous knowledge is a limitation of study and should be investigated in future research. Additionally, NGSS Performance Expectations (NGSS Lead States, 2013) were developed based on learning progressions of topics. While NGSS was adapted by the state after these students had started their education, some learning progressions were in place in order to cover topics in other Science courses. A NGSS learning progression was developed for this research, but the mention of Biology to explain topics show that more research into previous courses should occur.

From the qualitative codes for this research question, students did struggle with their explanations for both Part II and Part III of the CBDDA. Part II of the CBDDA could be answered correctly by both schools after reviewing Ash teachers' logs and the new unit used by Elm. With the post-interviews, students were asked to provide an explanation for their answers to the first tier to gain more insight into the students' thinking. In their post-interview, all of the interviewed students from Ash answered Questions 3 about electrons being transferred for forming ions correctly and they did not use the octet rule as part of their answer, but no one from either school mentioned ionization energy for forming ions. An Elm Medium Spatial student (232001) mentioned 8 valence electrons. Students from both schools struggled with Questions 9 and 17. Part of these questions had the students use electron configuration to determine whether or not an ion would form and the charge for this ion before they balanced the formula unit. Question 9 had a representation that the students were not familiar which may have caused issues, but Ash had a High Spatial student (520801) actually attempt to draw their answer (Figure 21). Rocky and Trek from Ash focused on using Lewis Electron Dot Diagrams to explain the balancing of the formula unit. This technique focuses mainly on the symbolics aspect of Johnstone's triangle and the sub-micro with the electron subatomic particle transfer. For their post-interviews, the Elm High Spatial student (233201) and the Elm no pre-interview High Spatial student (271701) used math and the valence electron to determine the formula unit. Once Elm students had visualized the lowest whole number ratio of cations to anions, they were supposed to utilize that knowledge with math to determine the formula unit for several examples in Lesson 3 incorporating sub-micro and symbolics aspects of Johnstone's triangle. Literature does state that students tend to focus on the octet rule (an algorithm) and not ionization energy for forming ions and balancing the formula unit (Coll & Taylor, 2001; Coll & Treagust, 2003; Robinson, 1998; Taber, 1994, 1997, 1998, 2002a; Tan & Treagust, 2009; Waldrip & Prain, 2012).

With Part II, students from both schools used vocabulary incorrectly such as molecule, atom, and compound in their explanations. To distinguish between the different types of particles, students should be able to visualize these particles to distinguish the differences between the particles (sub-micro representation). Due to the incorrect answers, the researcher found it difficult to determine if students were grasping for words or if they did not understand the vocabulary. Students from both schools answered True for sodium chloride is a molecule (Question 7). From literature, students have a tendency to confuse ions and ionic compounds as molecules (Ben-Zvi, et al., 1986, 1987;. Boo & Watson, 2001; Coll & Treagust, 2002, 2003; Harrison & Treagust 2000; Othman, et al., 2008; Taber, 1994, 1997, 1998, 2002a; Taber, et al., 2012)). An assumption for the new unit was that this terminology had already been covered, but more focus on the difference in terminology is needed. Additionally, students either did not understand or read Question 11 correctly due to extension of an element's physical properties (oxygen – need for a fire) and a compound's physical properties. The difference between elements and compounds was not part of either the new unit or Ash's activities. This difference can be aligned with the sub-micro aspect of Johnstone's triangle.

This research study encountered the same misconceptions as reported in literature. Students from both schools still had difficulty with distinguishing between ionic and covalent bonds (Coll & Taylor, 2001; Coll & Treagust, 2002, 2003; Luxford & Bretz, 2013; Robinson, 1998; Taber, 1994, 1997, 1998, 2002a). With the ionic bond definition, students still referred to the transfer of electrons (Ben-Zvi, et al., 1986, 1987; Taber 1994) which deals with ion formation. Another explanation for students answering False for Question 11 besides oxygen being required for a fire was they thought an ionic bond was weak which is a misconception (Coll & Taylor, 2011).

The initial phenomenon and new unit driving question dealt with the difference in conductivity between solid sodium chloride and a sodium chloride solution. Due to this phenomenon, the new unit included activities to explain the dissolving process for an ionic compound (Lesson 5). The dissolving process in water has some ambiguity, because the process can be thought as both a physical and chemical change or as a physical change only as Naah and Sanger (2012) discussed. Since a new substance is formed due to ions separating, dissolving can be classified as a chemical change, but the water can be evaporated to recover the solid which would classify it as a physical change. Dissolving in water can be further complicated due to the fact both polar covalent and ionic compounds are miscible causing students to have difficulties explaining both situations (Ebenezer and Gaskell, 1995).

Students from Elm did better on this portion of the assessment than Ash students, because Elm did cover the dissolving process. The dissolving process involves all 3 representations covered by Johnstone's triangle with the actual solid dissolving - macro, the dissociation equations – symbolics, and the particle diagrams – sub-micro. Ash did perform conductivity experiments on different substances to distinguish between ionic and polar covalent compounds (macro). Rocky did explain to her class that water acts as a curtain separating different ions. Only two Elm students (High Spatial student 231001 and the no pre-interview High Spatial student 441501) were able to explain the dissolving process in terms of ions being attracted to the oppositely charged portions of water. For the dissociation equations, Elm students' post-test scores ranged from 4 to 0 (Figure 29) and Ash students' post-test scores ranged from 2 to 0 (Figure 27) using the dissociation equation scoring rubric (Figure 10). The dissociation equations from both schools still had the same misconceptions as encountered in literature: water reacting, missing/incorrect charges, subscript errors, polyatomic ions separating, atoms not balanced, and charge not balanced (McBroom, 2011; Naah and Sanger, 2012).

Particulate diagrams were drawn by students for 3 different dissolving scenarios. Elm students' post-test scores ranged from 0 to 4 (Figure 30). Ash students' post-test scores ranged 0 to 3 (Figure 28). These students had difficulty drawing particulate diagrams similar to literature (Smith & Nakhleh, 2011). The teachers from both schools were amazed by the students' struggles with these diagrams. Both sets of teachers mentioned trying to incorporate these and similar particulate diagrams into their work.

More research about the activities high school teachers use to cover the sub-micro aspect of the Johnstone's triangle compared to the symbolics. From the Ash activities, the teachers focused on symbolics with Lewis Electron Dot Diagrams with analyzing molecular geometries for the sub-micro vertex.

Not every code had differences between the Spatial groups for the schools such as the ion formation code for Elm had both High Spatial students and a Medium Spatial student having a more in-depth explanation for their transfer of electrons answer compared to the Low Spatial students who either did not offer an explanation or simply "pulling" for sharing, For Ash, balancing of the formula unit code demonstrated a difference between the spatial groups with a High Spatial student (520801) attempting to draw the electron exchange between the elements to solve the problem. The other students did not talk about this electron exchange with their answers.

Discussion of Research Question 2

Research Question 2: How do spatial visualization skills compare for students using an electrostatic framework and students focused on a molecular framework?

From the multiple linear regression model, the pre-test score on the PVST-Rot was a predictor of the post-test score. The Treatment group (Ash versus Elm) was not found to be a predictor. The multiple linear regression model did support the null hypothesis that there would be no difference between the new curriculum unit (electrostatic- Elm) and the business-as-usual (molecular – Ash) spatial scores as this part of the model was not found to be significant. To interpret the constant, a student who is in the control group with zero spatial gains and a zero score for the pre CBDDA, the increase in post CBDDA score is estimated to be 2.326 on average. For a student with a pre PVST score of 0, the post PVST score was 3.331 points. For a one unit increase in pre PVST score, the post PVST score increased by 0.694 points holding all other variables in the model statistically constant.

When the new unit was developed, several activities were developed that required students to analyze 3-dimensional models (unit cells and using models for the dissolving process), 2-dimensional models (Lewis Electron Dot Diagrams and ionic compound unit cells), and graphs (periodic trends). After reviewing Ash teachers' logs, they also had students perform/participate in spatial-related activities including drawing 2-D Lewis Electron Dot Diagrams and reviewing molecular geometries for compounds' polarity. For low spatial ability students, Pribyl and Bodner, (1987) indicated that organic chemistry can be difficult due to the variety of images/diagrams required to learn different concepts. Lewis Electron Dot Diagrams and molecular geometry are utilized in organic chemistry. These representations require spatial ability (Harle & Towns, 2010).

With Part III of the CBDDA, students were required to utilize the different representations of Johnstone's triangle (Figure 3, 1991) by experiencing dissolving and/or measuring the conductivity of different substances (macro), representing the dissolving process with dissociation equations (symbolics), and drawing the particulate diagrams of the solution with an ionic compound (symbolics and sub-micro). Students did struggle with writing the dissociation equations and particulate diagrams as they require spatial skills. For both schools, students mentioned that the compound separates but did not provide an explanation for why the compound separates. From Elm, a High Spatial student (231001) and the no pre-interview High Spatial student (441501) discussed the attraction between the portions of water and the ions. While textbooks may have these diagrams (sub-micro), teachers may not always focus on these but rather the symbols (symbolics) and real-world explanations (macro).

Even though the quantitative portion of this research question was not significant for the difference in groups, different representations are needed to explain and understand Chemistry concepts as Kleinman, et al. (1987) discussed that faculty utilized more abstract images when explaining chemical concepts. Spatial ability with chemistry can also assist with concepts that require little spatial ability such as stoichiometry (Bodner & McMillen, 1986; Carter, et al., 1987). Wu and Shah (2004) hypothesized the ability to visualize a problem's solution path is related to a student's spatial ability.

Limitations

1. Convenience sampling and not random was utilized with this study. This study had two groups (schools) utilizing two teaching methods. Students were placed into a group based on their school.
2. The sample size differences between Ash and Elm may cause issues with the data as for every 1 Ash student there was 3.6 Elm students.
3. The pilot study had this study's researcher and an experienced University General Chemistry lecturer scored the dissociation equations and particulate diagrams for interrater reliability. This study's researcher was the only one to score Ash and Elm students' dissociation equations and particulate diagrams. This scoring took place after the pilot study had been completed.
4. This study's researcher is the only who transcribed and coded the data for the qualitative portion of this dissertation. The coding reliability may be affected by not having additional scorers.

5. The dissolving process was part of the initial phenomenon for the new unit and was covered by Elm students. Ash students did measure the conductivity of different solutions, but the dissolving process was not covered in great detail which could cause lower scores for the dissociation equations and particulate diagrams of the CBDDA. This highlights the conundrum of the findings: Is it the new intervention or the content addressed? The assessment was more aligned to the new curriculum.
6. The researcher attempted to attend the classes covering the material involved with this study, but not all classes were observed. Elm teachers were instructed to follow the 5E plans and if there were issues to note these in their teacher's logs. The Ash teachers were also instructed to describe their activities in their teaching logs. By not being able to observe all the teachers, some data was missed and not included in this study.

Future Research

After reviewing and analyzing this study's data, several improvements to the new unit can be made assist with covering the concepts. Some of these improvements are due to observations and comments from the teachers' logs. Others are due to reflecting upon the content Ash covered in their activities.

The building of the unit cells with marshmallows was difficult for students. From the researcher's and Elm teachers' observations, students appeared to be more focused on the building process than analyzing these initial unit cells. For future implementations, pre-built unit cells may help to streamline this unit and focus students on analyzing the unit cells. In Lesson 2 of the new unit, students modeled ion formation using the Bohr theory. According to discussions with Elm teachers, students had already covered this material earlier in the year. This activity may be moved from this Lesson for time issues, but the teachers have to remind the students after the periodic trends about ion formation with ionization energies and electron affinities as 2 of the students from Elm still answered sharing electrons occurs with ion formation.

Ash students had additional assessments and a review of their activities as part of their unit before the CBDDA post-test was administered. Another assessment directly over the content and a review of material may help with students' retention of the material. The new unit covers a large amount of material, and a review at the end may assist students to make connections between the different activities.

Due to the Ash student interviews and spatial scores, more Lewis Electron Dot Diagrams for covalent bonds should be considered as part of the new unit. In Lesson 4, the Lewis Electron Dot Diagrams was introduced, but this topic was not covered in depth like was done in Ash. Also, discussions with High School Chemistry teachers about the extent that molecular geometry is covered in their classrooms. These diagrams and molecular geometry show the polarity of covalent compounds assisting with understanding of dissolving for both polar covalent and ionic compounds in water. Students' spatial skills may improve by including more of these diagrams and molecular geometry as both Pribyl and Bodner (1987), and Harle and Towns (2010) indicated in their research.

The interviews for this study involved students' answers for CBDDA questions (Part II and III), ionic bond definition, and substances dissolving or not dissolving. Students struggled to answer questions about the dissociation equation and particulate diagrams. For future research, video in-depth interviews covering different dissolving scenarios should be performed to elucidate students' thinking about dissolving after the unit and asking specific questions about the water and the ions. Other questions to consider:

1. Ionic compound unit cells analyzed by the students for the formula unit to determine if there is a potential correlation between spatial skills and content.
2. Students explain the formula unit meaning and steps for balancing the formula unit. For the meaning, the answers should be reviewed for any connections to the ionic compound's unit cell and the lowest whole number ratio of cations to anions. The steps with balancing a formula unit answers examined for using either the criss-cross method, the Lewis Electron Dot Diagrams like Ash teachers used, or mathematical steps.

A future research project concerning Chemistry teachers' activities for covering the ionic bond plus the meaning and method for balancing an ionic compound's formula unit has to be considered as this information can provide insight to the teachers' background knowledge. With this project, the initial phenomenon used by the teachers to investigate different bond types will be gathered. With NGSS, initial phenomenon investigation and explanation is the driving force for covering PE and concepts. Interviews about their analysis of ionic bond unit cells for a formula unit correlated with their spatial skills can also be investigated. Also, more information about other Science courses in the schools should be investigated as 3 out 6 Ash students and 2 out of 7 Elm students referred to their previous knowledge in their interviews.

Another attempt of comparing the new unit with the business-as-usual has to be done with hopefully a more equal sample between the two groups. For this study, Ash student numbers were less than Elm. When the Ash teachers were first approached, they thought students would be interested in participating, but this did not occur even though the researcher recruited in-person. The students were told that the researcher was interested in exploring their understanding of ionic compounds when the assent and consent was distributed.

Conclusion

This research study was the first attempt at teaching a new unit using Taber's (1997) electrostatic framework and comparing students' learning to students who experience business-as-usual teaching. This project's significance was having the students first understand the balancing of the ionic formula unit by examining unit cells instead of introducing this concept using the criss-cross method or showing the transferring electrons with Lewis Electron Dot Diagrams.

The final multiple linear regression model for Research Question 1 was found to be significant based on the students' group. Students' explanations for Part II of the CBDDA showed some differences between the two groups with Ash doing better on both ion formation and water as a polar covalent compound. Students from Elm did not refer to the new unit's activities with their explanations. An assessment and a review more aligned with these activities may be needed to help students to grasp the material as the students would have to revisit the content. BSB wrote in her teaching log: "The first day I started teaching the basics of ionic bonding after we finished these lessons, the students started to make the connections and better understand what they'd just finished doing (light bulb)." The Elm teachers did revisit ionic bond concepts to ensure that students did understand the concept especially since there was no review as part of the unit. Elm teachers did say that by extending the unit to include a more explicit aspect to teach balancing the formula unit would be beneficial.

The teachers from both schools knew about NGSS but were interested in this unit due to the potential of having to develop initial phenomenon to be explored. They wanted to incorporate more initial phenomenon into their teaching. For this unit, the initial phenomenon was the difference in conductivity for sodium chloride as a solid and dissolved in water. Thus, the researcher decided to include dissolving as part of the new unit. Elm performed better on the scores for Part III (the dissociation equations and particulate diagrams mainly) which was associated with dissolving, partly because Ash did not cover this topic in-depth.

This unit adds to the literature by providing more insight to ionic bonds, formula unit, ion formation, dissolving of ionic compounds, and spatial skills. Overall, the new unit shows promise with students starting to learn the formula unit in a different way using ionic compound unit cells. As with any new unit/activities, improvements to the unit are needed with language (being explicit about the difference between compounds, elements, ions and molecules). Future versions of the unit should consider the possibility of incorporating more activities related to covalent compounds plus Lewis Electron Dot Diagrams. The teachers from Elm expressed interest in continuing with this unit and assisting the researcher with developing the unit.

APPENDICES

APPENDIX A: IONIC COMPOUNDS AND CRYSTAL UNIT

The overall question for the Ionic Bonding unit is “Why does solid salt (sodium chloride) from a grocery store shows such a low conductivity compared to salt dissolved in water and Gatorade?” This question starts the students considering solutions around them and what it takes for solution to be considered conductive. Ionic Bonding is the overall topic for the unit with ion formation, solid ionic crystal with emphasis on unit cell and ratio of ions, Coulomb’s Law, electronegativity to predict bond type (nonpolar, polar and ionic) and dissociation of ions. This unit was designed using a literature basis. This unit is an attempt to change these misconceptions such as ion molecules, ion-pairs, and electron transferred to an electrostatic framework.

With this unit, students must have the following background information: Periodic Table information, structure of an atom, electron configuration for main group elements, covalent bonds, and drawing of Lewis structures (expanded octet and not obeying the octet rule such as $AlCl_3$ are not necessary). This unit does not depend upon whether Bohr theory or quantum was used to teach electron configuration. The unit is being designed for integrated high school science either ninth or tenth grade. NGSS is the reason for choosing this education level because periodic trends, explaining bulk scale properties, balancing chemical equations, and Coulomb’s Law are High School PE not Middle School PE. The following are the 5 E Lesson Plans for this Unit. The worksheets utilized with this study are in Appendix B of this dissertation.

Lesson #1 – Introduction to Overall Question and Charge

“Why does solid salt (sodium chloride) from a grocery store shows such a low conductivity compared to salt dissolved in water and Gatorade? What is meant by charge and how many different types of charge can exist?”

Engagement: Will solid sodium chloride be conductive at room temperature? Has anyone ever heard about water being conductive? Teacher will poll the students. After polling the class the teacher explains that a probe will be used to read the conductivity of samples. Between samples the probe should be rinsed using distilled water. The worksheet for this lesson will have the following ranges for conductivities: 0-50 μS/cm is nonelectrolyte (no conduction); 50-120 μS/cm is a weak electrolyte (slight conductivity); and greater than 120 μS/cm is a strong electrolyte.

Exploration: Enough solid sodium chloride will be placed in a beaker to cover the tip of a conductivity probe connected to an appropriate data gathering device. Students will use conductivity probes to show that solid sodium chloride shows a conductivity that basically means there is not conduction (~13μS/cm) and recording this value on the worksheet. These probes must be dry before being inserted into the solid sodium chloride. Otherwise some of the solid may dissolve in water showing a higher conductivity reading than if the probe was dry. Students will place the conductivity probe into distilled water containing no ions. The water should also read a low conductivity value. After this reading is recorded on the worksheet, the student will add a small amount of the sodium chloride to the distilled water and mix the resulting solution. Using the probe, the conductivity of the salt solution will be found and should be high.

Explanation: Teacher will explain that for something to be conductive, a current has to be carried through the system. Teacher will ask the following questions (*answers in italics)*:

What is a current? *Flow of electrons*

How did we measure current? *Conductivity probe*

Which substance can carry a current? *The salt solution*

What is it about that solution that can carry a current? *Potential answers include negative items or negative ions*

With this unit, we are going to explore the reason salt is not conductive as a solid but can be conductive in a solution. Now on the worksheet write down your theory on why solid salt is not conductive but salt water solutions are conductive.

Elaboration: But first what other items register conductive and not. The students will then use the probe to measure the conductivity of Gatorade, sugar, sugar dissolved in water and tap water.

Between each solution the probe should be rinsed with distilled water. Before the solid sugar reading, the probe should be wiped dry. Students may not be able to dry the probe completely, but they should attempt to dry it as much as possible. Students will record their readings for these solutions on the worksheet. Since these are common household chemicals, the solutions and solids can be disposed down the sink with plenty of water.

Evaluation: The worksheet will be collected by the teacher to ensure that the conductivity readings were correct and the student theories can be reviewed. The students will answer two questions about their salt solution and sugar solution measurements comparing to the individual measurements.

Lesson #2 – Ion Formation

“How are positive and negative ions formed?”

Engagement: Is every solution conductive? *No*

What do you think makes some substances conductive? *Ions*

What are ions? *Positive or negative charged substances*

What are the three subatomic particles and their charges? *Protons- positive, neutrons-0 charge and electrons-negative charge*

What are the locations of these subatomic particles in the atom? *Nucleus – protons and neutrons; Electron cloud - electrons*

Students and Teacher will review the first paragraph of the worksheet which is a reminder about the organization of the periodic table, negative ions and positive ions.

Exploration: Students will use Worksheet #2 labeled Ion Formation and Periodic Trends for this lesson and answer questions associated with Part A of the corresponding worksheet. Part A has the students forming neutral atoms and ions for different elements using a posterboard depicting an empty nucleus and shells (principal quantum number). Students will summarize the findings using a periodic table which will also help review the locations of metals, transition metals, metalloids and nonmetals.

Explanation: In Part B of the worksheet, students will then plot the following trends: Atomic Radius, Ionic Radius, Ionization Energy and Electron Affinity. Students compare Atomic Radius to Ionic Radius. They should notice that cations have a smaller radius compared to anions that have the same overall number of electrons.

Students will also learn about ionization energy and electron affinity which helps explain the formation of ions involves energy. Ionization Energy is the minimum amount of energy required to remove an electron from an element while in the gaseous phase.

$$\mathrm{Na(g) \rightarrow Na^{+}(g) + \ e^{-} \quad I.E. = 459.9\ kJ/mol}$$

Electron Affinity is "the negative of the energy change that occurs when an electron is accepted by an atom in the gaseous state to form an anion" (Chang & Goldsby, 2014, p. 268).

$$\mathrm{F(g) + \ e^{-} \ \rightarrow F^{-}(g)} \qquad\qquad - 328\,\frac{\mathrm{kJ}}{\mathrm{mol}}$$

Since electron affinity is the negative of the change, the value used for electron affinity is +328 kJ/mol.

Elaboration:

Sodium has a First Ionization Energy value of 495.9 kJ/mol and a Second Ionization Energy value of 4,560 kJ/mol (Chang & Goldsby, 2014) which means a sodium atom will form a +1 ion but not a +2 ion. This jump in ionization energy will explain the charge for cations. Electron affinity helps explains the formation of negative ions but forcing another electron on an already negative ion actually requires additional energy due to the negative repulsion of electrons. The octet rule helps to explain these ion formations. Transition elements will be mentioned stating that their ion formation is due to the complex electron arrangement.

Evaluation: Students will fill in a periodic table using column numbers and summarizing the charges for the main group columns.

Lesson #3 – Crystals, Unit Cell and Formula Unit

"How are ions arranged in a solid?"

Engagement: Teacher starts the lesson by asking the following questions:

From our conductivity experiment, did salt dissolved in water register a high or low conductivity? *High*

Did the distilled water register high or low conductivity? *Low*

What does that high conductivity mean for the solution? *Ions are formed in water from the salt being dissolved.*

What conductivity did the solid salt have? *Low conductivity*

We know the way ions are formed but how are ions arranged in the solid phase? *Students may not answer this question.*

If you examined solid salt, how does it look? *Crystals*

Take a piece of paper out and draw your model for a salt crystal.

We will be exploring crystals and crystal shape.

Exploration: Using worksheet 3, students will build structures for simple cubic crystal structure using marshmallows. The crystal structure will be 3 marshmallows in length, 3 marshmallows in width and 3 marshmallows in height. The marshmallows will be joined using tooth picks. These marshmallows should all be the same color. This structure allows for the marshmallow in the middle to be shared by all the unit cells of the structure. Illustrating that this marshmallow is only 1/8th in every unit cell. For a Face-Centered cubic cell model, the students will then add skewered marshmallows of a different color then the corner marshmallows (such that the marshmallow is in the middle of the toothpick). These skewered marshmallows will be taped to the middle of two toothpicks for every face interior and exterior of the simple unit cell. For a Body-Centered cubic cell, the students make a simple 1 unit cell using 8 marshmallows preferably of the same color as the simple cubic cell. Then they will insert a different colored marshmallow diagonally into this cell.

Explanation: The youtube video (https://www.youtube.com/watch?v=KNgRBqj9FS8; Van Wyk, 2012) helps explain the models built by the students. For Worksheet 3, Part A questions are associated with this video. The teacher should stop the video and review pertinent information such as number of atoms for each unit cell and the coordination number as these are important points for the Elaboration stage of this lesson. For the sodium chloride structure, the teacher and students will discuss that only 1/3 of the sodium ions on the edge of the cube are associated with a unit cell of sodium chloride (Figure 31).

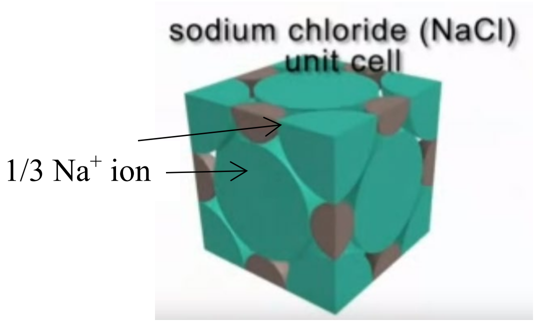


Figure 31. Sodium chloride unit cell (Van Wyk, 2012)

Elaboration: Students will use their knowledge from Exploration and Evaluation to analyze several different ionic crystals to determine the ratio of cations to anions.

Evaluation: Using their knowledge of the ratio of cations to anions students will develop the balancing for a formula unit trend based on the unit cell structure and the charges for the ions. These rules should be equal number of cations and anions for ions that are equal but opposite in charge. The second rule will be for cations and anions that are not equal in charge. This rule will be the number of cations * cation charge = number of anions * absolute value (anion charge).

Lesson #4 – Bond type

“How can we tell what type of bond will form?

Engagement: Teacher will ask the following questions:

When we dissolved sugar in water, what was the conductivity? *Low*

But when salt was dissolved, what was its conductivity? *High*

Do you think sugar forms ions? *No*

So if sugar does not form ions, is the type of bonding ionic for sugar? *No*

What type of bonding do you think occurs in sugar? *Covalent; May have to remind students that another type of bonding was discussed earlier.*

Can you think of common substances besides tables and furniture (joking) that does not dissolve in water? *Flour and oil are examples*

How can we tell what type of bonding occurs between elements in a compounds and how do we classify these compounds?

Exploration: Students will use the electronegativity table with the worksheet to plot the trend s in electronegativity. This exercise is Part A of this lesson’s worksheet.

Explanation: Part B contains information about Columb’s Law, electronegativity and identifying different types of bond. Bonds have potential energy associated with them. The amount of potential energy especially for an ionic bond is based on Coulomb’s Law which is represented by the following equation:

$$\mathrm{E} \propto \frac{\mathrm{Q_{cation}} * \mathrm{Q_{anion}}}{\mathrm{r}}$$

Q is the charge absolute value, r is the distance between the two ions, and E is the potential energy (Chang & Goldsby, 2014).

If the charges **increase** say the cation charge changes from +1 to +2 what happens to the potential energy? *Increases*

If the distance between the charges **decrease**, how does this affect the potential energy of the bond? *Increases*

Electronegativity is the ability of an atom to attract electrons when the atom is part of a chemical bond (Tro, 2015) If this difference between electronegativities is less than 0.4 the bond is considered a covalent bond meaning the electron cloud is fairly evenly distributed around the bond . The difference between electronegativities is between 0.4 and 2.0 the bond is considered a polar covalent bond meaning the electron cloud is around both atoms but concentrated around one of the atoms more than another. If the electronegativity difference is greater than 2.0, than the bond is considered ionic in character (Tro, 2015). Now review with the students the bond type.

Elaboration: Part C of the worksheet will have students determine the difference between elements for a bond and then identify the bond type.

Then students will answer if they think that the bond type determines whether or not a covalent compound is polar or nonpolar.

For Part D of the worksheet, students build a balloon structure for methane. Carbon is the center of the structure and each balloon represents the bond to a hydrogen atom. Students draw the Lewis Electron Dot Diagram for methane (CH_4) and draw arrows towards the most electronegative element. While the individual C-H bonds are polar, the three-dimensional structure is nonpolar because the electron cloud for the whole molecule is evenly distributed.

With Part D of the worksheet, students draw the Lewis dot structure for water (H_2O). Students builds a balloon structure for water but using different colored balloons representing the hydrogens and the lone pairs of electrons. Students are asked if the hydrogen balloons are evenly distributed around the center oxygen like they were in methane. Students should say no. Then the teacher discusses how the electron cloud is not evenly distributed.

After students are finished, the teacher draws Figure 32 on the board using δ+ for the positive region (lower electron density) and δ- for the negative region (higher electron density). Then reviews that water has polar bonds are polar, and the molecule is polar. This is different for methane which has polar bonds, but overall the molecule is nonpolar.

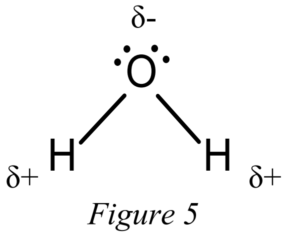


Figure 32. Lewis Electron Dot Diagram for Water

Evaluation: Part E of the worksheet will ask students to predict what part of the water molecule a cation would be attracted and what part of the water molecule an anion would be attracted.

Lesson #5 – Dissolving

Why does solid salt (sodium chloride) dissolve in water? How can the dissolving process be represented at the particulate level and using symbols?

Engagement: Teacher will draw the Lewis Electron Dot Diagram for water on the board. From our discussion of water, which part has a higher electron density oxygen or hydrogen? *Oxygen*

And how was this higher electron density represented on the Lewis Electron Dot Diagram for water i.e. what symbol was used? δ-

Thus, the hydrogens have a lower electron density and what symbol is used to represent this lower electron density? δ+

Exploration: Students will use the 3D Molecular Designs water kit (http://www.3dmoleculardesigns.com/3DMD.htm) to explore how water reacts with sodium chloride which is Part A of the worksheet. See Figure 33. (These kits contain the models needed to make ethanol which should be removed for this lesson as this model is more useful for intermolecular forces which this lesson does not address) In addition to the one set of sodium chloride the teacher splits a sodium chloride from the crystal lattice molecular model (also available from 3D Molecular Designs, Figure 34) and these extra pairs should be combined with the one pair that is part of the kit. Students will explore parts of water that will attach magnetically to the sodium chloride molecule and break apart their sodium chloride salt replicating what occurs when sodium chloride dissolves in water.

Figure 33. Magnetic Water kit from 3D molecular designs (3D Molecular Designs, n.d)

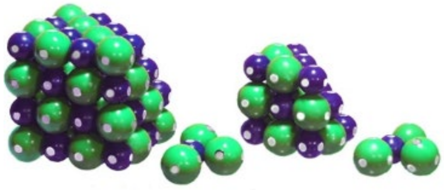


Figure 34. NaCl Lattice from 3D molecular designs (3D Molecular Designs, n.d)

Explanation: For a more in-depth explanation, the video from Vischem (CADRE Design Pty Ltd & Tasker, R., 2010) is shown explaining the dissolving of sodium chloride as a dynamic process at the particulate level. This video can be found using the following steps:

1. Access the website: http://vischem.com.au/
2. Click on the Online Resources menu at the top of the screen.
3. Scroll down til the Scootle site link is viewed. This link is above the "Types of Vischem Resources" title.
4. Another window will open with a variety of videos. Note these videos are not in numeric order.
5. Scroll down to the video title - M008653 VisChem topic 2: dissolution of an ionic salt
6. Click the title and another window will open. Click on the video which is about middle of the webpage and starts off as a blue screen with fish.

Elaboration: Two groups bring their sodium chloride ions to each other and assembles the sodium chloride lattice. Then you must take this lattice apart putting all the sodium ions in one pile and all the chloride ions in another pile. Mix these piles keeping all the sodium ions in one pile and all the chloride ions in another pile. The worksheet asks the following questions:

When the lattice was assembled the second time, was every sodium ion connected with the exact same chloride ions from when you first assembled the lattice? *Some students may say yes but any student thinking about the mixing of the ions should say no*

One of the students removes a sodium ion and places it somewhere else in the lattice. The students answer the following question: Does it truly matter if I attach this ion to a different chloride ion? *No*

So is an ionic bond just a sodium ion attached to a chloride ion? *Students may have varying opinions here but the answer is no.*

Or can a sodium ion be ionically bonded to ALL the chloride ions surrounding it? *Yes*

For dissolving these bonds are broken and the sodium ions and chloride ions enter the solution but do not stay together. The students and teacher look at the first question of this lesson's worksheet which is the dissolution of sodium chloride using particles and symbolically.

From your conductivity results, how did you classify solid sodium chloride (nonelectrolyte or electrolyte and why? *Nonelectrolyte. Did not register a conductivity.*

From your conductivity results, how did you classify distilled water (nonelectrolyte or electrolyte and why? *Nonelectrolyte. Did not register a conductivity.*

You dissolved a small amount of solid sodium chloride in distilled water. From your conductivity results, how did you classify the sodium chloride solution (nonelectrolyte or electrolyte and why? *Electrolyte as it did register a conductivity*

But we mixed two nonconductive substances to form a conductive solution, what happened to the salt to form a conductive solution? *The salt crystal split into ions with the sodium ion being attracted to the oxygen of water and the chloride ion being attracted to the hydrogen of water.*

We also mixed two nonconductive substances to form a non-conductive solution, what happened to the sugar to forma a nonconductive solution? *The sugar molecules dissolved but did not split into ions. Sugar has polar covalent bonds.*

Evaluation: Students work on the next four questions for both particles which is the dissolution of lithium fluoride, calcium chloride, potassium sulfate and copper (II) nitrate. At the end of the lesson, the teacher revisits the unit's driving question: "Why does solid salt (sodium chloride) from a grocery store show such a low conductivity compared to salt dissolved in water and Gatorade? What is meant by charge and how many different types of charge can exist?"

Why do you think that sodium chloride dissolved in water showed a higher conductivity compared to solid sodium chloride and compared to distilled water? *Ions in the solution. Solid sodium chloride and distilled water separately does not have free ions.*

Was the conductivity high or low for the Gatorade sample? *High*

Why does Gatorade have a high conductivity value? *Contains ions.*

Why do you think it is important for athletes who sweat to drink Gatorade? *When athletes sweat they lose salts (skin tastes salty), Gatorade helps replaces these salts in the body.*

APPENDIX B: WORKSHEETS FOR IONIC UNIT

The following worksheets were used with this research study. The worksheet number corresponds with the Lesson number.

Name_______________________________________ Date_______________

Worksheet 1: Why does solid salt (sodium chloride) does from a grocery store shows such a low conductivity compared to salt dissolved in water and Gatorade? What is meant by charge and how many different types of charge can exist?

Conductivities - For any measurements involving solids make sure that the probe is dry with paper towels. Between measurements rinse the probe with distilled water. Units: μS/cm

Part A: Using the conductivity probe to take the following reading (Enough to cover the probe area):

1. Conductivity of solid sodium chloride _________________________

2. Conductivity of 50 mL distilled water _________________________

3. Conductivity of salt solution (mix ~2g _________________________
of sodium chloride with distilled water).

Part B: For 1-3 determine if the conductivities are low, medium or high based on:
Low 0-50 μS/cm; Medium 50 – 120 μS/cm; High +120 μS/cm

1. Solid sodium chloride _________________________

2. Distilled Water _________________________

3. Sodium chloride + Distilled Water _________________________

Part C: Take conductivity readings for the following solutions and classify these solutions as low, medium or high:

Solution	Conductivity Reading	Classification
Gatorade (50 mL)		
Sugar (dry the probe as best as you can)		
Sugar + 50 mL of Distilled Water (Add the water to your sugar sample and stir)		
50 mL Tap Water		

Part D: Using your conductivity data answer the following questions:

1. Explain why you think that your salt + water was different than their individual measurements:

____

____

____

____

On the next page draw your image of how the phenomenon of solid sodium chloride would look as a solid (left box) and dissolved in water (right box) if you viewed it under an extremely powerful scope that allowed you to see each component separately. Note: we are exploring your thinking. Do not consult any other resources such as the book or the Internet.

$\xrightarrow{H_2O}$

Solid sodium chloride

Sodium chloride in water

2. Explain why you think that your sugar + water was similar to their individual measurements:

In the space below draw your image of how the phenomenon of solid sugar would look as a solid (left box) and dissolved in water (right box) if you viewed it under an extremely powerful scope that allowed you to see each component separately. Note: we are exploring your thinking. Do not consult any other resources such as the book or the Internet.

$$\xrightarrow{H_2O}$$

Solid sugar

Sugar in water

Name____ Date_______________

Worksheet 2: Ion Formation and Periodic Trends

Atoms are the building blocks of matter. They are made up of protons, neutrons, and electrons, also known as subatomic particles. The elements are arranged in the periodic table based on increasing proton number. As such, hydrogen being the first element has a single proton. As you move from left to right in the periodic table, the proton numbers increase by one. For example, helium is the next element in the periodic table and has two protons. ***Note that the number of protons will equal the atomic number listed on the periodic table***. Neutrons and electrons are the subatomic particles that can vary depending on isotopes or charges.

For electrons, their number can be determined by the number of protons (*so long as the element is a neutral or zero charge state*). If the atom contains a charge, this would have to be factored into the electron total. If the ion has a negative charge, the atom has extra electrons and therefore the charge number must be added to determine the total. Negative ions are called anions. If the ion has a positive charge, the atom has lost electrons and therefore the charge number must be subtracted to determine the total. Positive ions are called cations. See example 1 and 2 below:

Example 1: Cation

Calcium (Ca)	Calcium ion with +2 charge (Ca^{2+})
20 protons	20 protons
20 electrons	(20-**2**) = 18 electrons
(40-20) = 20 neutrons	(40-20) = 20 neutrons

Example 2: Anion

Flourine (F)	Flouride with -1 charge (F^{1-})
9 protons	9 protons
9 electrons	(9+**1**) = 10 electrons
(19-9) = 10 neutrons	(19-9) = 10 neutrons

Note: When atoms of elements become anions (negative ions), the last syllable of the element's name is dropped and the ending –ide ion is added. For a cation, the element's name is used with the word ion added.

For neutrons, their number is determined through the number of protons and the mass number. The answer is simply subtraction. Take the mass number, and subtract the atomic number, or number of protons. E.g. Neutrons = Mass Number - # of protons. (Also think as Mass Number = # of protons + # of neutrons). The number of neutrons can vary for the same element. For example carbon can have 3 different mass numbers: 12, 13 or 14. These varying mass numbers refer to each isotope of carbon. **Mass Number is NOT on the Periodic Table.** See example 3.

Example 3: Isotopes

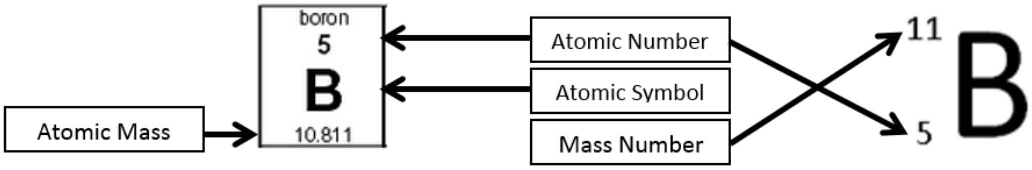
Carbon-12	Carbon-13	Carbon-14
6 protons	6 protons	6 protons
6 electrons	6 electrons	6 electrons
(12-6) = 6 neutrons	(13-6) = 7 neutrons	(14-6) = 8 neutrons

You will be given poster page with atom template on one side, cardboard pieces to use for protons, neutrons, and electrons.

Procedure

A. Diagrams of Atoms and Isotopes

Use atom templates and the cardboard markers to map out the atom's subatomic particles listed below. Remember that the atomic number (Z) is the number of protons; the mass number (A) is the number of protons plus neutrons; and the number of electrons equals the number of protons in a neutral atom. The first shell nearest the nucleus can only hold 2 electrons; the second shell can hold 8; and the third shell can hold 18 but this includes the transition elements. For potassium and calcium, these elements fill the fourth shell before the third shell is completely full. (We won't try to diagram sublevels in this experiment).



Calculate the number of protons, neutrons, and electrons in each atom shown. Then, make a diagram with the supplies provided in lab. The cardboard pieces with p^+ are protons, n are neutrons, and e^- are electrons.
Make a model of the lithium atom below and fill in the box with the appropriate numbers using the atom template and labeled cardboard: electrons, protons, and neutrons. You may need to use a Periodic Table. Then make models for the chlorine atom and then oxygen atom below

^{7}Li

________ protons

________ neutrons

________ electrons

^{35}Cl

________ protons

________ neutrons

________ electrons

^{16}O

________ protons

________ neutrons

________ electrons

Atoms can gain or lose electrons during chemical reactions. When electrons are lost or gained, atoms become charged. We called these charged particles ***ions***. Atoms tend to gain or lose electrons so that they can get to an outer shell of 8 electrons (an *octet*), which is a stable number of electrons. If electrons are lost, the result is a positive ion (cation). If electrons are gained, the result is a negative ion (anion). Use the subatomic particles to make models of the atoms and ions shown on the next several pages using the atom templates and the cardboard particles for electrons, protons and neutrons.

sodium atom	sodium ion
^{23}Na	$^{23}\text{Na}^{+}$
________ protons	________ protons
________ neutrons	________ neutrons
________ electrons	________ electrons

potassium atom	potassium ion
^{39}K	$^{39}\text{K}^{+}$
________ protons	________ protons
________ neutrons	________ neutrons
________ electrons	________ electrons

Where are sodium and potassium in relationship to each other in the periodic table?

____

Predict the charge of all the ions in the same column as sodium and potassium of the periodic table: _______________

Construct a model for the magnesium atom and its respective ion.

magnesium atom	magnseium ion

^{24}Mg

________ protons

________ neutrons

________ electrons

$^{24}\text{Mg}^{+2}$ ion

________ protons

________ neutrons

________ electrons

In what column of the periodic table is magnesium located (use the number above the column with the letter A)? _________________

Predict the charge of all the ions in same column as magnesium of the periodic table:

____

Construct a model for the aluminum atom and its respective ion.

aluminum atom

^{25}Al

________ protons

________ neutrons

________ electrons

aluminum ion

$^{25}\text{Al}^{+3}$ ion

________ protons

________ neutrons

________ electrons

In what column of the periodic table is aluminum located (use the number above the column with the letter A)?? _________________

Predict the charge of all the ions in the same column as aluminum of the periodic table:

____

Construct a model for the nitrogen atom and its respective ion.

nitrogen atom	nitride ion
^{14}N	$^{14}N^{-3}$ ion
________ protons	________ protons
________ neutrons	________ neutrons
________ electrons	________ electrons

In what column of the periodic table is nitrogen located (use the number above the column with the letter A)? __________________

Predict the charge of all the ions in the same column as nitrogen of the periodic table if the elements are a nonmetal: _______________

Make a model of the sulfur atom and sulfide ion

sulfur atom	sulfide ion
^{32}S	$^{32}S^{2-}$
________ protons	________ protons
________ neutrons	________ neutrons
________ electrons	________ electrons

In what column of the periodic table is sulfur located (use the number above the column with the letter A)?? __________________

Predict the charge of all the ions in the same column as sulfur of the periodic table:

____

Lastly, take a look at chlorine and the chloride ion. (Remember that an outer shell of 8 electrons is stable). Make a model of the chlorine atom and chloride ion.

chlorine atom	chloride ion
^{35}Cl	$^{35}\text{Cl}^{-}$
________ protons	________ protons
________ neutrons	________ neutrons
________ electrons	________ electrons

In what column of the periodic table is chlorine located (use the number above the column with the letter A)?? __________________

Predict the charge of all the ions in the same column as chlorine of the periodic table:

____

Reviewing the charges for all the examples in this section, do you predict that Column 8A will have a charge? **And explain your reasoning** ______________________________

____

____

B. Graphs of periodic properties

There are many chemical and physical properties that vary in a regular way in the columns and rows of the periodic table. A folder contains several different periodic tables for these properties. Note each Data Table Number is associated with a Graph using the same number.

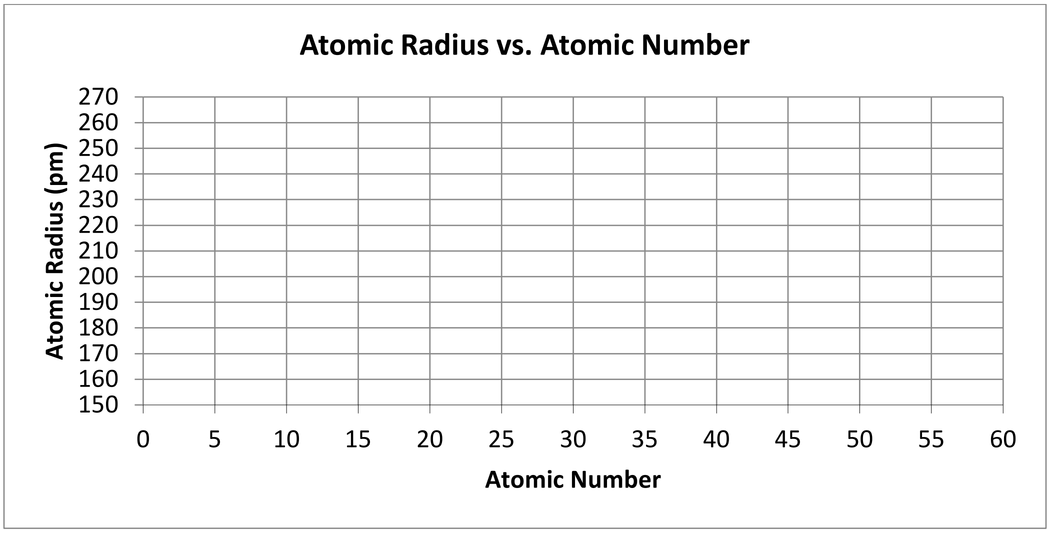
Graph 1 and Graph 2. Radius of an atom

Find the periodic table that has data for the radius of an atom (not ionic). Fill in the two tables below with information from the table. After you have this data, use the blank Graph 1 to plot the atomic number vs the radius for elements in the same column and Graph 2 to plot the atomic number vs the radius for elements. Draw a line connecting the dots that shows the trend of the points.

Data Table 1

Atomic number	Symbol for element	Radius (picometers)
3		
11		
19		
37		
55		

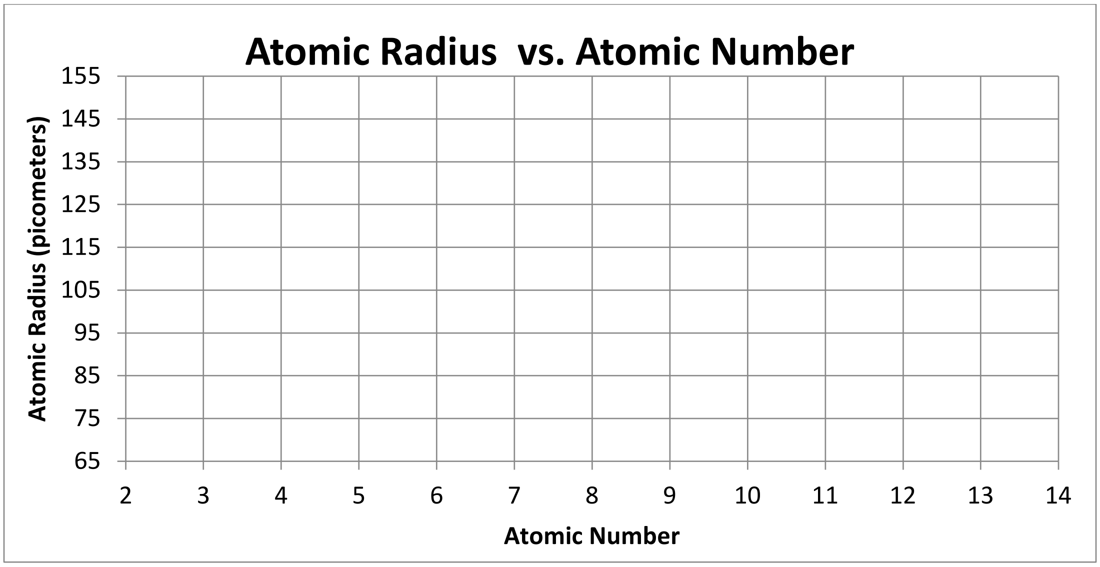
Graph 1:



Data Table 2

Atomic number	Symbol for element	Radius (picometers)
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		

Graph 2:



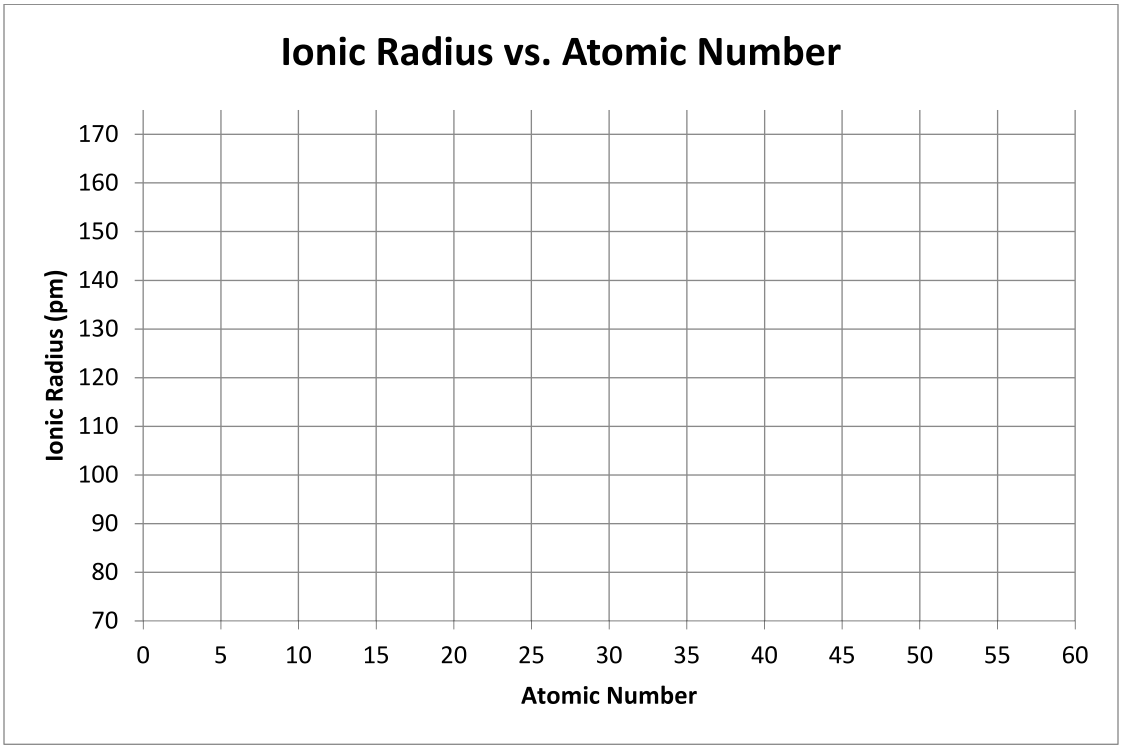
Graph 3 and Graph 4. Radii of ions

Find the periodic table that has data for the radii of ions. Fill in the two tables below with information from the table. After you have this data, use the blank Graph 3 to plot the atomic number vs the radius for ions in the same column and Graph 4 to plot the atomic number vs the radius for ions. Draw a line that shows the trend of the points.

Data Table 3

Atomic number	Symbol for ion	Radius (picometers)
3		
11		
19		
37		
55		

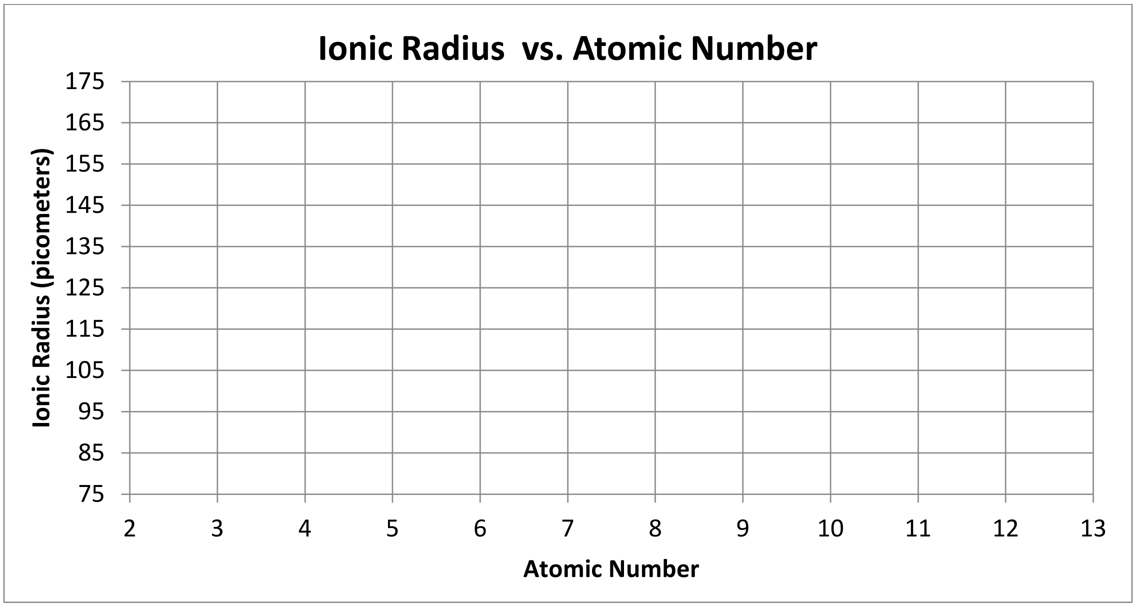
Graph 3:



Data Table 4

Atomic number	Symbol for element	Radius (picometers)
3		
4		
7		
8		
9		
11		
12		

Graph 4:



1. What trend is observed as you move down a family with respect to atomic radii?

2. What trend is observed as you move across a row of the periodic table with respect to atomic radii?

3. What trend do you observe when you compare the radii of cations to their respective atomic radii?

4. What trend do you observed when you compare the radii of anions to their respective atomic radii?

Graph 5 and 6. Ionization Energy

Ionization Energy is the minimum amount of energy required to remove an electron from an element while in the gaseous phase.

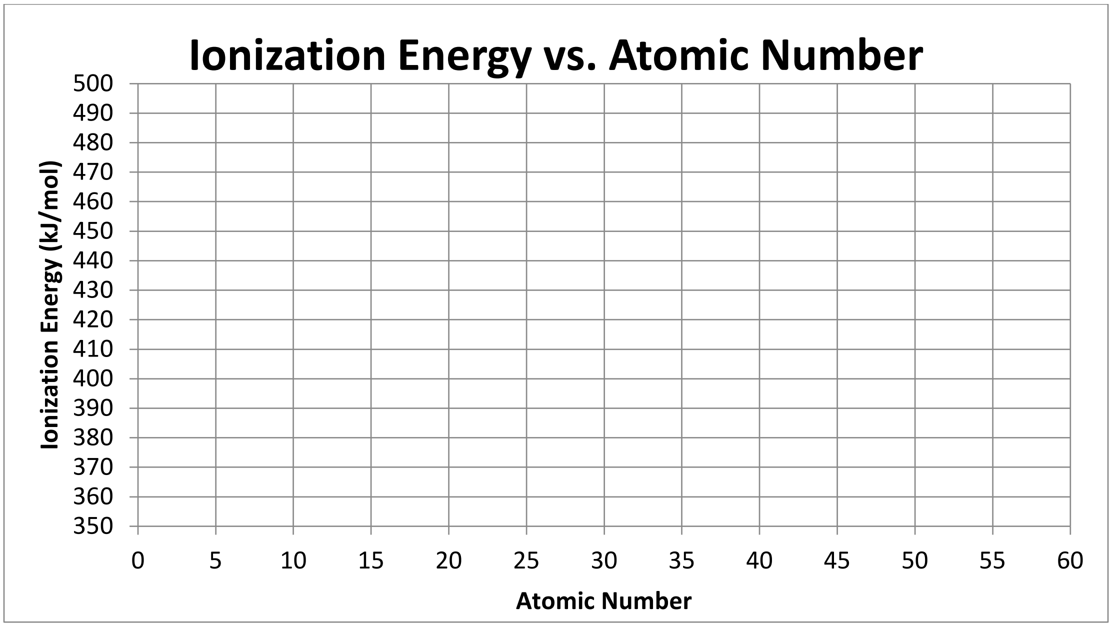
$$\mathrm{Na(g)} \rightarrow \mathrm{Na^{+}(g)} + \mathrm{e^{-}} \quad \mathrm{I.E.} = 459.9\ \mathrm{kJ/mol}$$

Find the periodic table that has data for ionization energy. Fill in the table below with information from the table. After you have this data, use the blank Graph 5 to plot the atomic number vs ionization energy for elements in a column of the periodic table. Draw a line that shows the trend of the points. Then fill in the data for Graph 6 to plot the atomic number vs ionization energy for elements in a row of the periodic table

Data Table 5

Atomic number	Symbol for ion	Ionization Energy (kJ/mol)
3		
11		
19		
37		
55		

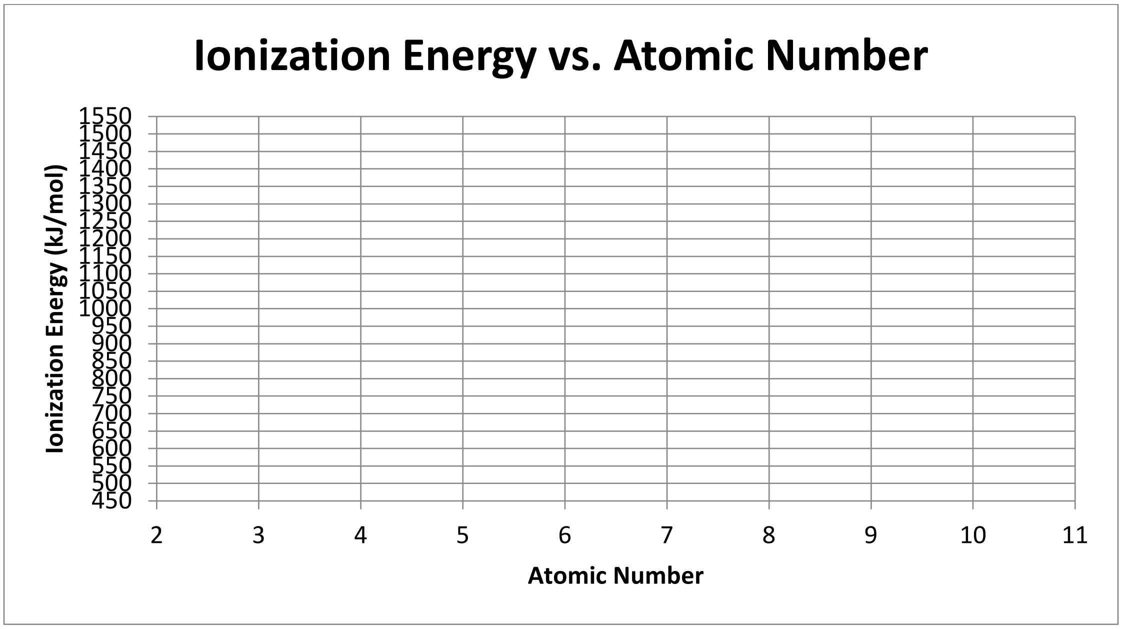
Graph 5:



Data Table 6

Atomic number	Symbol for element	Ionization Energy (kJ/mol)
3		
4		
5		
6		
7		
8		
9		
10		

Graph 6:



1. What trend is observed as you move down a family with respect to ionization energy?

2. What overall trend is observed as you move across a row of the periodic table with respect to ionization energy?

Graph 7 and 8. Electron Affinity

Electron Affinity is "the negative of the energy change that occurs when an electron is accepted by an atom in the gaseous state to form an anion" (Chang & Goldsby, 2014, p. 268).

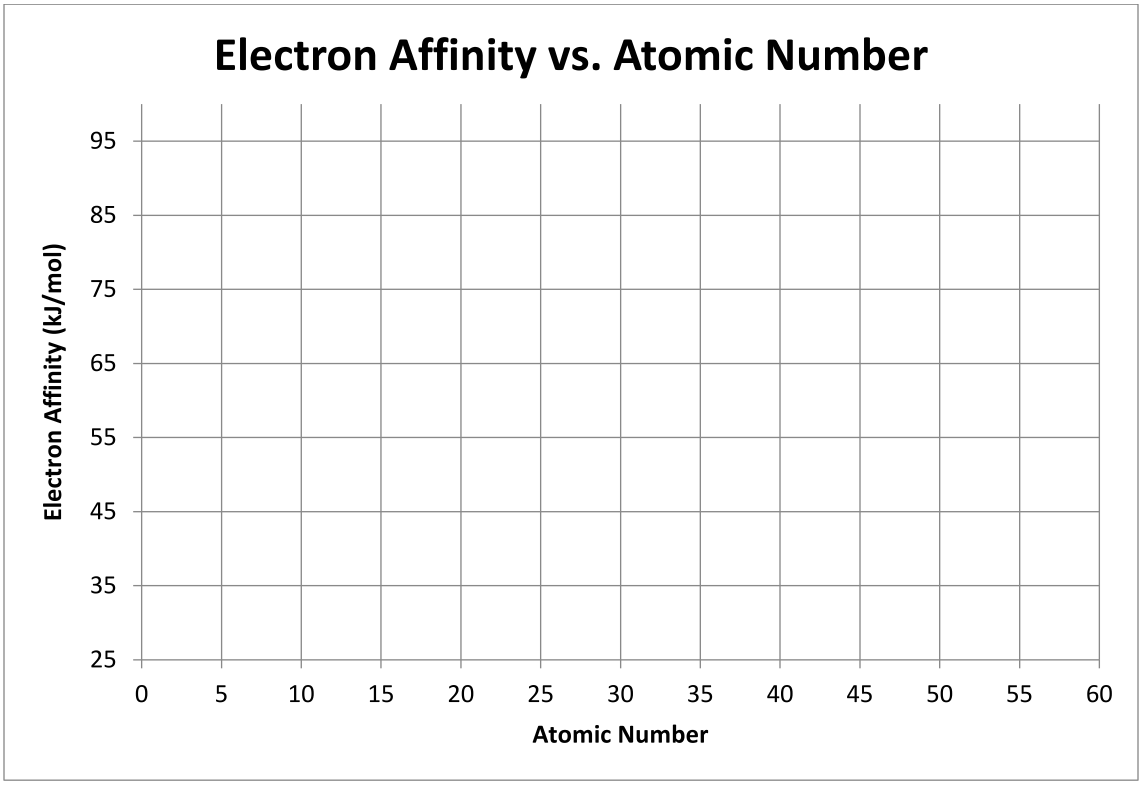
$$\mathrm{F(g)} + \mathrm{e^-} \rightarrow \mathrm{F^-(g)} \qquad -328\,\frac{\mathrm{kJ}}{\mathrm{mol}}$$

Since electron affinity is the negative of the change, the value used for electron affinity is +328 kJ/mol.

Data Table 7

Atomic number	Symbol for ion	Electron Affinity (kJ/mol)
3		
11		
19		
37		
55		

Graph 7:

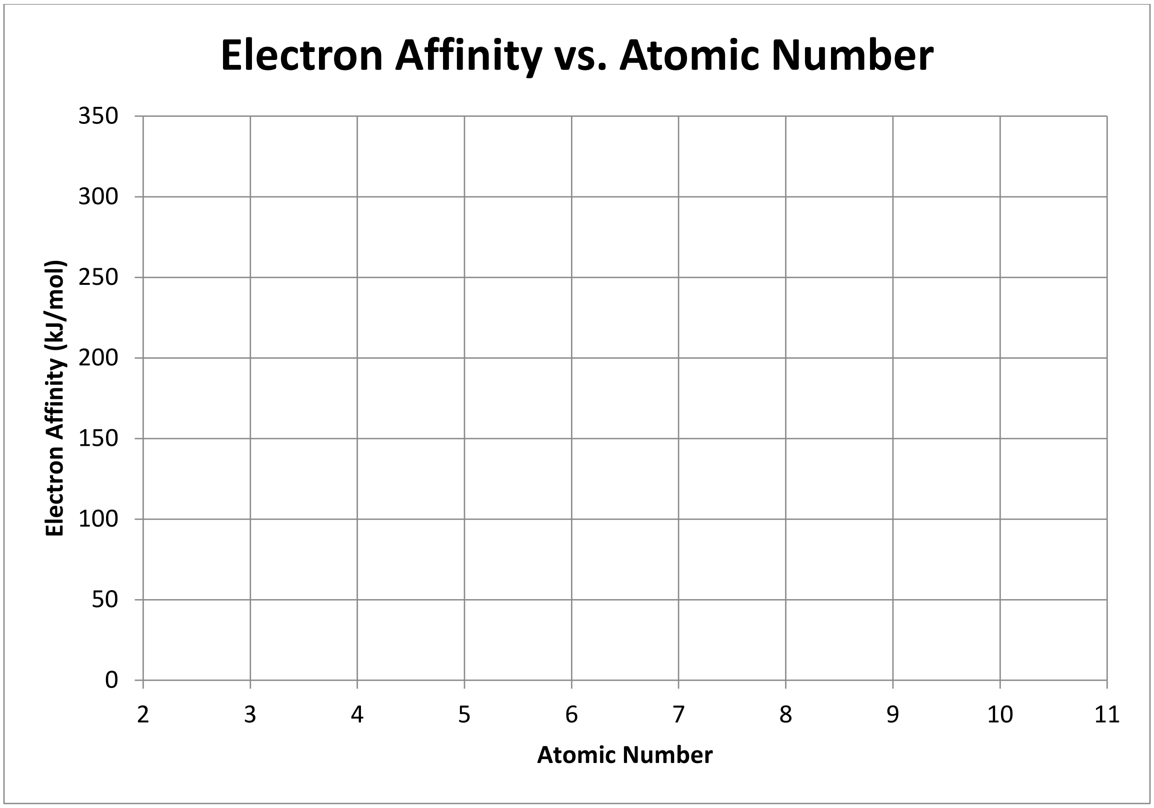


Data Table 8

Atomic number	Symbol for element	Ionization Energy (kJ/mol)
3		
4		
5		
6		
7		
8		
9		
10		

If the reference table says *, give this a 0 value.

Graph 8:


Electron Affinity vs. Atomic Number
Electron Affinity (kJ/mol)
350
300
250
200
150
100
50
0
2
3
4
5
6
7
8
9
10
11
Atomic Number

1. If the following groups are trying to obtain the same electron configuration as Group 8A, how many electrons would have to be added to the elements from these groups to form anions? What would the resulting charge be?

Group Number	Number of Added Electrons	Charge
5	____________________	______________
6	____________________	______________
7	____________________	______________

Part C Ionization Energy with determining charge for main group elements

More than one electron can be removed from an atom. The Sodium has a First Ionization Energy value of 495.9 kJ/mol and a Second Ionization Energy value of 4,560 kJ/mol (Chang & Goldsby, 2014) which means a sodium atom will form a +1 ion but not a +2 ion. When you review the table below you will be looking for these large jumps in values. If you are unsure of a jump, use your knowledge of families (columns) of the periodic table to double check yourself.

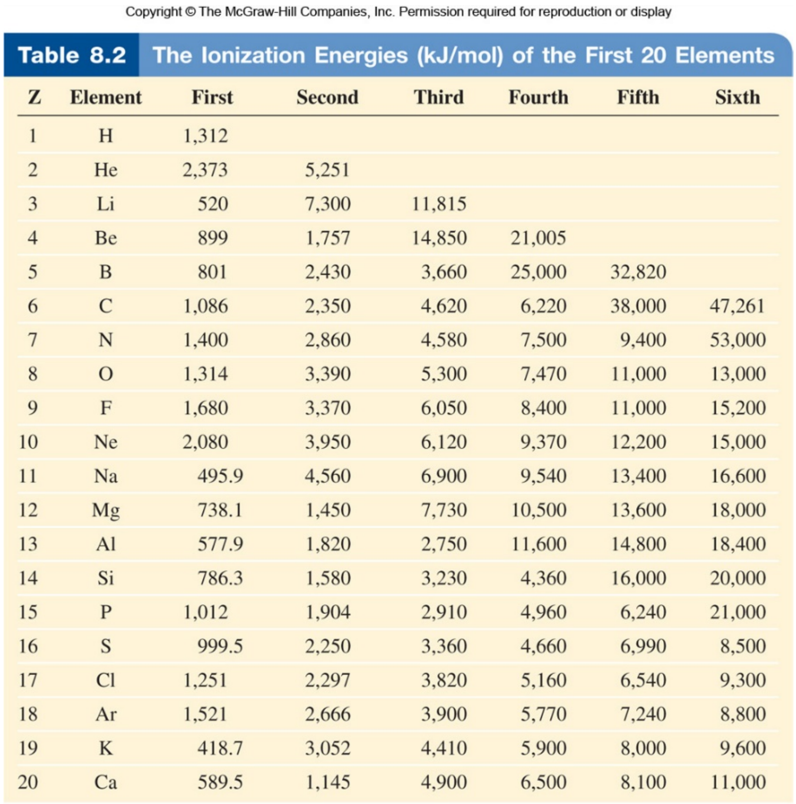


Table 8.2 The Ionization Energies (kJ/mol) of the First 20 Elements

Z	Element	First	Second	Third	Fourth	Fifth	Sixth
1	H	1,312					
2	He	2,373	5,251				
3	Li	520	7,300	11,815			
4	Be	899	1,757	14,850	21,005		
5	B	801	2,430	3,660	25,000	32,820	
6	C	1,086	2,350	4,620	6,220	38,000	47,261
7	N	1,400	2,860	4,580	7,500	9,400	53,000
8	O	1,314	3,390	5,300	7,470	11,000	13,000
9	F	1,680	3,370	6,050	8,400	11,000	15,200
10	Ne	2,080	3,950	6,120	9,370	12,200	15,000
11	Na	495.9	4,560	6,900	9,540	13,400	16,600
12	Mg	738.1	1,450	7,730	10,500	13,600	18,000
13	Al	577.9	1,820	2,750	11,600	14,800	18,400
14	Si	786.3	1,580	3,230	4,360	16,000	20,000
15	P	1,012	1,904	2,910	4,960	6,240	21,000
16	S	999.5	2,250	3,360	4,660	6,990	8,500
17	Cl	1,251	2,297	3,820	5,160	6,540	9,300
18	Ar	1,521	2,666	3,900	5,770	7,240	8,800
19	K	418.7	3,052	4,410	5,900	8,000	9,600
20	Ca	589.5	1,145	4,900	6,500	8,100	11,000

(Chang & Overby, 2010)

1. For the following elements, a jump in the Ionization Energy occurs. Review the table on the previous and choose between which 2 levels do these elements experience the biggest jump? Circle your choice

Li:	1st→2nd	2nd→ 3rd		
Be:	1st→2nd	2nd→ 3rd	3rd→4th	
B:	1st→2nd	2nd→ 3rd	3rd→4th	
C:	1st→2nd	2nd→ 3rd	3rd→4th	4th→5th
N:	1st→2nd	2nd→ 3rd	3rd→4th	4th→5th
Na:	1st→2nd	2nd→ 3rd	3rd→4th	4th→5th
Mg:	1st→2nd	2nd→ 3rd	3rd→4th	4th→5th
Al:	1st→2nd	2nd→ 3rd	3rd→4th	4th→5th
Si:	1st→2nd	2nd→ 3rd	3rd→4th	4th→5th
P:	1st→2nd	2nd→ 3rd	3rd→4th	4th→5th

2. For Group 1, between which levels does the ionization energy jump? ________

How many electrons are lost? ______What would the charge on this ion be? ___________

3. For Group 2, between which levels does the ionization energy jump? ________

How many electrons are lost? ______What would the charge on this ion be? ___________

4. For Group 13, is there a trend for the ionization jump?_________

between which levels does the ionization energy jump? _________

How many electrons are lost? ______What would the charge on this ion be? ___________

5. For Group 14, is there a trend for the ionization jump?_________

between which levels does the ionization energy jump? _________

How many electrons are lost? ______What would the charge on this ion be? ___________

While ionization energies help explain the main group elements charges, the transition elements and metals in groups 13 and 14 in the fourth period on may form more than one possible positive ion such as Fe^{2+} and Fe^{3+} due to the more complex arrangement of electrons. These ions are named using the element's name with the charge as a Roman numeral in parentheses. For example, Fe^{+2} is iron (II) and Fe^{+3} is iron (III).

What is the name for the following?

Pb^{2+} ____________________________ Pb^{4+} ____________________________

Cu^{+}____________________________ Cu^{2+}____________________________

Co^{2+}____________________________ Co^{3+}____________________________

Mn^{2+}____________________________ Mn^{7+}____________________________

Sn^{2+}____________________________ Sn^{4+}____________________________

Ni^{2+}____________________________ Ni^{3+}____________________________

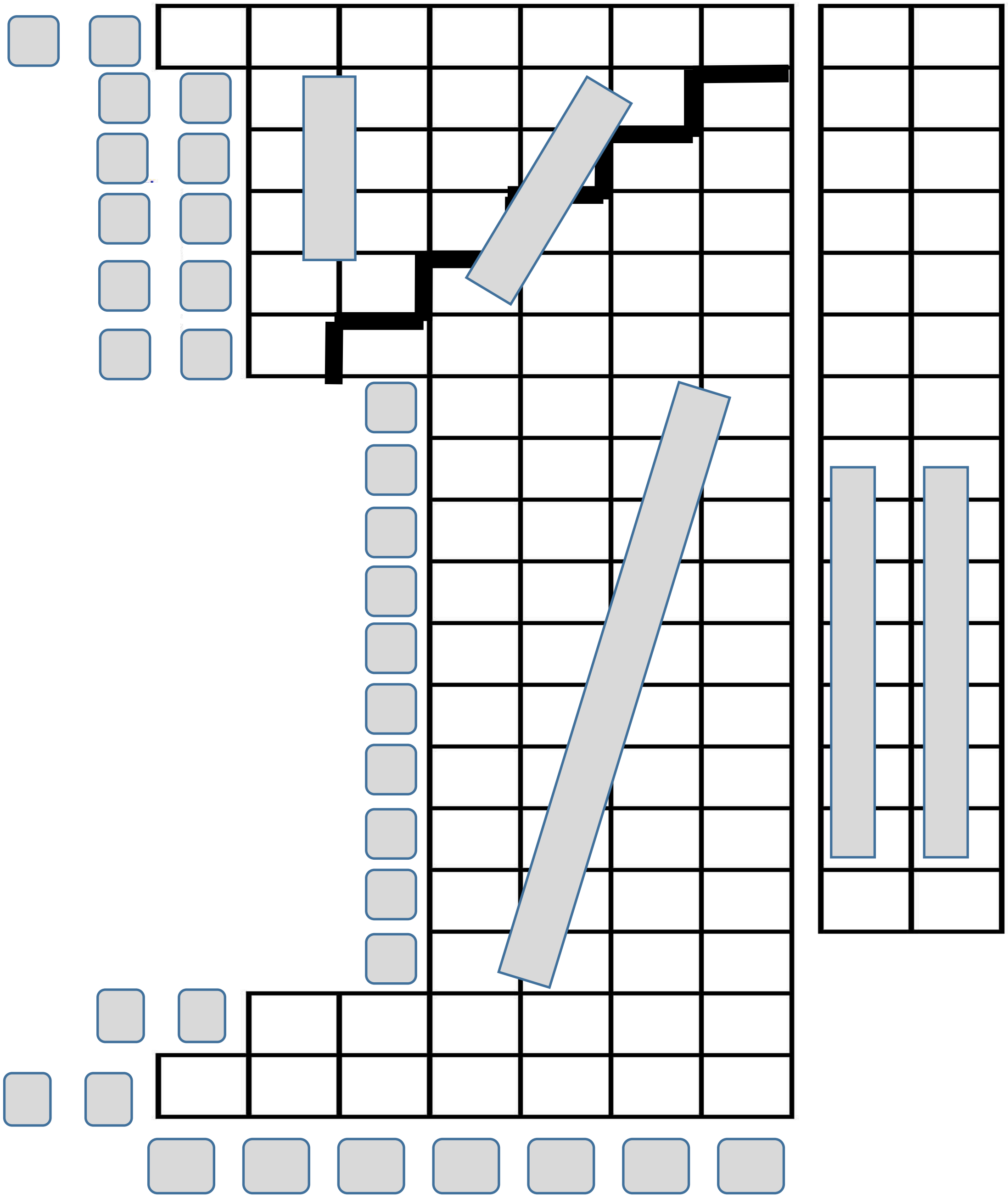
Au^{+}____________________________ Au^{+3}____________________________

Some transition elements only have one charge and are named similarly to the main group metals such as Zn^{2+} →zinc ion; Ag^{+} → silver ion

D. The periodic table

The periodic table is arranges the elements so that elements with similar properties fall into the same area of the periodic table. Label that table with the following information.

i. the atomic numbers for the first 10 elements
ii. the period numbers in the boxes on the left of each row
iii. the column numbers in the boxes at the top of each column (1-18)
iv. the location of the transition metals
vi. the metalloids
vii. the nonmetals
viii. label columns 1, 2, and 13-18 with their respective charges. Put the charge in the other box on top of the column.



Name______________________________________ Date______________

Worksheet 3: Unit Cell and the Formula Unit

Part A: Unit Cell Information – Your group has a large Ziploc bag containing three Ziploc bags. One containing white marshmallows, a second containing pastel color marshmallows and the third containing toothpicks. Be careful with the toothpicks.

Creating Structure 1:

Make a structure using white marshmallows that is 3 marshmallows in length, 3 marshmallows in width and 3 marshmallows in height. Toothpicks will be used to help build this structure with marshmallows attached to the ends of the toothpicks. For answering the following questions consider that a marshmallow represents an atom.

1. Look at the marshmallow that is in the center of your structure – how many cubes share this marshmallow? ______________________

2. This structure can be extended to include more cubes on top, bottom and extending on the sides. Each corner represents what fraction of an atom for a cube?________________

3. How many atoms are made from one cube?_________________

You have constructed simple cubic unit cell model with Structure 1. Each cube of Structure 1 is considered a unit cell with this unit cell model containing 8 unit cells.

Creating Structure 2:

Now remove the top layer of marshmallows including the toothpicks that attached the top layer to the second layer from Structure 1 and set aside. Now you have a 3 marshmallows in length, 3 marshmallows in width and 2 marshmallows in height. Obtain a marshmallow from the Ziploc with the pastel color marshmallows and using one toothpick skewer the marshmallow such that the marshmallow is in the middle of the toothpick. Staring with the interior first, tape this toothpick to the middle of two of the toothpicks in your unit cell. Keep adding pastel marshmallows so that all the faces (interior and exterior; sides, top and bottom) have these marshmallows.

1. Consider the skewered marshmallow. What fraction of a skewered marshmallow can be considered for 1 cube?_______________

2. How many skewered marshmallows does one cube have (how many faces for a cube?) .

______

3. What is the total number of atoms from the skewered marshmallows?________

4. For a Structure 2, what is the total number of atoms for each cube taking into account the corners and the faces for one cube?___________

With Structure 2, you have created 4 Face-Centered cubic unit cell model.

Creating Structure 3:

Now using the top layer you removed when creating Structure 2, build 2 simple cubic unit cells (3 marshmallows in length, 2 marshmallows in width and 2 marshmallows in height) build one basic unit cell. Obtain a pastel marshmallow and add 2 toothpicks with the ends of the toothpicks have been inserted into the top and bottom of this marshmallow. Insert this marshmallow into one of the simple cubic unit cells such that the pastel marshmallow is hanging diagonally in the middle. Add another pastel marshmallow to the second simple unit cell.

2. How many atoms are represented by the diagonal atom? __________________

3. For Structure 3, what is the total number of atoms for each cube taking into account the corners and the diagonal atom for one cube? ____________

With Structure 3, you have created 2 Body-Centered cubic unit cell model.

Part B: From the video:

1. What is a unit cell?____

____

2. What is the coordination number?____________________________________

____

3. For a Simple Cubic Unit Cell, what is the coordination number?________________

4. For a Body-Centered Unit Cell, what is the coordination number?_______________

5. For a Face-Centered Unit Cell, what is the coordination number?_______________

6. For a Body-Centered Unit Cell, if the different colored marshmallows represent different elements, how many atoms of each element is part of your structure?

____

7. For a Face-Centered Unit Cell, if the different colored marshmallows represent different elements, how many atoms of each element is part of your structure?

____

8. If a Body-Centered Unit Cell had 2 marshmallows (same color) as part of the center instead of one and a different color marshmallow at the corners, how many atoms of each element is part of your structure?

____

Part C: Unit cells and Ions

Instead of atoms, the marshmallows can also represent ions.

Cations have a __________________ charge.

Anions have a __________________ charge.

From the conductivity lab, we discovered that solid sodium chloride is considered a nonelectrolyte meaning overall there is no charge for this ionic crystal.

I. Sodium chloride

1. Find the figure for the sodium chloride in the handouts. The muted yellow sphere is the sodium ion and the green spheres are the chloride ions. Use this unit cell to answer the questions.

2. For sodium chloride:

Which atom is the cation?_______________

Which atom is the anion? _______________

3. From the figure, how many cations?_________________

How many anions?_____________________

What is this ratio of cations to anions__________________

4. Is this the lowest whole number ratio? ________

If not, what would be the lowest whole number ratio? (leave blank if you answered yes to the previous question)__________________

5. Using your knowledge of ionization energy, what is the charge for sodium ion?______

Using your knowledge of the periodic table, what is the charge for chloride ion?________

II. Cesium chloride

1. Find the figure for the cesium chloride in the handouts. The orange sphere is the cesium ion and the green spheres are the chloride ions. Use this unit cell to answer the questions.

2. For cesium chloride:

Which atom is the cation?_______________

Which atom is the anion?_______________

3. From the figure, how many cations?_________________

How many anions?____________________

What is this ratio of cations to anions__________________

4. Is this the lowest whole number ratio? ________

If not, what would be the lowest whole number ratio? (leave blank if you answered yes to the previous question)__________________

5. Using your knowledge of ionization energy, what is the charge for cesium ion?______

Using your knowledge of periodic table, what is the charge for chloride ion?___________

III. Calcium fluoride

1. Find the figure for the calcium fluoride in the handouts. The gray sphere is the calcium ion and the light green spheres are the fluoride ions. Use this unit cell to answer the questions.

2. For calcium fluoride:

Which atom is the cation?_______________

Which atom is the anion? _______________

3. From the figure, how many cations?_________________

How many anions?_____________________

What is this ratio of cations to anions__________________

4. Is this the lowest whole number ratio? ________

If not, what would be the lowest whole number ratio? (leave blank if you answered yes to the previous question)__________________

5. Using your knowledge of ionization energy, what is the charge for calcium ion?______

Using your knowledge of periodic table, what is the charge for fluoride ion?___________

IV. Potassium oxide

1. Find the figure for the potassium oxide in the handouts. The blue-gray spheres are potassium ions and the red spheres are the oxide ions. Use this unit cell to answer the questions.

2. For potassium oxide:

Which atom is the cation?_______________

Which atom is the anion? _______________

3. From the figure, how many cations?_________________

How many anions?_____________________

What is this ratio of cations to anions__________________

4. Is this the lowest whole number ratio? ________

If not, what would be the lowest whole number ratio? (leave blank if you answered yes to the previous question)__________________

5. Using your knowledge of ionization energy, what is the charge for potassium ion?____

Using your knowledge of periodic table, what is the charge for oxide ion?_____________

IV. Manganese oxide

1. Find the two figures for the manganese oxide in the handouts. The gray spheres are manganes ions and the red spheres are the oxide ions. Use this unit cell to answer the questions.

2. For the unit cell labeled A:

Which atom is the cation?_______________

Which atom is the anion? _______________

3. From unit cell A, how many cations?________________

How many anions?____________________

What is this ratio of cations to anions__________________

4. Is this the lowest whole number ratio? ________

If not, what would be the lowest whole number ratio? (leave blank if you answered yes to the previous question)__________________

5. What is the charge for the oxide ion?________________

Using the charge for the oxide ion, what is the charge for the manganese ion? (Note: you will have to back calculate this using both the oxide ion and the ratio of cations to anions)

______

6. For the unit cell labeled B:

Which atom is the cation?_______________

Which atom is the anion? _______________

6. From unit cell B, how many cations?________________

How many anions?____________________

What is this ratio of cations to anions__________________

7. Is this the lowest whole number ratio? ________

If not, what would be the lowest whole number ratio? (leave blank if you answered yes to the previous question)__________________

8. Using the charge for the oxide ion, what is the charge for the manganese ion? (Note: you will have to back calculate this using both the oxide ion and the ratio of cations to anions)______

9. Are the two charges for the manganese the same?____________

10. Transition metals and metals in Period 4 and below may have different charges. When naming these compounds, we indicate the charge using Roman numerals such as I, II, III, IV, etc. These Roman numerals are written in ( ) such as copper (I) oxide. The cation is named first and then the anion is named.

For unit cell A, name this ionic compound ______________________________________

For unit cell B name this ionic compound____

Part D:

1. From Part C, for the cases where the cation and anion charges were equal in value but opposite, what was the ratio of cations to anions?_________________________________

Does this ratio make the unit cell neutral?_________________________________

If no, then how can you make the unit cell to be neutral?___________________________

____

Develop a rule for when charges of cations and anions are equal numerically but opposite in charge:____

____

____

2. From Part C, for the cases where the cation and anion charges were not equal but opposite, what was the ratio of cations to anions for the first case?________________

What was the ratio of cations to anions for the second case?____________________

Do these ratios make the unit cell neutral?__________________________

If no, then how can you make the unit cell to be neutral for the first case?__________

____

For the second case?____

____

Develop a rule for when charges of cations and anions are not equal numerically but opposite in charge:____

____

____

Ionic compounds are represented by the formula unit. The lowest whole number ratio of cations to anions. This ratio is written as subscripts for the elements unless the subscript is to be 1 such as NaCl or Na_2S.

3. Write the formula unit for cesium chloride ______________

4. Write the formula unit for calcium fluoride ______________

5. Write the formula unit for potassium oxide ______________

Using your information determine the charge for ions balance the formula unit for the following ionic compounds. ***The lowest whole number ratio should be written***:

6. Magnesium oxide. What is the charge for magnesium ion?________________

What is the charge for the oxide ion? _________________

Write the formula unit for magnesium oxide ___________

7. Calcium phosphide. What is the charge for calcium ion?____________

What is the charge for the phosphide ion? _____________

Write the formula unit for calcium phosphide ________________

8. Lead (II) oxide. What is the charge for lead (II) ion?_______________

What is the charge for the oxide ion? _________________

Write the formula unit for lead (II) oxide ______________

8. Lead (IV) oxide. What is the charge for lead (IV) ion?______________

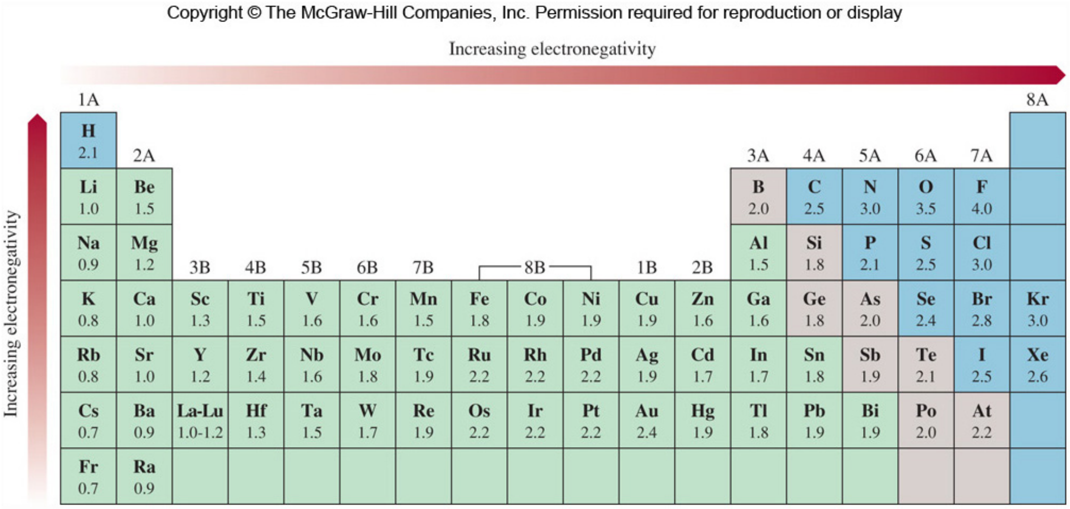
What is the charge for the oxide ion? ___________________

Write the formula unit for lead (IV) oxide _______________

Name______________________________________ Date_______________

Worksheet 4: Bond Types

Part A: Graphing Electronegativity



1A	2A	3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A
H 2.1																	
Li 1.0	**Be** 1.5											**B** 2.0	**C** 2.5	**N** 3.0	**O** 3.5	**F** 4.0	
Na 0.9	**Mg** 1.2											**Al** 1.5	**Si** 1.8	**P** 2.1	**S** 2.5	**Cl** 3.0	
K 0.8	**Ca** 1.0	**Sc** 1.3	**Ti** 1.5	**V** 1.6	**Cr** 1.6	**Mn** 1.5	**Fe** 1.8	**Co** 1.9	**Ni** 1.9	**Cu** 1.9	**Zn** 1.6	**Ga** 1.6	**Ge** 1.8	**As** 2.0	**Se** 2.4	**Br** 2.8	**Kr** 3.0
Rb 0.8	**Sr** 1.0	**Y** 1.2	**Zr** 1.4	**Nb** 1.6	**Mo** 1.8	**Tc** 1.9	**Ru** 2.2	**Rh** 2.2	**Pd** 2.2	**Ag** 1.9	**Cd** 1.7	**In** 1.7	**Sn** 1.8	**Sb** 1.9	**Te** 2.1	**I** 2.5	**Xe** 2.6
Cs 0.7	**Ba** 0.9	**La-Lu** 1.0-1.2	**Hf** 1.3	**Ta** 1.5	**W** 1.7	**Re** 1.9	**Os** 2.2	**Ir** 2.2	**Pt** 2.2	**Au** 2.4	**Hg** 1.9	**Tl** 1.8	**Pb** 1.9	**Bi** 1.9	**Po** 2.0	**At** 2.2	
Fr 0.7	**Ra** 0.9																

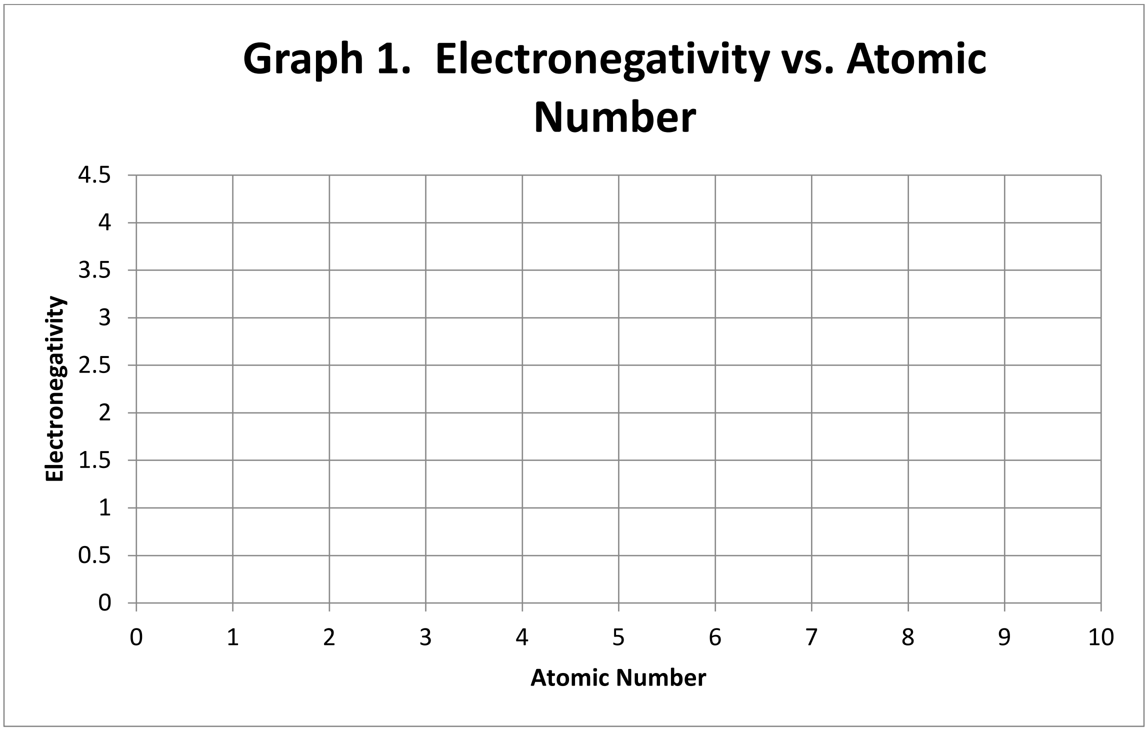
(Chang & Overby, 2010)

Graph 1. Electronegativity

Electronegativity is an indication of how strongly an atom attracts electrons. Using the periodic table above that has data for electronegativity. Fill in the table below with information from the table. After you have this data, use the blank Graph 1 to plot the atomic number vs the radius. Draw a line that shows the trend of the points.

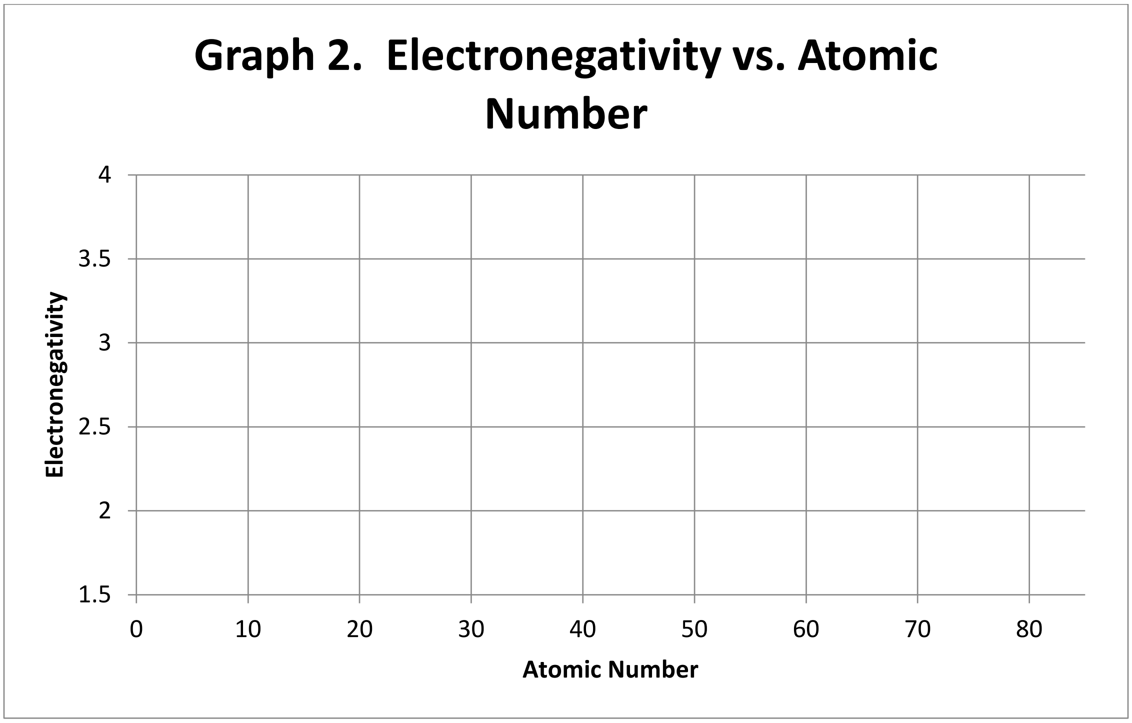
Data Table 1

Atomic number	Symbol for element	Electronegativity
	Li	
	Be	
	B	
	C	
	N	
	O	
	F	



Data Table 2

Atomic number	Symbol for element	Electronegativity
9		
17		
35		
53		



2. Looking at electronegativity, which element is the most electronegative? What is the general trend as you move across a period? What is the general trend as you move down a group?

Part B: Electronegativity Difference

Bonds have potential energy associated with them. The amount of potential energy especially for an ionic bond is based on Coulomb's Law which is represented by the following equation:

$$E \propto \frac{Q_{cation} * Q_{anion}}{r}$$

Q is the charge absolute value, r is the distance between the two ions, and E is the potential energy (Chang & Goldsby, 2014). If the charges increased say the cation charge changes from +1 to +2 what happens to the potential energy (increases or decreases)? ______________________

If the distance between the charges decrease, how does this affect the potential energy of the bond (increases or decreases)? ________________________________

Atoms can bond in different ways. Covalent bonding can fall into two categories based on the distribution of the electron sharing. When a covalent bond between two elements has a fairly even distribution of electrons being shared and this is classified as a nonpolar covalent bond. When this distribution is unevenly shared, the bond is classified as a polar covalent. When the electrons are associated with one type of an atom creating anions and not around another atom creating a cations. To determine if a bond is covalent, polar covalent or ionic, the difference in electronegativity of the two elements in the bond is calculated with the lower electronegativity subtracted from the higher electronegativity.

Then the following table is a rough guide to determining the bond type.

Nonpolar Covalent Bond Range	Polar Covalent Bond Range	Ionic Bond Range
<0.4	0.4≤ to 2.0	>2.0

For example from the figure above, Ca: 1.0 F: 4.0

Electronegativity difference: F-Ca bond: 4.0 – 1.0 = 3.0 Type: Ionic

Part C: Identify the bond type

Instructions: Using the figure on the previous page, find the electronegativity for each element. Determine the electronegativity difference between the elements (positive number) and identify the bond.

1. O:________ O:__________ O-O bond__________ Type:________

2. Na:_______ Cl:_________ Cl-Na bond_________ Type:________

3. C:________ O:__________ O-C bond__________ Type:________

4. Mg:_______ S:__________ S-Mg bond_________ Type:________

5. P:________ Cl:_________ Cl-P bond__________ Type:________

6. C:________ H:__________ C-H bond__________ Type:________

7. O:________ H:__________ O-H bond__________ Type:________

Name______________________________________ Date______________

Worksheet 5: Dissociation equations

Part A: Exploring Water and Sodium Chloride Interaction

Drawing of Water Molecule from the Board:

Your group has been given a cup of water molecules (red and white) and 2 formula units of sodium chloride (green and blue). Explore how the water molecules from the cup interact with sodium chloride. Break the sodium chloride into individual ions and explore the interaction between the individual ions and the water molecule. Answer the following questions:

1. Which part of the water molecule is attracted to the sodium ion? __________________

2. Which part of the water molecule is attracted to the chloride ion?__________________

3. Why do you think that water interacts with the ions this way?_____________________

Part B: Sodium Chloride Lattice

1. Two groups bring their sodium chloride ions to each other and assembles the sodium chloride lattice (lattice → crystal structure). Then you must take this lattice apart putting

all the sodium ions in one pile and all the chloride ions in another pile. Mix these piles keeping all the sodium ions in one pile and all the chloride ions in another pile.

2. After mixing assemble the sodium chloride lattice again. When the lattice was assembled the second time, was every sodium ion connected with the exact same chloride ions from when you first assembled the lattice? Explain your reasoning _______________

____

____

____

3. Someone from the group should remove a sodium ion and place this ion somewhere else in the lattice. Does it truly matter if you attach this ion to a different chloride ion? __

Is an ionic bond just a sodium ion attached to a chloride ion? _______________________

Or can a sodium ion be ionically bonded to ALL the chloride ions surrounding it? ______

____

____

Part B: Dissociation of sodium chloride in water.

1. From your conductivity results, how did you classify solid sodium chloride (nonelectrolyte or electrolyte and why?____

____

2. From your conductivity results, how did you classify distilled water (nonelectrolyte or electrolyte and why? ____

____

3. You dissolved a small amount of solid sodium chloride in distilled water. From your conductivity results, how did you classify the sodium chloride solution (nonelectrolyte or electrolyte and why? ____

____

4. But we mixed to nonconductive substances to form a conductive solution, what happened to the salt to form a conductive solution and what role does water play in dissolving the sodium chloride? ____

____

____

____

5. In the space below draw your image of how the phenomenon of solid sodium chloride would look as a solid (left box) and dissolved in water (right box) if you viewed it under an extremely powerful scope that allowed you to see each component separately.

$\xrightarrow{H_2O}$

Solid sodium chloride

Sodium chloride in water

Write the symbolic equation for sodium chloride dissociating in water.

______________ $\xrightarrow{H_2O}$ _____________ + ________________

Explain your drawing:____

____

____

____

If you have your worksheet 1: Conductivities, explain how your drawings from worksheet 1 for dissolving sodium chloride has changed to the drawing above on this worksheet.

Part C: Other Compounds dissolving.

In the space below draw your image of how the phenomenon of the appropriate solid would look as a solid (left box) and dissolved in water (right box) if you viewed it under an extremely powerful scope that allowed you to see each component separately.

1. Lithium fluoride

$\xrightarrow{H_2O}$

Solid lithium fluoride Lithium fluoride in water

Write the symbolic equation for lithium fluoride dissociating in water.

______________ $\xrightarrow{H_2O}$ _____________ + __________

Explain your drawing:____

____

____

2. Calcium chloride

$\xrightarrow{H_2O}$

Solid calcium chloride   Calcium chloride in water

Write the symbolic equation for calcium chloride dissociating in water.

______________ $\xrightarrow{H_2O}$ ______________ + __________

Explain your drawing:____

____

____

____

3. Potassium sulfate

$\xrightarrow{H_2O}$

Solid potassium sulfate potassium sulfate in water

Write the symbolic equation for potassium sulfate dissociating in water.

______________ $\xrightarrow{H_2O}$ _____________ + __________

Explain your drawing:____

____

____

____

4. Copper (II) nitrate

$\xrightarrow{H_2O}$

Solid copper (II) nitrate

copper (II) nitrate in water

Write the symbolic equation for copper (II) nitrate dissociating in water.

______________ $\xrightarrow{H_2O}$ ______________ + __________

Explain your drawing:____

____

____

____

APPENDIX C: IONIC BONDING UNIT SCIENCE STANDARDS

Table 14: Ionic Bonding Unit Science Standards

Lesson Number	NGSS Performance Expectations
1	HS-PS1-3: Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.
2	HS-PS1-1: Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms.
3	HS-PS1-3: Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.
4	HS-PS1-1: Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms. HS-PS2-4: Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.
5	HS-PS1-1: Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties. HS-PS1-7: Use a mathematical representation to support the claim that atoms, and therefore mass, are conserved during a chemical reaction.

(NGSS Lead States, 2013)

APPENDIX D: CHEMICAL BONDING AND DISSOCIATION DIAGNOSTIC ASSESSMENT

Name ____________________________________

This instrument was developed to test your understanding of chemical bonding and dissociation. There are two parts to this assessment. For each part answer on the sheet by answering on your scantron sheet for Parts I and Parts II. For Part III please circle the answer for any multiple choice and answer the questions asked including any appropriate drawings. The results from this instrument will be for research purposes. Please answer to the best of your knowledge.

Part I Demographics
Please indicate the appropriate answer.

1. A. Female B. Male

2. A. Native American or Alaskan Native B. Asian C. Middle Eastern

D. African American E. Caucasian AB. Hispanic AC. Other

Part II
Directions: This portion of the assessment has 11 paired questions which are paired with the odd number answers are the multiple choice answers to the question and the even numbers answers are the reason for your choice. A total of 22 questions should be answered with this assessment.

3. For forming ions, electrons will be:
A. Shared B. Transferred C. Destroyed

4. The reason for my answer in question 3 is:
A. Electrons of atoms will be shared with the same number of electrons.
B. Electrons of atoms will be entirely transferred to other atoms.
C. Electrons of atoms will be entirely destroyed.
D. Electrons of atoms will be entirely divided with other atoms.

5. The state of ionic compounds at room temperature is:
A. Gas B. Liquid C. Solid

6. The reason for my answer in question 5 is:
A. Ionic compounds have a strong lattice force
B. Ionic compounds have a strong ionic bonding force.
C. Ionic compounds have a large size ion.
D. Ionic compounds have a large ionic charge.

7. Sodium chloride, NaCl, exists as a molecule.
A. True B. False

8. The reason for my answer in question 7 is:
A. The sodium atom shares a pair of electron with the chlorine atom to form a simple molecule.
B. After donating its valence electron to the chlorine atom, the sodium ion forms a molecule with the chloride ion.
C. Sodium chloride exists as a lattice consisting of sodium ions and chloride ions.
D. Sodium chloride exists as a lattice consisting of covalently bonded sodium and chlorine atoms.

9. Element C (electronic configuration 2,8,18,8,2) and element E (electronic configuration 2,7) react to form an ionic compound CE_2.
A. True B. False

10. The reason for my answer in question 9 is:
A. An atom of C will share one pair of electrons with each atom of E to form a covalent molecule, CE_2.
B. A macromolecule consists of covalently bonded atoms of C and E.
C. Atoms of C will each lose two electrons and twice as many atoms of E will each gain one electron to form an ionic compound CE_2.
D. An atom of element C will lose one electron to an atom of E to form an ionic compound CE.

11. The compound formed between magnesium and oxygen can be used a heat-resistant material to line the walls of furnaces.
A. True B. False

12. The reason for my answer in question 11 is:
A. The lattice of magnesium oxide resembles that of silicon dioxide.
B. The covalent bonds between magnesium and oxygen atoms are strong.
C. The intermolecular forces between the magnesium oxide molecules are weak.
D. There are strong ionic forces between magnesium and oxide ions in the lattice.

13. Water (H_2O) and hydrogen sulfide (H_2S) have similar chemical formula and structures. At room temperature, water is a liquid and hydrogen sulfide is a gas. This difference in state is due to:
A. forces between molecules B. forces within molecules

14. The reason for my answer in question 13 is:
A. The difference in the forces attracting water molecules and those attracting hydrogen sulfide molecules is due to the difference in strength of the O-H and the S-H covalent bonds.
B. The bonds in hydrogen sulfide are easily broken whereas those in water are not.
C. The hydrogen sulfide molecules are closer to each other, leading to greater attraction between molecules.
D. The forces between water molecules are stronger than those between hydrogen sulfide molecules.

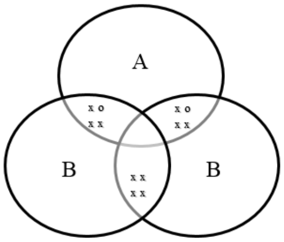
15. The type of bonding to make the water molecule (H_2O) is:
A. Ionic bonding B. Polar covalent bonding C. Non-polar covalent bonding

16. The reason for my answer in question 15 is:
A. Hydrogen loses an electron be the hydrogen ion H^+.
B. Oxygen gains two electrons to be the oxide ion O^{2-}.
C. Hydrogen and oxygen share electrons equally.
D. The electronegativity of oxygen is larger than that of hydrogen.

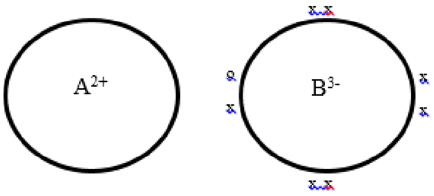
17. An atom of element A has two electrons in its outermost shell while an atom of element B has five electrons in its outermost shell. When A reacts with B, the compound will be:
A. Covalent B. Ionic

18. The reason for my answer in question 17 is:
(o represents an electron of A; x represents an electron of B)

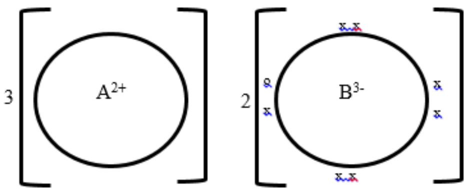
A.



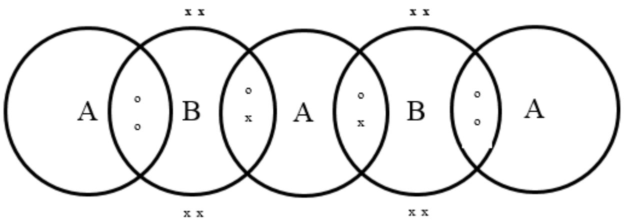
B.



C.



D.



Part III

Directions: For multiple choice, circle the appropriate answer. For open-ended responses, please answer in the provided area. There are a total of 12 questions.

1. When solid potassium iodide (KI) is placed in a beaker of water,
A. it melts into the liquid phase.
B. it separates into individual molecules.
C. it separates into its component ions.
D. it breaks apart into individual atoms.

2. Write the chemical equation that represents the chemical phenomenon described in item #1.

3. In the space below draw your image of how the phenomenon in item #1 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately.

Drawing

4. Explain your drawing above and why this phenomenon occur.

5. When solid lead (II) nitrate, $Pb(NO_3)_2$, is placed in a beaker of water,
A. it melts into the liquid phase.
B. it separates into individual molecules.
C. it separates into its component ions.
D. it breaks apart into individual atoms.

6. Write the chemical equation that represents the chemical phenomenon described in item #5.

7. In the space below draw your image of how the phenomenon in item #5 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately.

Drawing

8. Explain your drawing above and why this phenomenon occur.

9. When solid sodium hydroxide, NaOH, is placed in a beaker of water,
A. it melts into the liquid phase.
B. it separates into individual molecules.
C. it separates into its component ions.
D. it breaks apart into individual atoms.

10. Write the chemical equation that represents the chemical phenomenon described in item #9.

11. In the space below draw your image of how the phenomenon in item #9 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately.

Drawing

12. Explain your drawing above and why this phenomenon occur.

APPENDIX E – INTERVIEW PROTOCOL

The following protocol will be used for semi-structured interviews to probe students' understanding of the Chemical Bonding and Dissociation Diagnostic Assessment, ionic bond, ionic formula, and dissolving of an ionic solid.

1. Explain your understanding of an ionic bond.

2. For question 3 of the assessment, you answered *(dependent on students' answer)* for forming ions. Why did you choose this answer and can you provide/draw an example of your answer?

Potential probe: For your reason you answered *(dependent on students' answer)* can you provide an explanation on why you changed your reasoning?

3. You stated for question 5 for the assessment that ionic compounds exist as *(dependent on students' answer)* at room temperature why did you chose this answer?

Potential probe: For your reason, you answered *(dependent on students' answer)* can you provide an explanation on why you changed your reasoning?

4. For question 7 of the assessment, you answered *(dependent on students' answer)* for sodium chloride, NaCl, existing as a molecule, what proof do you have for your answer?

5. Element C (electronic configuration 2, 8, 18, 2) and element E (electronic configuration 2,7) react to form an ionic compound CE_2. Do you think this is the appropriate formula and what is your basis for your answer?

6. You thought magnesium and oxide *(dependent on students' answer)* formed a heat-resistant material to line the walls of a furnace, why or why not do you think magnesium oxide can be used in this application?

7. Water (H_2O) and hydrogen sulfide (H_2S) have similar chemical formula and structures. At room temperature, water is a liquid and hydrogen sulfide is a gas. Why do you think there is a difference in state?

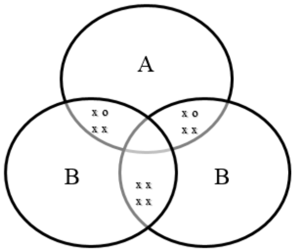
Potential probe: Explain the difference between intermolecular forces between molecules and intramolecular forces within molecules?

8. For a water molecule what type of bonding is needed for one water molecule and why did you chose that type of bonding?

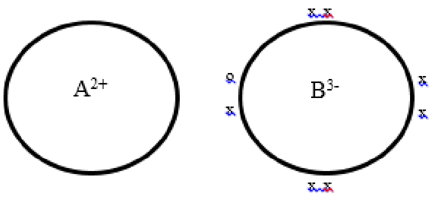
9. An atom of element A has two electrons in tis outermost shell while an atom of element B has five electrons in its outermost shell. How can you tell if the resulting compound will be covalent or ionic?

10. For the previous question, which of the following diagrams would represent the compound and please explain why you chose that particular diagram. o represents an electron of A; x represents an electron of B

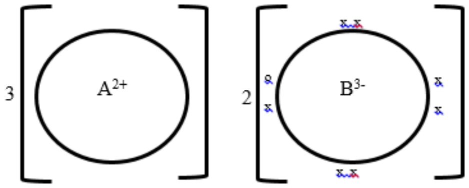
A.



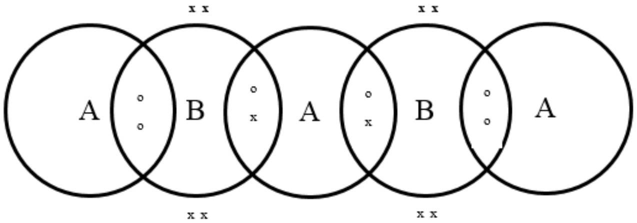
B.



C.



D.



For the second part of the assessment

11. When placing a solid piece of potassium iodide (KI) in a beaker of water you chose *(dependent on students' answer)* why?

Probe: A copy of their chemical equation and particulate drawing will be given to them with their previous written explanation removed.

Why did you represent this chemical phenomenon with this equation?

Can you please provide me a verbal explanation of your drawing of how this chemical phenomenon would look through a powerful microscope? Why did you chose to represent KI as such?

12. When a solid piece of lead (II) nitrate, $Pb(NO_3)_2$, is placed in a beaker of water, you answered *(dependent on students' answer)* why?

Probe: A copy of their chemical equation and particulate drawing will be given to them with their previous written explanation removed.

Why did you represent this chemical phenomenon with this equation?

Can you please provide me a verbal explanation of your drawing of how this chemical phenomenon would look through a powerful microscope? Why did you chose to represent $Pb(NO_3)_2$ as such?

General Questions for the Unit, student's opinion about science and potential career path

13. How would you define an ionic bond?

14. Why do you think some substances such as salt (sodium chloride dissolve in water and other substances do not?

15. Why do you think some substances conduct electricity and other substances do not conduct electricity?

16. Do you enjoy science? Why or Why not? (Student only question)

17. What is your opinion of yourself as a scientist?

18. What potential career path do you see for yourself? (Student only question)

19. Have you considered what other science courses you are potentially going to take in high school and what are they? (Student only question)

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VITA

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Academic Degrees And Certifications

2003	Graduate Certification for Secondary Mathematics**,** Avila University
1996	MS Chemical Engineering, Missouri University of Science & Technology (formerly University of Missouri-Rolla) Thesis: *An Expansion and Guide to Adding a New Unit to DYNUMR*
1993	BS Chemical Engineering, Missouri University of Science & Technology (formerly University of Missouri-Rolla)

Professional Work Experience

2019-Present	Eastern Kentucky University	Chemical Storage Facility Manager
2009- 2019	Eastern Kentucky University	Lecturer/Science Manager
	(Fall 2018 – Present: 100% teaching; Fall 2009-Spring 2018: ~60% teaching; ~40% science management)	
2005-2009	Eastman Chemical Company	Advanced Chemical Engineer
2003-2005	Johnson County Community College	Adjunct Assistant Professor Chemistry Tutor
2001-2002	George Butler Associates, Inc	Engineer I
1996-2001	Bayer Corporation	Process Development Engineer III (1998-2001) Production Process Engineer II (1996-1998)

Publications

Townsend, J.S., Lamar, M. Walach, M. and Hodge, C. (2019/2020) Teaching Technology through History. *Technology and Engineering Teacher, 79*(4), 16-20.

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Patent

D.T. Erdman, J.D. Spicher, M.F. Lamar, D.E. Cockrill, Methods for Preparing Primary Alkyl Bromides, U.S. Patent 6,489,525 (December 3, 2002)

Awards & Honors

2019	Nominated for Critical Reading Teacher of the Year, Eastern Kentucky University
2017	Received Arvle & Ellen Turner Thacker Research Fund, University of Kentucky, $1000
2015	Nominated for Critical Thinking Teacher of the Year, Eastern Kentucky University
2013	Nominated for the Presidential Fellowship, University of Kentucky
2015	Kappa Delta Pi (Education Honor Society)
2006	Received Employee/Team Recognition Award, Eastman Chemical Company
1999	Received Special Recognition Award for “Business Goals and Beliefs,” Bayer Corporation
1991	Omega Chi Epsilon (Chemical Engineering Honor Society)