DESIGNING AN EDUCATIVE CURRICULUM UNIT FOR TEACHING MOLECULAR GEOMETRY IN HIGH SCHOOL CHEMISTRY

by

Nader N. Makarious

An executive position paper submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Education

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Nader N. Makarious

Approved: _____
Ralph Ferretti, Ph.D.
Director of the School of Education

Approved: _____
Carol Vukelich, Ph.D.
Dean of the College of Education and Human Development

Approved: _____
Ann Ardis, Ph.D.
Senior Vice Provost for Graduate and Professional Education

I certify that I have read this executive position paper and that in my opinion it meets the academic and professional standard required by the University as an executive position paper for the degree of Doctor of Education.

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Zoubeida R. Dagher, Ph.D.
Professor in charge of executive position paper

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Signed: _____

Danielle J. Ford, Ph.D.
Member of executive position paper committee

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Signed: _____

Nancy Lavigne, Ph.D.
Member of executive position paper committee

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Signed: _____

Michelle Kutch, Ed.D.
Member of executive position paper committee

I certify that I have read this executive position paper and that in my opinion it meets the academic and professional standard required by the University as an executive position paper for the degree of Doctor of Education.

Signed: _____

Jacqueline L. Fajardo, Ph.D.
Member of executive position paper committee

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ABSTRACT

Chemistry is a highly abstract discipline that is taught and learned with the aid of various models. Among the most challenging, yet a fundamental topic in general chemistry at the high school level, is molecular geometry. This study focused on developing exemplary educative curriculum materials pertaining to the topic of molecular geometry. The methodology used in this study consisted of several steps. First, a diverse set of models were analyzed to determine to what extent each model serves its purpose in teaching molecular geometry. Second, a number of high school teachers and college chemistry professors were asked to share their experiences on using models in teaching molecular geometry through an online questionnaire. Third, findings from the comparative analysis of models, teachers' experiences, literature review on models and students' misconceptions, the curriculum expectations of the Next Generation Science Standards and their emphasis on three-dimensional learning and nature of science (NOS) contributed to the development of the molecular geometry unit. Fourth, the developed unit was reviewed by fellow teachers and doctoral-level science education experts and was revised to further improve its coherence and clarity in support of teaching and learning of the molecular geometry concepts. The produced educative curriculum materials focus on the scientific practice of developing and using models as promoted in the Next Generations Science

Standards (NGSS) while also addressing nature of science (NOS) goals. The educative features of the newly developed unit support teachers' pedagogical knowledge (PK) and pedagogical content knowledge (PCK). The unit includes an overview, teacher's guide, and eight detailed lesson plans with inquiry oriented modeling activities replete with models and suggestions for teachers, as well as formative and summative assessment tasks. The unit design process serves as a model for redesigning other instructional units in science disciplines in general and chemistry courses in particular.

Chapter 1

INTRODUCTION AND PROBLEM STATEMENT

For the last ten years, I have taught chemistry at Brandywine High School in Wilmington, DE. Throughout my years of teaching, I used a variety of pedagogical approaches most of which are student-centric. I expanded the use of Process Oriented Guided Inquiry Learning (POGIL) in my classroom. I introduced every new topic using a POGIL activity where students have to work in groups of three or four. POGIL activities introduce a new concept in the form of a model (i.e. a diagram, an analogy, an image, or even a story) followed by a series of questions. The level of difficulty of questions increases as students proceed through the activity starting with inquiry questions, moving to exercise questions, and then end with application/prediction questions. The design of POGIL activities promotes student-student interaction and minimizes teacher interference. I found that using simple models stimulate students to initiate some basic ideas about the new concepts. However, students often struggle to formulate deep conceptual understanding through a single activity or a class period. When class reconvenes, I typically provide more analogies and examine with students various models to help them either to grasp the new concept or to promote a deeper understanding of the recently taught materials. In the process of doing so, I rely on my observations of student learning and intuitions about the effectiveness of the

analogies and models I introduce but I have not examined systematically the nature of these models or how to best sequence them to facilitate learning.

At Brandywine High School, I teach three different levels of chemistry: Advanced Placement (AP), Honors, and College preparatory (CP). The topics and concepts vary according to the level; however, at any level, chemistry remains the most challenging subject for high school students. Among the most challenging, but provocative topics in general chemistry is molecular geometry (Schurmeirer, Shepler, Lautenschlager, & Atwood, 2011). The complexity of the topic requires not only the application of various concepts such as classifications of elements, electronegativity, and bond order, but also spatial intellectual capacity. Geometrical shape of molecule is an essential element to decide the molecular polarity and thus the intermolecular forces (IMF). Many chemistry concepts are centered on chemical bonds, polarity, and IMF. The acquisition of these concepts is critical for understanding many other concepts in chemistry.

For many students, it is a challenge to visualize an object from different angles, faces, and orientations. The ability to create and manipulate mental images and the orientation of bodies in space requires spatial intelligence. According to Gardner (1983), spatial intelligence deals with spatial judgment and the ability to visualize with the eyes of the mind. Furthermore, conceptual understanding requires students to be able to build a meaningful and appropriate mental representation, i.e., a mental model, of the system being taught (Lowe, 1993).

For students to structure covalently bonded molecules they need to use logical thinking, complex steps, and apply prior knowledge to produce the most valid molecular structure. Figure 1 summarizes the essential concepts students need to master in order to structure a valid molecular shape (hybridization: relates only to the AP level). I will continue to develop this figure in the following two chapters to build a logic model. In Chapter 2, the developed logic model will illustrate how models mediate chemistry concepts and the desired outcomes of the teaching unit. Finally, in chapter 3, I will explain how the logic model will be used to guide the assessment section of the educative curriculum unit.

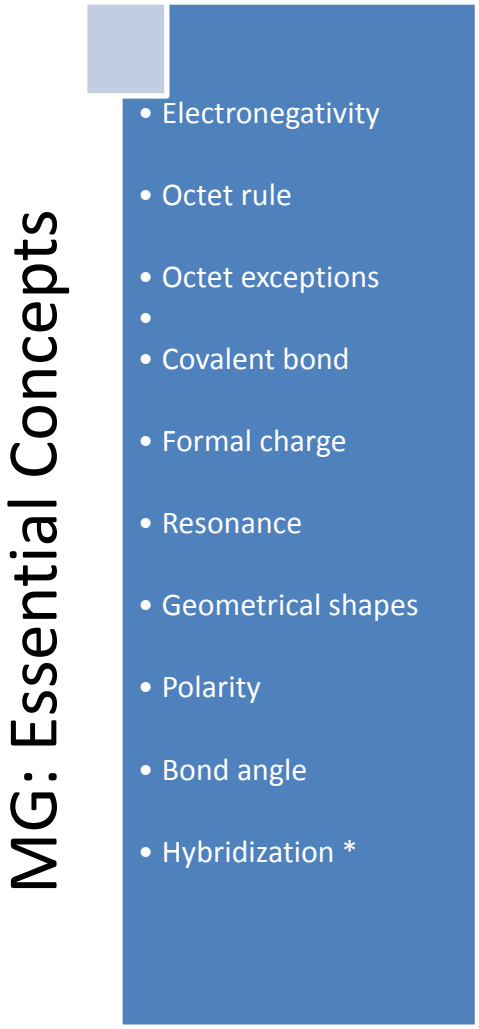


Figure 1 Essential Concepts in the Molecular Geometry Unit

The Complexity of Molecular Geometry

In order to produce the most valid structure of molecules, the multiple step process demands that learners:

1. Identify the central atom which is the least electronegative one.
2. Distribute the terminal atoms around the central one, as far apart from each other as possible in three dimensional spaces.
3. Calculate the total number of valence electrons.
4. Create single covalent bonds between the central atom and the terminal ones.
5. Distribute valence electrons to satisfy the octet rule for terminal atoms.
6. Revise bond order and create double or triple bonds between the central atom and the terminal ones to satisfy the octet rule for terminal atoms.
7. Assign any leftover electrons to the central atom where in most cases the octet rule could be violated for elements on the third period or below in the periodic table.
8. Calculate the formal charges for each atom and revise the structure accordingly to reduce the formal charge of each atom to fall between -1, 0, +1.
9. Explain why specific molecules violate the octet rule.

10. Position the most electronegative atom in a way that minimizes electrons' cloud repulsion (axial or equatorial).

Structuring the molecular geometry process takes additional steps to validate the structure according to the formal charges and the existence of any resonance structures (Figure 2). Students need to make rational decisions regarding which structure is more valid, a dominant structure, based on elements' electronegativities, formal charges, atoms position (axial or equatorial), and bond steric energy. The final step in structuring a molecule is to predict its polarity.

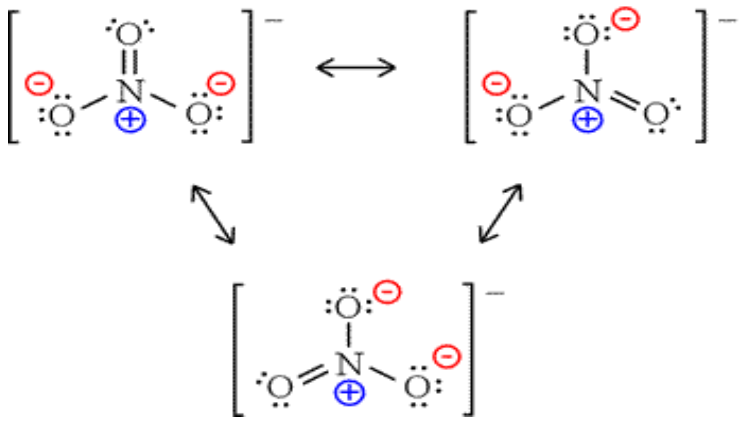


Figure 2 Resonance Structure and Formal Charges of the Nitrate ion, NO_3^{-1}

To help students approach this sophisticated level of high order thinking and to develop a valid prediction on the polarity of mental 3D visualization of Nano-scaled sized molecules, the use of models is a necessity. According to Gilbert (2005), models are vital when the visualization of entities, relationships, and cause and effect, within exemplar phenomena are to take place. In particular, "this process of simplification

and representation within the scope of human senses with the aid of models becomes of greater importance as, later in a sequence of inquiries, explanations for exemplar phenomenon are sought at the sub-micro level" (Gilbert, 2006, p.11). These visualizations have the power to augment spatial thinking; for example, by providing external visualizations of phenomena that are too complex to be visualized internally (Hegarty, 2010). For example, students who struggle to picture a geometrical shape of Carbon tetra Chloride (CCl_4) with 109.5^0 bonding angels can easily see it with the aid of an image manipulation program (animation).

With the implementation of the Next Generation Science Standards (NGSS), (NGSS Lead States, 2013) in the State of Delaware, there is increased emphasis on constructing and using models and modeling as one of eight scientific and engineering practices. In this sense, using models and modeling is not only a pedagogical approach intended to simplify difficult concepts but is also a tool to develop and evaluate new knowledge. According to the NGSS, students should develop, revise, and critique models. Models can be used to summarize data, form predictions, justify results, and facilitate communication in science. The NGSS point to the use of models to generate and analyze data:

> Analyzing data in 9–12 builds on K–8 and progresses to introducing more detailed statistical analysis, the comparison of data sets for consistency, and the use of models to generate and analyze data. Use tools, technologies, and/or models (e.g., computational, mathematical) to generate and analyze data in order to make valid and reliable scientific claims or determine an optimal design solution. (NGSS Lead States, 2013, p. 95).

In line with this emphasis, the NGSS promotes the use of models and modeling for atomic and molecular structures as early as middle school where students are expected to draw a diagram or build a 3D model using a ball and stick structure.

> **MS-PS1-1.** Develop models to describe the atomic composition of simple molecules and extended structures. Clarification Statement: Emphasis is on developing models of molecules that vary in complexity. Examples of simple molecules could include ammonia and methanol. Examples of extended structures could include sodium chloride or diamonds. Examples of molecular-level models could include drawings, 3D ball and stick structures, or computer representations. (NGSS Lead States, 2013, p. 54).

At the high school level, the use of models in teaching molecular structures extends to the use of the periodic table as a model to predict relative properties and patterns of elements based on the number of electrons in the valence shell. Determining the type of element and its electronegativity is considered an initial step to decide the type of bond and to structure a basic geometrical shape of the molecules.

Standard, HS-PS1-3, matter and interaction highlights the concept of Intermolecular Forces (IMF) such as dipole-dipole, hydrogen bond, and induced dip. Students do not need to only identify the IMF that exists between different molecules, but also to apply this knowledge to explain the behavior of molecules at the bulk scale.

> **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. Clarification Statement: Emphasis is on understanding the strengths of forces between particles, not on naming specific intermolecular forces (such as dipole-dipole). Examples of particles could include ions, atoms, molecules, and networked materials (such as graphite). Examples of bulk properties of substances could include the melting point and boiling point, vapor pressure, and surface tension. (NGSS Lead States, 2013, p. 82).

As the State of Delaware implements the NGSS across the science curriculum at all levels, the Brandywine School District is working on aligning its science curricula with the NGSS. Developing curriculum materials that exemplify the incorporation of modeling practices in high school chemistry can support the state and district's initiative in implementing the NGSS.

Goals for the Study

The main goal of the study is to develop a new educative curriculum for the molecular geometry unit by examining multiple models that support teaching geometric shapes of molecules. The search for models that are most efficient in teaching molecular geometry were guided by seeking answers to the following questions:

- Which models serve as thinking tools that help to predict and explain the structure and the behavior of molecules?
- What misconceptions are the models likely to produce and what interventions or modifications can be introduced to minimize misconceptions and maximize the educational benefits?
- What is the optimal sequence for introducing the set of selected models?

The answers to the research questions guided my development of the educative curriculum materials for molecular geometry. The choice of the appropriate types of models and the way they should be introduced in the classroom are intended to help students to construct a deeper understanding of geometrical shapes and its applications in chemistry. In addition, the newly designed unit aims to minimize students'

misconceptions and to open the door for more curriculum development and revisions to better help students to excel in chemistry courses.

The product of this study, educative curriculum materials, includes resources designed to be used by teachers in classrooms to guide their instruction such as: teacher guides, student worksheets, and assessment materials. The intended approach in designing the educative curriculum materials is Model Based Teaching (MBT). MBT is based on generating, examining and revising scientific models to develop evidence-based explanations of the way the natural world works. This is the way in which many scientists work (Windschitl, Thompson & Braaten, 2008). MBT is a teaching approach that is student centered and requires collaboration with emphasis on creating opportunities for students to use models to predict the structure and the behavior of molecules.

Significance

By providing an assemblage of selected scientific models and addressing their historical context (when applicable), the new curriculum materials could help teachers appreciate the value of models as well as their limitations. Furthermore, embedding the MBT approach to modeling molecular geometry in research-based pedagogical approaches, such as POGIL and Learning-Focused Solutions (LFS) will help facilitate the incorporation of these materials into chemistry teaching. The educative features of the newly developed unit will support teachers' pedagogical knowledge (PK) and pedagogical content knowledge (PCK) as they relate to scientific practices and the nature of science (Beyer & Davis, 2009).

The newly designed unit will be beneficial not only for my students at Brandywine High School, but also for other teachers in the Brandywine School District, who may use the same pedagogical approach either in chemistry or in any branch of science. Teachers' perceptions are important; if science teachers do not have the core understanding of the nature and role of models in the development of a discipline, they will not be able to incorporate them properly in their teaching (Barnea & Dori, 1999).

In order to set the foundations for the MG unit development, in the following chapter I summarize research on the different types of models and their role in teaching chemistry, students' misconceptions in learning MG, and the use of MBT ideas that support students' understanding of molecular geometry concepts.

Chapter 2

CONCEPTUAL FRAMEWORK

The purpose of this chapter is to summarize productive areas of research that informed the development of the molecular geometry unit. These areas of research include studies on 1) the role of models and modeling in teaching chemistry and supporting understanding the nature of science, 2) how models are classified and on what basis, 3) students' misconceptions in learning MG, and 4) the use of model-based-teaching (MBT) in the context of molecular geometry given its fit with and potential for structuring my teaching unit.

Models and Modeling in Chemistry

Chemistry is a discipline that is taught, learned, and practiced with the aid of a vast range of models. Teaching chemistry depends on models such as modeling atomic structures, the Lewis models, the periodic table, the shape of molecules, etc. (Taber, 2010). Models and modeling can provide some insight and may help students to make scientists' understanding accessible. In the words of Gilbert (1995, cited in Gobert & Buckley, 2000), chemistry as a discipline is dominated by the use of models. The range and sophistication of the scientific models used by chemists to understand chemical bonding is one factor that contributes to the difficulties students typically face in this topic. Understanding the particulate nature of matter and visualizing spatial

structures of molecules are essential skills students need for solving problems in both organic and inorganic chemistry (Barnea & Dori, 1999).

A prominent value of models in science education is their contribution to visualization of complex ideas, processes, and systems (Dori & Barak, 2001). The uses of molecular models enable visualization of complex ideas, processes, and systems in chemistry teaching (Peterson, 1970). It is impossible to teach molecular structure and decide the polarity of a molecule without the aid of scientific models. The choice of the type of model has an impact on the mental image that the student creates. The Lewis model, VSEPR model, analogies, ball-stick models, computer animation models, for example, all are tools that help students to visualize complex ideas and enable them to predict the behavior of molecules.

Gilbert and Boulter (1998) defined a model as a representation of an idea, object, event, or a system. It could also be a device, a plan, a drawing, an equation, a computer program, or a mental image (Rutherford & Ahlgren, 1990). Gilbert and Boulter classified models into four main categories: mental, expressed, consensus and teaching. A mental model is a cognitive representation of an object or a phenomenon which can later turn into an expressed model when it is put in action, speech or writing. A consensus model is an expressed model that is subject to testing by a social group (scientists or classroom) which opens the door for revisions and modifications. A teaching model is an especially constructed model used to aid in the understanding of a consensus model (Erduran & Duschl, 2004).

According to Justi and Gilbert (2002) models and modeling play a central role in science education for three main reasons: to learn science, to learn about science, and to learn how to do science. To learn science, students should come to know the

nature, scope, and limitations of major scientific models. To learn about science, students should be able to appreciate the role of models in accreditation and dissemination of the outcomes of scientific enquiry. To learn how to do science, students should be able to create, express, and test their own models. Research regarding the use of models in science education shows that models included in the curriculum may often be incoherent hybrids of different scientific models. Students' limited appreciation of the nature and roles of models results from considering models as scaled versions of what is being modeled and leads to a lot of confusion among learners (Taber, 2010). Students believe the old models, which are replaced by the newly designed ones, are totally useless and they believe in the new model as the perfect representation of the phenomena of the study. Students think that models are small incomplete copies of actual objects and therefore they may not seek purposes in the model's form (Harrison & Treagust, 1998).

It is impossible to decide the polarity of a molecule without using one of the classic models, Lewis mode or VSEPR model, to structure the molecule first and then decide its polarity. Students may be able to create some mental models to express their understanding of molecular geometry in the form of an analogy, a game, or even a story. Teachers use models as aids to help explain scientific phenomena and students often make their own models of scientific phenomena to display their understanding (Treagust, Chittleborough & Mamiala, 2010).

Chemistry knowledge is represented in three main facets known as the "Triplet": macroscopic, submicroscopic, and symbolic (Johnstone, 1991) Many high school students find it difficult to understand macroscopic changes on the basis of submicroscopic explanations. The macroscopic perspective (sensory level) deals with

phenomena we can observe with the naked eye such as taking observations, naming a color of solution, or describing what happens when mixing two chemicals together. The submicroscopic level deals with the unseen where students study atomic structure, molecules, ions radius, and the nucleus. The last perspective is the symbolic one. Students write chemical equations, name compounds, and draw Lewis structures of molecules. Students face difficulties relating to these three perspectives in chemistry: macroscopic, submicroscopic, and symbolic (Gabel, 1996).

Research clearly shows that the concepts associated with chemical structure and bonding, such as molecules, ions, hydrogen bonds, and giant lattices are abstract and are highly based on the sub-microscopic nature of chemistry (Nahum, Mamlok-Maaman, Hofstein, & Taber, 2010). Models and modeling connect the macro and the sub-micro facets in chemistry. According to Woody (1995), “Modeling as a process operates between the microscopic and macroscopic levels in the characterization of structure and function of matter." (p.125). Models explain chemical behavior. Indeed, chemists use models to explain submicroscopic properties (Erduran, 2001).

Submicroscopic representations are invisible and abstract which make it most difficult for students to comprehend. Thus, students need to use multiple visual models such as Computer Animations (CA), constructed physical models, maps, equations, and analogies. The microscopic level and static particle models, as a teaching pedagogy, are useful in showing the submicroscopic world. The use of models improves students’ ability to visualize the submicroscopic occurrences of the phenomena (Adadan, Trundle, & Irving 2010; Ozmen, 2011). Molecular modeling software enables one to interactively construct ball-and-stick, space-filling, and electron density models even for large molecules. Interactive modeling programs

provide opportunities for the construction of molecules from atoms, find the lowest energy geometric structure, measure bond lengths and angles, and manipulate and rotate the model to be viewed from different angles (Dori & Kaberman, 2011).

Models and the Nature of Science

Models have dual functions: to help understand how things work or how they might work and assist in predicting the mechanical properties or the engineering principles, which may later lead to revisions or improvements of the models. Models are important in scientific research for two reasons: 1) formulating hypotheses to be tested and 2) describing scientific phenomena (Gilbert, 1995). The use of models in teaching and learning chemistry aligns with the science education initiative which was started in the 1960s. This explored the concept of doing science like real scientists, or learning by "doing science." Models are not only important in teaching and learning chemistry but they also possess a special status in the discipline. Chemists tackle many problems in their field through modeling the structure and function of matter (Erduran& Hotchkiss, 1995). For example, since the late 19^{th} and early 20^{th} century the atom structure history shows that the models of J.J. Thompson, Rutherford, and N. Bohr evolved quickly and had to contend with competing models. Rutherford's model provided greater explanatory power as compared to Thompson's model. Similarly, Bohr's model provided greater explanatory power as compared to Rutherford's model. That does not mean either of the previous models were wrong, rather this shows the tentative nature of scientific knowledge and its importance for science education (Cardellini, 2010).

Science curriculum design should promote understanding of the nature of science and provide students with experiences that are similar to those of scientists. The US National Science Education Standards (NRC, 1996) advocates the study of the NOS, science as inquiry, and unifying concepts and processes of science. Scientists and science educators agree that science is a way of explaining the natural world. Science in its essence is both a set of practices and the historical accumulation of knowledge. The recently developed Next Generation Science Standards (NGSS Lead States, 2013) emphasize learning scientific and engineering practices associated with learning the core ideas and cross-cutting concepts that are foundational to the science disciplines. In addition to developing modeling practices (as one of eight other practices), students are expected to develop an understanding of the enterprise of science as a whole as a result of engaging in questioning, investigating, data collecting and analyzing, explaining, and arguing about evidence. Consequently, there is a close connection between the goals of the Next Generation Science Standards (NGSS) and achieving a better understanding of the nature of science (NGSS Lead States: three dimensional learning, Appendix G).

The National Science Education Standards specifies that: "Models are tentative scheme of structure that correspond to real objects, events, or classes of events, and that have explanatory power. Models help scientists and engineers understand how things work. Models take many forms including the following: physical objects, plans, mental constructs, mathematical equations, and computer simulations" (NRC, 1996, p. 117). Building on earlier reforms, *A Framework For K-12 Science Education* (NRC, 2012) accentuates the importance of engaging in inquiry-based practices in order to fully understand scientific and engineering ideas:

> Standards and performance expectations that are aligned to the framework must take into account that students cannot fully understand scientific and engineering ideas without engaging in the practices of inquiry and the discourses by which such ideas are developed and refined. At the same time, they cannot learn or show competence in practices except in the context of specific content. (NRC, 2012, p. 218)

Teaching chemistry as a set of models with different levels of sophistication and applications is not an instant solution to many learning difficulties that students face in chemistry principles. Students tend to ask which model actually is the true representation of reality. The way we talk about models in class is a question for future investigation. We should teach students that scientists developed these models as ways of making sense of a range of physical and chemical properties and to predict materials behavior. As the limitations of the models were identified, they were developed, replaced, or supplemented (Taber, 2010).

The studies just reviewed provide clues for how models can be used in teaching as mediators between target concepts and learning outcomes. By revisiting the first section of the logic model that was created in Chapter 1 (Figure 1), it is now possible to summarize the essential concepts that students need to master in order to structure a valid molecular shape. Using ideas from studies summarized in this chapter, the logic model that illustrates how models mediate the chemistry concepts and the desired learning begin to take shape. Apparently, some models can serve more than a single concept while a single concept could be taught through the use of various models. For example, the Lewis model could be used to calculate the formal charge, to fulfill the octet rule, and to show any possible resonance structures. Figure 6 illustrates at-a-glance, the complexity of the molecular geometry topic and how adopting various models overlap in teaching concepts of molecular geometry. The

description of asterisked models can be found in Tables 1-3. Models followed by a single asterisk are listed in Table 1, two asterisks in Table 2, and three asterisks in Table 3. The logic model will be used in Chapter 3 alongside other criteria to guide decisions regarding the assessment materials that pertain to the curriculum unit.

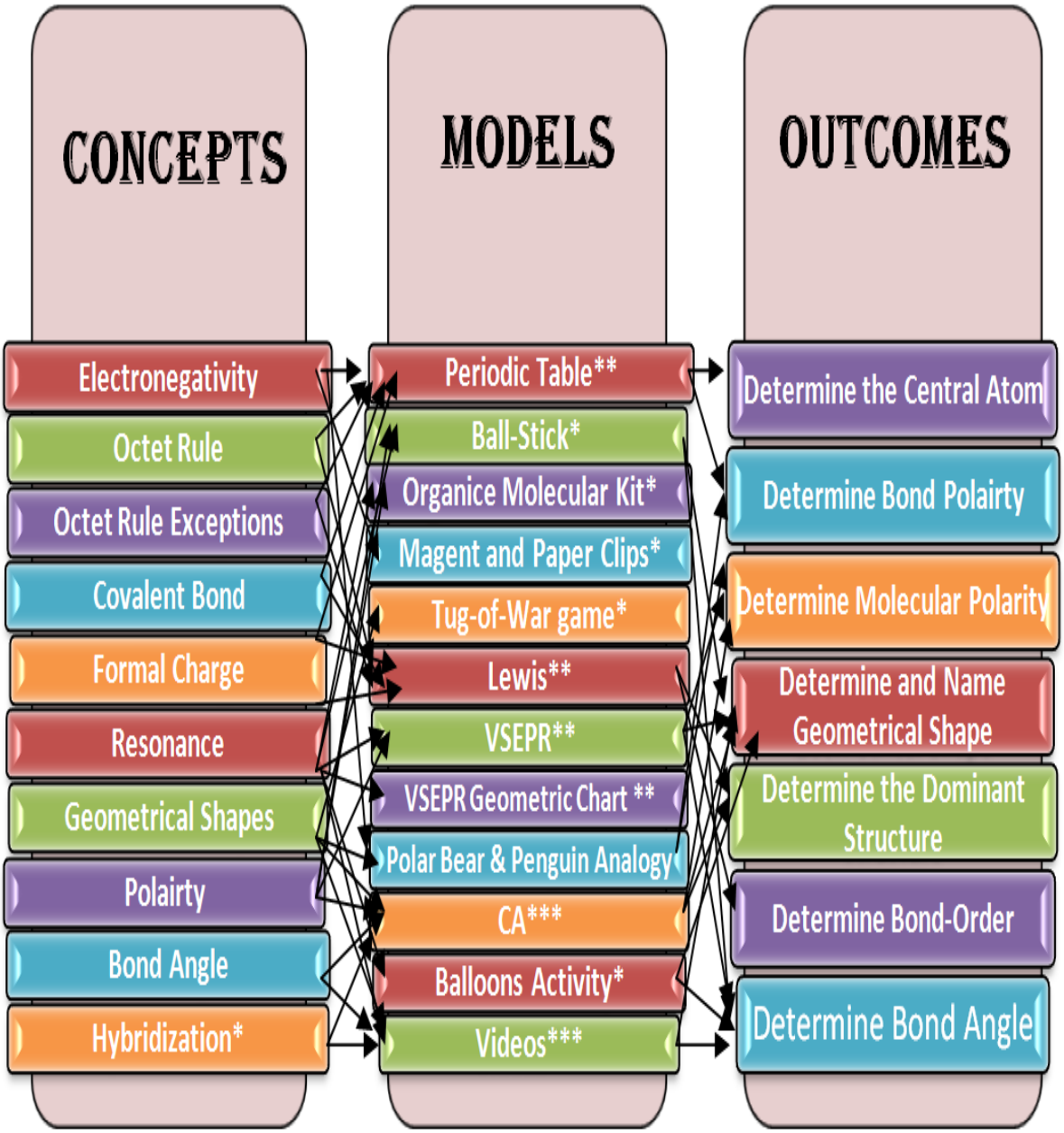


Figure 3 Models Mediating Concepts and the Learning Outcomes

Types of Models

We are diverse learners, the way our brains perceive information and comprehend it differ from one another. Some of us learn by structuring a model, drawing an image, analyzing a diagram, or looking at a map. Others learn by playing a game or, watching a video or 3D animation. In teaching molecular geometry, there are various types and modes of models which target an aspect of the phenomenon under study as well as diversify teaching.

There is a common ground among philosophers of science in their classification of models. Some categories are identical in description and simply carry a different name even though it has the exact same meaning while other categories represent different aspects of models and their uses. Bruner (1996), a cognitive psychologist, identified three types of models: enactive, iconic (image) and symbolic (conceptual). An enactive model allows for an individual to translate her experience into a model through action. For example, sometimes when scientists tackle a problem they try to mimic a phenomenon with their hands. The second model, iconic, is based on summarizing images. These kinds of models could be small scale buildings, maps, or even full scale versions of the phenomenon. Finally, the symbolic model or conceptual model is a mental construct such as an algebraic equation. On the other hand, Giere (1991) classified models into three categories: scale, analog and theoretical. The scale models and the iconic models are a common area between Giere and Bruner because both of them refer to the structure of real objects. Analog models refer to the developing of a theory of a new system based on the similarities between known systems. Finally, the theoretical model is another commonality between Giere and Bruner, both of them point to the mathematical form of scientific laws. It is clear

that there are various classifications of models. Bruner (1996), Giere (1991), Woody (1995) , and Gilbert and Boulter (1998), have defined and/or classified models based on their epistemic, cognitive, or pedagogical perspectives Bruner's and Giere's perspectives present cognitive and philosophical definition of models, while Woody's outlines some properties of models, and finally Gilbert and Boulter's framework applies models in education. Erduran and Duschl (2004) summarized the work of philosophers of science on models and modeling. They illustrated the different kinds of models, different properties of models, different classifications, and different applications in educational context (just explored earlier).

The five most commonly used types of models are as follows: the materials (constructed) - where a physical object is used, the visual- where a diagram is used, the digital-where animations and movies are used, the verbal (expressed) - where some oral description is employed; and the symbolic, where the conventions of mathematics are evoked (Gilbert & Boulter, 1998). Due to technological innovations, models take further dimensions and new shapes. Models vary from physical objects to 3D animations and software imitations (visual models). Each model brings to the table a new dimension to examine as well as some limitations or even misconceptions.

In order to determine which model or set of models are likely to be most appropriate in teaching molecular geometry, it is necessary to set main criteria to examine each candidate model and its dimensions. Using the five types of models listed above, I examine each candidate model against the four common features of scientific models identified by Woody. These features include: approximate, projectability, compositionality, and visual representation (Woody, 1995).

The projectability feature of the scientific models indicates that the model does not come with well-defined fixed boundaries, rather it is open for revisions which lead to its compositionality feature; this gives the model a potential application to new and more complex cases. Thus, I decided to consolidate the last two features under projectability. In addition to the preceding properties of scientific models (approximate, productivity, projectability, and visual representation), I expanded these properties to include two more features, predictability and flexibility, in order to situate scientific models into their educational purpose.

In the following section, I describe the different features/properties of scientific models and use examples that demonstrate the function of each in teaching the geometrical shapes of molecules.

1. Approximate: A model's structure is approximate because it omits some details and highlights others based on the criteria driving its construction. For example, the Lewis model highlights which atom is placed at the center of the molecule and which one is terminal. The model also provides a primitive demonstration of the molecular geometry which may help to identify any resonance structures. Another advantage of the Lewis model is the distribution of valence electrons around the central atoms and the prediction of the bond order. The Lewis model is a static model, it omits any kind of electron movement, electrons' cloud, or wave properties. Moreover, the Lewis model omits any other electrons in the molecules, but valence electrons bring the focus to the bonded electrons.

2. Productivity or projectability is important because the model does not come with well-defined fixed boundaries, but it is open for revisions. There is always room for improvement. A scientific model is not a goal in itself but a representation between a source and a target. The target is an unknown object or phenomenon to be explained, and the source a familiar object or phenomenon based on prior knowledge that helps to understand the target (Erduran, 2004). Having this in mind, there are no set boundaries for scientific models; rather there is room for revisions, improvements, and additions. Models and modeling can provide some insight and may help students make scientists' understanding accessible. Those kinds of models promote higher level thinking and make room for more applications.

3. Predictability: In addition to the previous characteristics of scientific models, predictability is an important feature. In an engineering design, the designer needs to depict the nature, visualize the form, and predict the structure and the behavior of the product through the use of models. The designer needs to construct models with sufficient accuracy and resolution to predict actual system behavior so design decisions can be made correctly (Radhakrishnan & McAdams, 2005). The focus of the NGSS on models and modeling highlight the importance of students being able not only to predict, but also to design scientific models. For example, students should use the Lewis model to predict the polarity of chemical molecules.

4. Flexibility: A model could be made flexible to show the motion of the atoms in the molecule. The simple representation as small-scale versions of

macroscopic objects does not reflect the nature of the electron nor its wave-particle duality. Molecule motions follow quantum mechanics rather than classical, atoms cannot be assigned a precise location, and so on (Erduran & Duschl, 2004).

5. Visual representation: A model provides a means of visual representation to typically invisible specific aspects of a phenomenon. Visual models may be expressed in one or more different representational modes. The purpose of each model dictates the mode and the functionality of the model.

The details analysis of different models relevant to molecular geometry was conducted using the five criteria of scientific models approximate, productivity (projectability), visual representation, predictability and flexibility. The results of this analysis presented in chapter 4.

Students' Misconceptions

Schurmeier et al. (2011) classified molecular geometry and molecular polarity among the eight most difficult topics for students in general chemistry. The topic requires deep conceptual understanding in addition to algorithmic proficiency; a combination of skills that many students must work to develop. Students struggle with molecular geometry and molecular polarity because they have specific misconceptions, including the notion that individual atoms have polarity; some students cannot combine the two concepts of electronegativity and polarity while others have trouble visualizing molecular shapes.

Understanding of bond polarity versus molecular polarity is also difficult for many students. A single molecule of a carbon atom and a chlorine atom is polar

covalent due to the difference in electronegativity between the chlorine atom (more electronegative) and the carbon atom. Nevertheless, the molecule of Carbon tetra Chloride, CCl_4, which composed of four chlorine atoms covalently bonded to a central carbon atom, is a non-polar molecule (Figure 4). Understanding of bond polarity versus molecular polarity is difficult for many students. By recognizing which concepts students do not grasp, instructors can plan their lessons accordingly to emphasize specific topics (Schurmeier, et al., 2011).

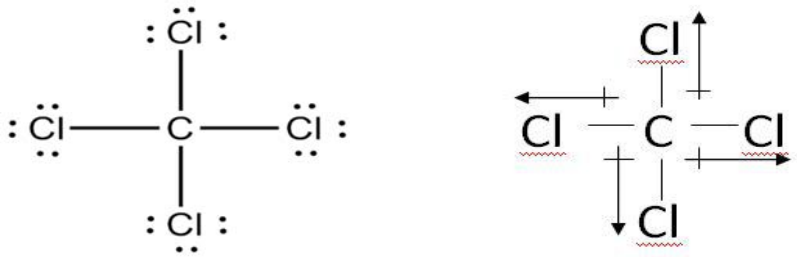


Figure 4 A Non-Polar CCl_4 Molecule

Both the flat and the 3D models of methane gas, CH_4, represent non-polar molecules. Substituting two hydrogen atoms with two chlorine atoms, dichloromethane CH_2Cl_2, (Figure 5) creates a challenge for most students. Looking at the flat model, the majority of students decide the molecule is non-polar assuming equal pull on opposite directions of the carbon atoms leading to a zero net force. On the other hand, looking at the 3D model of the same molecule, tetrahedral shape, students can more easily determine there is a net force due to the angle of the tetrahedral shape, 109.5^0, which makes the molecule of CCl_2H_2 a polar molecule. Any

misconceptions that students harbor about the fundamental concepts of atoms and molecules will impede further learning (Griffiths & Preston, 1992).

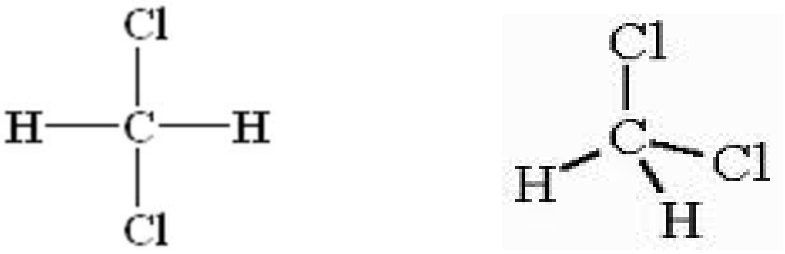


Figure 5 A Flat Molecule versus a 3D Molecule of CH_2Cl_2

Students should be made aware of the fact that models, employed in a variety of research, study and design contexts, are not complete representations of the realities they are supposed to represent (Coll, France & Taylor, 2005). In teaching molecular geometry, the representations of the Lewis model or the ball-and-stick model include dashes and sticks that are of equal length, contrary to expert understandings of molecular bond lengths. A double covalent bond is shorter than a single covalent bond and so the triple covalent bond is the shortest in comparison to the first two. Students' presumption of the identical bond lengths misleads their prediction of the structure of the molecule and therefore its polarity.

The majority of students possess a misconception about the nature of a chemical bond. Students see the chemical bond as a physical entity. This notion of a chemical bond as matter thus appeared to be linked to the everyday observation that building any structure requires energy input and its destruction releases energy, to form the basis for the prevalent alternative conception that bond making requires input

of energy and bond breaking releases energy (Boo, 1998). This misconception could be a result of earlier instruction in a Biology classroom! In the Biology course, students learn that molecules, such as carbohydrates and ATP (adenosine tri-phosphate), are source of energy and have strong bonds that store needed energy. While this is a valid concept, it gives rise to misleading concepts. What is the correct representation? Stable chemical bonds release energy as they form. Having this in mind, students could validate a molecular structure with a higher bond steric energy over another molecular structure with less bond steric energy!

In the following chapter, methodology, I present how the conceptual framework on models and modeling, types of models, and students' misconceptions were analyzed to shape the design process of the Molecular Geometry unit.

Chapter 3

METHODOLOGY

This chapter describes the curriculum design process of the Molecular Geometry unit which consisted of four phases: 1) Analyzing research on models and modeling, 2) Soliciting information from teachers about how they implement models in their curriculum, 3) Selecting a structural framework for developing the unit and integrating a number of design principles, and 4) Obtaining feedback from colleagues and experts in the fields of chemistry and circular design. The chapter concludes with an overview of the methodology.

Information obtained in each of the four phases contributed significantly to the final product. In phase one, researching models and modeling practices contributed to developing an analytical framework for determining the different characteristics of models and their contributions to understanding MG concepts. In phase two, obtaining information from teachers about their experience with teaching models provided practitioners' perspectives, other than my own, that were useful in developing the unit. In phase three, merging information obtained from model analysis and teacher input, along with research on Model-Based-Teaching, and nature of science played an important role in developing the units' content and related assessment. In phase four, obtaining feedback from colleagues provided an external perspective for further revising and refining the unit. A detailed description of the methods used in each of the four phases is described after Table 1which provides an overview of how the research questions were addressed using different data sources.

Table 1 **Mapping of Data Sources to Research Questions**

Question	Source of data	Analysis of data	Expected Outcome
Which models serve as tools for thinking that help to predict and explain the structure and the behavior of molecules?	Literature Electronic sources Printed sources Colleagues via personal interactions and social media UD college professor during STEM workshop Teacher questionnaire Logic model	Refer to tables (1-3) Analysis of literature	Advantages and disadvantages of each model which will be useful for selecting candidate models
What misconceptions are the models likely to produce and what interventions or modifications can be introduced to minimize misconceptions and maximize the educational benefits?	Classroom experience Misconceptions' literature review Teacher questionnaire High School chemistry teachers input College chemistry professor's input	Content analysis of literature Analysis of common students' misconceptions	Determine models that should be modified or supplemented by others to minimize misconceptions
What is the optimal sequence for introducing the set of selected models?	Classroom experience Mapping out unit material College professor input	Logical analysis based on information collected from the literature and colleagues	Minimizing misconceptions Improving understanding

Phase 1: Research on Models and Modeling

A very important step in preparing for unit development consisted of conducting a thorough review of students' misconceptions on molecular geometry and researching different types of models that can be used to support student learning of these concepts. The selection of optimal models constituted a foundational step in designing the new curriculum unit. After selecting a broad spectrum of different types of models, I analyzed the scope and limitations of these models, their purpose, their role in teaching molecular geometry and the possible misconceptions they may create. I chose the framework of Erduran and Duschl (2004) because it examines different perspectives of models. The work of Woody (1995) opens the door for further applications and modifications of the model itself, while the work of Gilbert and Boulter (1997) points to the models in action which refer to how the models are used in classroom. Even though Bruner (1996) and Giere (1991) provided excellent definitions of models from cognitive psychology and philosophy of science perspectives, their work is limited to the classifications and definitions of models and did not extend to cover the functionality and/or the application of models in educational settings. However, it is the application perspective in the classroom that I am most interested in as a chemistry teacher. For this reason, it was important to consider what models or sets of models serve as tools for thinking, thus enabling students to predict and explain the structure and the behavior of molecules while minimizing their misconceptions.

In order to determine which set of models will be employed for each lesson in the MG unit, I examined the properties of each model against the criteria: predictability, productivity, approximate, flexibility, and visual. Furthermore, I

considered the potential for each model to serve as a scientific tool that minimize students' misconceptions and meets the needs of diverse learners.

Phase 2: Input from Teachers

I invited 15 high school chemistry teachers and two college professors to complete a teacher questionnaire. I reached out to colleagues who are teaching at the Brandywine School District (BSD) where I teach (four teachers), science education colleagues from the same EdD program at the University of Delaware (two teachers), and colleagues from my Masters program in Chemistry Education at the University of Pennsylvania (nine teachers). A total of eight teachers completed the questionnaire; three teachers from my school district, three teachers from my Maters' program at the University of Pennsylvania, one teacher from the EdD program at the University of Delaware and a college professor teaches at a major university in Delaware.

The teacher questionnaire was administered online. It consisted of four questions:

1. What models, animations, or resources do you typically use to teach the topic of molecular geometry?

2. What do your students typically find most challenging when learning this topic?

3. What instructional tools have you used that you found most effective in addressing these learning difficulties? Please describe why

4. What instructional tools approaches have you used that you found to be least effective in addressing learning challenges? Please describe why

Responses received to these questions were analyzed. The frequency of therecurring ideas were tabulated to discern patternsamong theresponses.

Phase 3: Unit Development

The Brandywine School District implements LFS and EATS lesson format. The acronym EATS refers to the lesson design which starts with Essential question(s) followed by Activating, Acceleration, Teaching, and Summarizing strategies (Appendix B). I utilized the LFS strategies and the EATS lesson template in designing the molecular geometry lessons for two reasons: 1) It provides a planning framework that focuses on learning, and 2) It is already used by my school district, which makes the product easy to share with other teachers in the district.

Many science teachers use a limited number of models, and do not emphasize how models are developed, recognize their essential role in science learning, or consider their advantages and limitations (Gilbert, 1997). The teaching unit uses the conceptual framework of model-based teaching with a focus on students in all levels of high school chemistry. Each lesson uses an assembly of carefully selected models to address one or more aspects of the teaching unit goal(s)/ essential question(s). The teaching unit employs a diverse set of models: material, visual, digital, and mental models. The selected group of models is sequenced in such a way as to minimize the development of misconceptions.

In designing the new curriculum materials, I took into consideration the nature of science and the tentative nature of scientific theory. Science does not provide absolute truths. The history of science shows that scientists continually look for theories that provide greater explanatory power. The development of scientific theories, at times is based on inconsistent foundations. Furthermore, scientific

knowledge relies heavily, but not entirely on observation, experimental evidence, and rational arguments (Niaz & Maza, 2011).

The molecular geometry curriculum unit not only targets teaching science, but also teaching about science and teaching how to do science (Justi & Gilbert, 2002). Thus, the unit focuses on developing student understanding of practices and historical aspects pertaining to the concepts of molecular geometry, and how to use models to explain and predict related phenomena. The outcome of the design effort resulted in a total of eight lessons, formative and summative assessments.

The curriculum design process should ensure that the base curriculum materials are accurate, complete, and coherent in terms of content and effective in terms of pedagogy with good representation of concepts, a clear purpose for learning them, and multiple opportunities for students to explain and share their ideas (Davis & Krajcik, 2005). The educative curriculum unit is deliberately designed to enhance teachers' pedagogical content knowledge (PCK) in molecular geometry especially in relation to using scientific instructional representations (such as models, diagrams, analogies) and implementing the scientific practice of "developing and using models" (NGSS Lead States, 2013) more effectively. In the words of Cochran, DeRuiter and King (1993,p. 263), "increasingly strong PCK enables teachers to use their understandings to create teaching strategies for teaching specific content in a discipline in ways that enable specific students to construct useful understandings in a given context."

Phase 4: Feedback on Unit

After desgining the educative unit materials for MG, I shared the unit with a total of six teachers: Four high school teachers, three chemistry teachers, and a former

physics teacher who holds a PhD degree in chemistryto obtain their comments and feedback on the newly desgined unit.I asked them to provide their feedback on the following: 1) lessons sequences, 2) how the use of models addess students' misconceptions, and 3) unit alighment with the NGSS expectations. Of the eight teachers contacted, only two provided feedback. In addition, the designed unit was shared with a total of six chemistry college professors: two from the University of Delaware, one from Widener University, one from Ohio State University, and two instructors from Delaware Community College to review the accuracy of the content and provide their feedback and comments in addition to the committee members. Of the six college professors, only two provide comments on the designed unit.

Methodology Overview

The methods used for unit development are summarized in Figure 6. The process started with the problem statement and the challenges students face to conceptualize the topic of Molecular Geometry (MG) followed by the sources of data used to develop the teaching unit: classroom teaching experiences, literature reviews, Professional Learning Community (PLC), teacher questionnaire, logic model (see Figure 3, Chapter 2), and content analysis. Figure 6 highlights the types of models which were analyzed and selected to develop the educative curriculum materials for the teaching unit. The organizers section in this figure encompasses various components that were taken into consideration in designing the unit's pedagogical approach as NGSS, NOS, POGIL, LFS, and the EATS lesson template. This is followed by the contributions of high school chemistry teachers, college chemistry professors, and the EPP committee members to the designed unit which led to revisions, edits, and refinement of the final product.

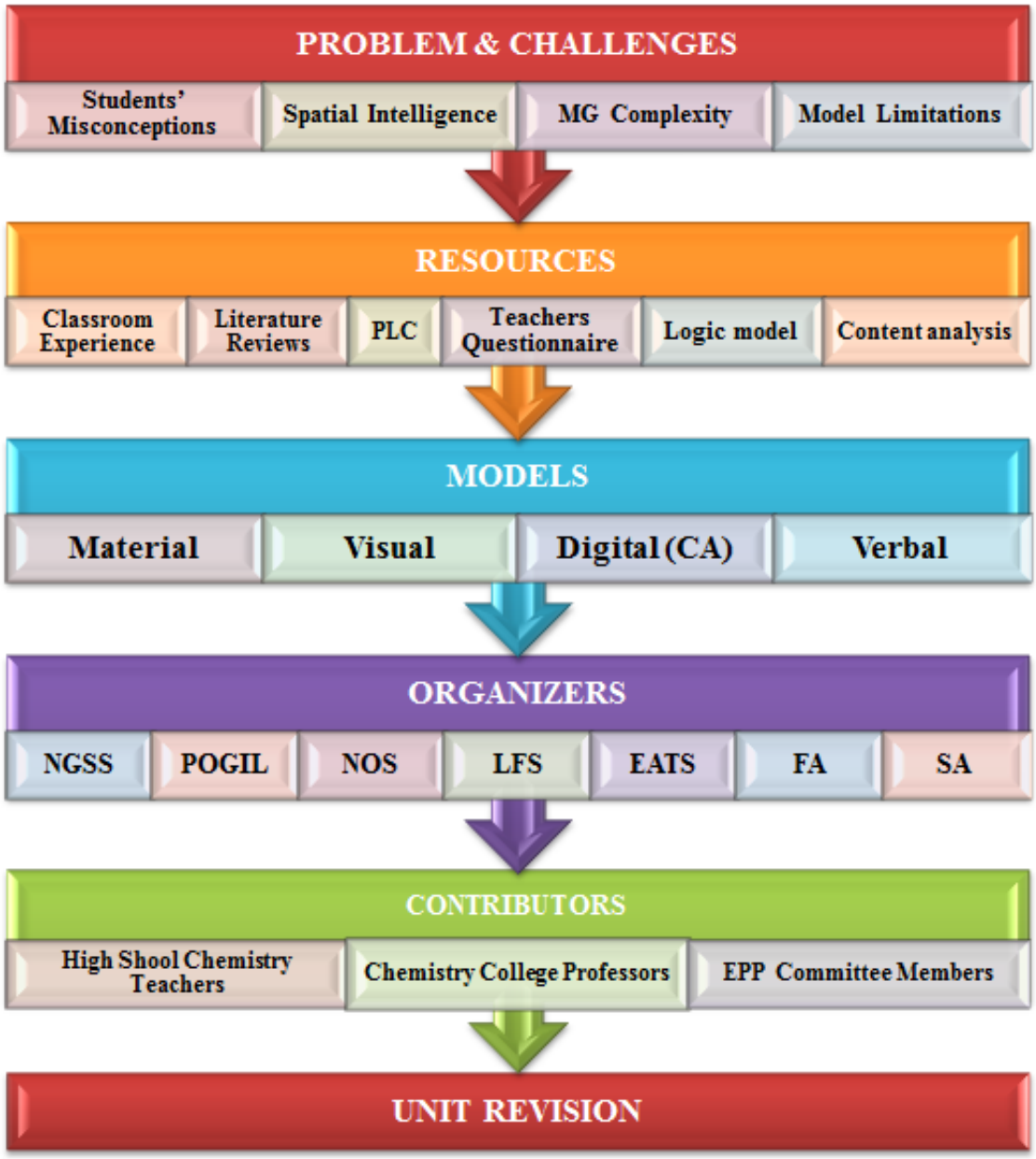


Figure 6 Unit Development Methods, Organizers, and Contributors

Chapter 4

FINDINGS AND UNIT DEVELOPMENT PROCESS

The purpose of this chapter is to report findings from the analysis of data obtained from different sources and describe how these findings contributed to the development of the molecular geometry unit. The chapter is organized along four main sections. The first section describes the analysis of research on models and modeling. The second section summarizes findings from teachers' responses to questions about their implementation of models. The third section details the various considerations that contributed to the design of the unit such as: nature of science, students' misconceptions, and how assessments are aligned with the three dimensions of the NGSS. The fourth and last section provides a summary of feedback on the unit obtained from colleagues and chemistry education experts.

Section One

Model Analysis

Analysis of data sources and development of the unit was guided by my classroom teaching experience, literature reviews, consultations with colleagues via personal interactions and social media, input from the teacher questionnaire, and professional learning community (PLC) discussions at school and district.

In order to choose the most suitable set of models for the developed unit, I identified and analyzed each model against the criteria of scientific models: approximate, productivity (projectability), visual representation, predictability and flexibility. This comparative analysis provided means for evaluating the extent to which each candidate model serves its purpose in teaching molecular geometry. In addition, I explored if a potential model is likely to create misconceptions, and if so how the model could be revised or supplemented to minimize the misconception outcomes. In order to reach that optimal goal, I utilized various resources. In addition, I used electronic sources and printed materials in my research to select the appropriate models for the educative curriculum.

The outcome of researching and analyzing different models that can be used in teaching molecular geometry is presented in Tables 2-4. The three Tables provide detailed description of each type of models; material, visual, and digital, its properties and its limitations. Table 2 introduces the properties of the selected material (constructed) model, Table 3 introduces the properties of the selected visual models, and Table 4 introduces the properties of the selected digital models. Each type of modes was examined using the analytical framework mentioned in chapter 3.

Table 2 **Properties of Select Material (Constructed) Models**

Type of Model	Model Description	Approximate	Productivity	Visual aid	Predictability	Flexibility
Ball-and-stick	A 3D display of atoms and bond angles. Single, double, and triple bonds are represented by one, two, or three sticks. Each ball is color coded for certain element and has specific number of holes with defined angels.	Yes Bond order	No	Yes Atoms, bonds order and bonding angles	Yes Polarity, angels, shape	No Very ridged model
Organic molecular kit	Color coded plastic sticks in different shapes and angles are used to build simple molecules encountered in organic/inorganic chemistry. Includes space-filling models. Provides realistic single, double, and triple bonds. Allows smooth rotation of the bonds and used to build open and cycle chains of carbons.	Yes	No	Yes Atoms, bond order, bond angles, confirmation, steric energy	Yes	Limited To organic molecule
Balloons	Group of inflated balloons tied tightly at the center. Different number of balloons and various sizes are used for different geometrical shapes	Yes	Limited Number and size of balloons	Yes Geometrical shapes	Limited Shapes	Yes
Molecular Visions (Demonstration kit)	Different sizes of plastic colored sticks used to demonstrate organic/inorganic molecules, hybridization, sigma and pi bonds. Provide well-representations of VSEPR model with color codes and defined angels.	Yes	Yes	Yes	Yes	Limited
Magnet and paper clips	Magnet (atom), paper clips (valence electrons), and paper boards present EN and shielding factors (paper boards).	Yes	Yes	Yes	Yes	Yes
Drops on a penny lab/demo	Demonstrates the Intermolecular Force (IMF) among molecules of different solutions/liquids (polar and nonpolar molecules).	Yes	Yes	Yes	Yes	Yes
Tug of war game	Use a rope and play “tug of war” to demonstrate two different models of covalent bonds; polar and nonpolar.	Yes	Yes	Yes	Yes	Yes

Table 3 **Properties of Select Visual Models**

Type of Model	Model Description	Approximate	Productivity	Visual aid	Predictability	Flexibility
Lewis	Diagram that shows bonding between atoms and none bonding electrons (lone pairs. Non- bonded electrons are represented by dots while bonded electrons are represented by lines. Sometimes wedges and dashes are used for 3D representation.	Yes	No	Yes	Yes	No
VSEPR	Each atom in a molecule achieves a geometry that minimizes the repulsion between electrons in the valence shell of that atom.	Yes	No	Yes	Yes	No
VSEPR geometries chart	The chart represents different geometrical shapes of electrons domains. For example, linear, bent, tetrahedral, trigonal planar, etc.	Yes	Yes	Yes	Yes	No
Periodic table	The periodic table of element with some basic information on atomic number, atomic mass, and type of element (metal, nonmetal and metalloid).	Yes Based on what features are presented	Yes	Yes	Yes	No
EN chart	The chart provides specific EN for most of the elements on the periodic table	Yes	No	Yes	Yes	No
POGILs	Multiples POGILs activities contain various models and address many topics in the unit following the same format of Process Oriented Guided Learning.	Yes	Yes	Yes	Yes	Yes

Table 4 **Properties of Select Digital Models, Animations, and Movies**

Type of Model	Model description	Approximate	Productivity	Visual aid	Predictability	Flexibility
PhET Colorado.edu	Multiples applets provide the ability to build single, double, and triple bonds, adding electrons lone pairs, rotate the molecules and show bond angles.	Yes	Yes	Yes	Limited Fail to represents higher bond order	Yes
Animated molecules Chemmybear.com	Pre-designed molecules provide shapes, steric numbers, polarity and hybridizations	Yes	No	Yes	Limited Pre-made tables and shapes	Limited
undergrad-ed.chemistry.ohio-state.edu	Self-tutorial on Lewis structure and VSEPR model including rules and online tests. Provides animated visual guide with online quiz where shapes, angels, and rules are provided. Explanations of right/wrong answers are available to reinforce learning.	Yes	Yes	Yes	yes	yes
PBS learning media	Tutorial presentation with limited interaction. Covers basic structure of VSEPR. Use textual and visual explanations	Yes	No	Yes	Yes	Limited
FIDO University of Arizona	Limited simulations of Lewis and VSEPR shapes. Bonding angels are not provided. Flexible vectors are available to point to angles and atoms positions.	Yes	No	Yes	Does not provide any bond angels or illustration of electrons' domain	Yes
Crash Course Chemistry series	Series of videos merges multiple approaches of teaching content; historical, NOS, PBL, MBT, analogies, etc.	Yes	Yes	Yes	Yes Depends on what kind of model is presented	Yes
The Ohio State University website	Provides useful simulations of molecular geometries. The molecules are pre-built and rotate automatically. The website provides a tutorial on how to use the Jmol applet in addition to a link on how to draw Lewis model, calculate the formal charge, resonance, and bond polarity.	Yes	Yes	Yes	Yes	Yes
Ted Edu website video series	Four minute video introduces the shape of molecules in a simplified way to introduce the VSEPR model where atoms are arranged to maximize the attraction of opposite charges and minimize the repulsion of the like charges.	Yes	Yes	Yes	No	No

The analysis of models presented in Tables (2-4) formed the basis for the rationale provided in each lesson regarding how and why the selected models were introduced in a specific order during the unit using textboxes. Furthermore, to address the nature of science, I introduced the historical context of each model (when applicable). Teaching the history of each model helps students to appreciate how the now-discredited historical models played a useful role in the development of current knowledge (Taber, 2010). Similar to lesson I, in lesson III, the Lewis model Part I, the lesson started with a brief biography on the work of Gilbert Newton Lewis (1875-1946) which includes an image of his memorandum of 1902 showing his speculations about the role of electrons in atomic structure from valence and structure of atoms and molecules.

The Strategic Use of Models in Teaching MG

According to Gabel (1996), chemistry is a very complex subject from both the research on problem solving and misconceptions. Students possess these misconceptions not only because chemistry is complex, but also because of the way the concepts are taught. A model is a simplified representation of a system, which illuminates specific aspects of the system and enables other aspects of the system.

> Models include diagrams, physical replicas, mathematical representations, analogies, and computer simulations. Although models do not correspond exactly to the real world, they bring certain features into focus while obscuring others. All models contain approximations and assumptions that limit the range of validity and predictive power, so it is important for students to recognize their limitations. (NGSS Lead States, 2013, p. 6)

Some models successfully represent an aspect or more of a system and help students to predict other aspects as well. Teachers need to handle models with care. Teachers should fully understand the model; what it presents and what it prevents. For example, the ball-and-stick model presents basic geometrical shape and eliminates other aspects of atomic and molecular structure; electrons lone pairs, electron cloud, hybridization, and formal charges. Understanding the advantages and limitations of each model leads to better teaching and as a result better understanding. In teaching a model, it is important to make it explicit how the model may represent the system and how it fails to convey other aspects of it. In other words, teachers need to teach not only the model itself but also the use of the model.

Teachers tend to simplify abstract concepts (such as molecular geometry) to improve student understanding. In the process, however, they may create more misconceptions. The use of a single model or even a set of models that belong to the same type (e.g. materials models) may contribute to students' misconceptions in molecular geometry. For example, when teaching the Lewis model to structure molecules, the bonded electrons are represented as dashes and lone pairs of electrons, which are represented as dots (Figure 7).

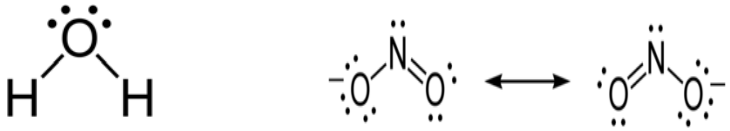


Figure 7 Water Molecule & The Resonance Structure of the Nitrite Ion

In such instances, students may perceive covalent bonds as static entities in the space between atoms. The idea of drawing dashes and dots may help students to visualize the basic structure of the molecules; however, it may also initiate a misunderstanding of the nature of chemical bonds as well as the dimensions of the geometrical shape.

The use of the material (constructed) model, ball and stick, is not merely enlargements of the molecules it is intended to represent. It is an analogue model that is used to explain new abstract concepts. The model represents some of the properties similar to aspects of the molecular structure, such as the relative diameter of the spheres represents the size of the different atom. However, in the ball-and-stick model, all sticks are of equal length, while the real molecular bond lengths are not. Other models focus on different properties of the molecule, thereby creating multiple modes of representing the same molecule. Teachers frequently use just one type of model, limiting students' experience with models and causing their model perceptions to be partially or completely inadequate (Barnea & Dori, 1999).

In my experience, the use of a single type of model may not only simplify the complexity of the bonded atoms, which is one purpose of using models, but also may create a flat image of the atomic structure! This is one of the most common student misconceptions in the area of atomic structure and the geometrical shapes of molecules. The introduction of the Lewis dot structure model should be followed by the VSEPR (Valence Shell Electrons Pair Repulsion) model. The use of the VSEPR model may help students to add a third dimension to molecular geometry. Moreover, the use of the VSEPR model helps students to determine the geometric arrangement of terminal atoms (or group of atoms) around the central one.

In addition to Lewis and VSEPR models, the use of ball-and-stick kits may enable students to manipulate the molecular structure and examine its lines of symmetry. It also may help students who are incapable of visualizing a 3D model due to the lack of spatial capacity. Each of the previous models adds a dimension to the geometrical structure as well as a limitation, such as a flat molecular structure, identical bond-length, or a ridged static molecule. However, all of these models are static and emphasize the idea of the static molecules and still electrons.

The use of a Computer Animation (CA) model may add another magnitude to the geometrical structure. Both Lewis and VSEPR models lack representations of the constant movement of electrons. Students come to the conclusion that bonded electrons are static still line(s) between the central atoms and the terminal ones. Moreover, the use of lines or dashes in the previous models emphasizes the misconception of covalent bonds as a pair of electrons lined up that hold two atoms together in the space. The reality of the increase of the electrons' density in the shared area between the two bonded atoms cannot be represented by either Lewis or VSEPR models. It is difficult if not impossible to visualize electron density between atoms by using lines, dots, dashes, wedges, or even ball and stick models.

CA models are sophisticated in the sense that they provide accurate and precise data, visualization, and manipulation options. However, students need to also learn how to represent their understanding of molecular geometry using paper and pencil. In addition, CA models are not available in every classroom and many teachers lack the proper training to use them. On the other hand, the nature of CA models may lack the predictability aspect of a model. CA models limit the ability to predict either the most valid structure or molecule polarity. Moreover, the design of the computer-based

animation provides significant data, pre-structured molecules, and a complete analysis of the geometrical shape.

In summary, each model contributes to understanding and predicting molecular structure while limiting it another way. Students may develop misconceptions not only because of the number and the types of models but also because of the order these models are introduced in classroom. For this reason, it is important to pay special attention to the types of models selected to target a given content and how they can be sequenced to reduce their individual limitations.

Section Two

Analysis of Teachers 'Responses

As mentioned in Chapter 3, during Phase 1 of the study a total of seven high school chemistry teachers and a college professor completed a teacher questionnaire (Appendix H) on teaching the molecular geometry unit. I analyzed teachers' responses in order to determine the most common types of models they used in teaching MG, how they address students' misconceptions, and their views on the most and least effective tools/instructional approaches in teaching the MG unit. The range of teachers' responses for all four questions is presented in Table 5.

Mapping teachers' responses against the literature review on students' misconceptions in learning MG and the analysis of models and modeling, presented in Chapter two "Conceptual Framework", helped me make a number of foundational decisions in developing the MG unit regarding: 1) the most common students' misconceptions, 2) the most effective groups of models, 3) the least effective models,

4) the most effective sequence in presenting models or groups of models in the teaching unit.

The analysis of teachers' responses (Table 5) show uniformity in their use of traditional physical models in teaching MG such as: ball-stick models, toothpicks-marshmallows models, and origami as can be noted in the high frequency of reference to these types of models compared to the low frequency noted when referring to visual and computer-generated models.

Teachers' responses also noted students' misconceptions and struggles when teaching molecular geometry. In particular, they highlighted two main struggles that contributed to student misconceptions:

1) Transition from a flat model (the Lewis model) to a 3-Dimenstional model (the VSEPR model) and vice versa.

2) Visualizing/conceptualizing where the bonded atoms are placed in 3D space and around the central atom.

In addition, teachers noted student struggle to understand other concepts such as: Interactions between electron lone pairs and bonded electrons, electron dot structure, valence electrons belong to the whole molecule and are distributed so that all atoms achieve octet, naming VSEPR shapes, and distinguishing between linear and bent molecules.

Table 5 **Analysis of Teachers' Responses**

Question	Most Common Responses	Frequency of Response
What models, animations, or resources do you typically use to teach the topic of molecular geometry?	Model kit (ball-stick), toothpicks and marshmallows, origami	8
	Drawing: paper and pencil, wedges and dashes	3
	Balloon activity	2
	Look up shapes online and computer generated models	2
	Visual: projector demonstration	1
	POGIL	1
What do your students typically find most challenging when learning this topic?	Translate 3D into 2-dimentional and vice versa	4
	Visualization and distinguishing between shapes	2
	Naming VSEPR shapes	1
	Interaction between electron lone pair and bonded electrons	1
	Predict molecular polarity	1
What instructional tools have you used that you found most effective in addressing these learning difficulties? Please describe why?	Casting shadows of models on a screen, individual oral quiz to identify students' misconceptions, use various examples, teaching the Lewis model fist followed by the VSEPR model, use VSEPR flowchart, use the Lewis model first and then build molecules, recognizing shape pattern, and keep it simple	
What instructional tools/approaches have you used that you found to be least effective in addressing leaning challenges? Please describe why.	Relying solely on memorization	3
	Using standard models with pre-drilled holes (students do not think).	3
	Introduce the Lewis model first, spend time on drawing and then introduce animations	2
	Videos and images do not convey the true shapes of molecules, students have to build them	1

Regarding tools considered to be most effective in addressing students' learning difficulties, teacher responses again show limited use of models: mainly physical and visual. Furthermore, only two teachers refer to how they used the Lewis model first before introducing the VSEPR model, which helped their students toward a smooth transition from a 2-dimentional model to a 3-dimentional one.

Teachers listed memorization and the use of standard models with pre-drilled holes as the least effective in addressing learning challenges. Their responses reflect their recognition that the pre-designed models limit students' thinking in learning MG. Despite recognition of their limitations, teachers' responses indicated that they use mostly the rational physical models. The limited range of types of models mentioned in teachers' responses could be due to one of two reasons: 1) limited experiences with computer modeling and simulations in relation to MG, and/or 2) narrow perception of the term 'model' as referring to some physical entity such as molecular kit. They may not think of, or refer to, a simulation for instance as a type of model.

While data obtained from the questionnaire does not help discern the actual reason for their focus on physical models, the fact that they did is useful for designing this unit. It underscores the importance of including background information in the educative curriculum unit on the different types of models and the importance of sequencing them so as to limit misconceptions and support understanding. In this regard, expanding the repertoire of teachers' use of models can address the conceptual and motivational dimensions of learning. Recent technological advancements in computer modeling and simulations are part of students' everyday life. Students play simulation games, test their own ideas in strategy games, and get extensive exposure to visual stimuli. Creating opportunities to use computer modeling and simulations in

teaching MG can be very appealing to students and can help them visualize abstract molecular structures. Furthermore, this can facilitate their conceptual understanding of what models are and the way the models work in learning science (Treagust, Chittleborough, and Mamiala, 2002).

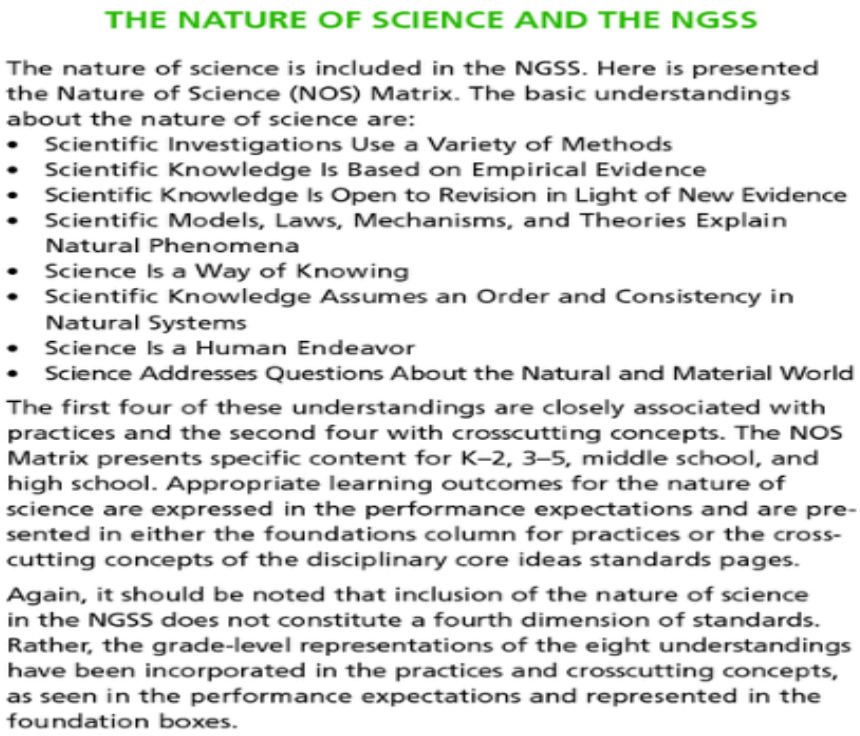
The outcome of teachers' responses and the literature review contributed to identifying the most common misconceptions students are likely to develop while learning the MG unit. Furthermore, the use of traditional models in isolation of other types of models contributes to students' misconceptions. The use of a single model or one type of model, as noted in teachers' responses, does not support model-based reasoning as promoted by the NGSS. On the contrary, it increases students' struggle to conceptualize the geometrical shapes of molecules. The literature and the majority of teachers (88%) agreed on the use of models as effective tools that help students to visualize the molecular level and support a smooth transition from two- to three-dimensional shapes.

Section Three

The Nature of Science

Most science curricula are not explicit about the Nature of Science (NOS). Thus, one goal for the newly designed curriculum unit was to promote understanding of the nature of science. In this respect, I outlined the historical context of each model (when applicable) noting how certain models were developed and revised based on the foundation of new scientific knowledge. The *Next Generation Science Standards*

advocate for making connections among the standards' three-dimensions (SEPs, DCI's, CCCs) and the Nature of Science (NOS). According to the NGSS Appendix H (NGSS Lead States, 2013), one fundamental goal for K-12 science education is a scientifically literate person who can understand the nature of scientific knowledge and has the ability to explain the natural world using evidence-based explanations. Appendix H in the NGSS, offers eight different categories of nature of science ideas that should be integrated with science standards (see Figure 8 for an overview).



THE NATURE OF SCIENCE AND THE NGSS

The nature of science is included in the NGSS. Here is presented the Nature of Science (NOS) Matrix. The basic understandings about the nature of science are:

- Scientific Investigations Use a Variety of Methods
- Scientific Knowledge Is Based on Empirical Evidence
- Scientific Knowledge Is Open to Revision in Light of New Evidence
- Scientific Models, Laws, Mechanisms, and Theories Explain Natural Phenomena
- Science Is a Way of Knowing
- Scientific Knowledge Assumes an Order and Consistency in Natural Systems
- Science Is a Human Endeavor
- Science Addresses Questions About the Natural and Material World

The first four of these understandings are closely associated with practices and the second four with crosscutting concepts. The NOS Matrix presents specific content for K–2, 3–5, middle school, and high school. Appropriate learning outcomes for the nature of science are expressed in the performance expectations and are presented in either the foundations column for practices or the crosscutting concepts of the disciplinary core ideas standards pages.

Again, it should be noted that inclusion of the nature of science in the NGSS does not constitute a fourth dimension of standards. Rather, the grade-level representations of the eight understandings have been incorporated in the practices and crosscutting concepts, as seen in the performance expectations and represented in the foundation boxes.

Figure 8 The Nature of Science as Described in the NGSS

Of the eight NOS ideas presented in the NGSS, the second and the third one are most relevant to the MG unit. These NOS categories state that “scientific knowledge is open to revision in light of new evidence” and “science, models, laws, mechanisms, and theories explain scientific phenomena. Figure 9 captures the learning progression expected for these NOS ideas. The learning progression outlines the level of detail that high school students should specifically know about NOS. However, these NOS ideas are not explicitly referenced in the unpacking of the performance expectations relevant to MG in the NGSS document (under the Standard: Structure and Properties of Matter), as is typically done in the NGSS document

The lack of explicit reference to highly relevant NOS categories signals a serious oversight that requires a focused effort to ensure that NOS is explicitly tied to educational goals at the high school level. The reconstruction of this unit ensured that this oversight is remedied and missing connections in the NGSS curriculum document are made explicit in the curriculum materials (educative curriculum unit). The intense use of models and modeling throughout the unit and the way in which they are introduced in the lessons provide ripe opportunities to explicate the tentative NOS and the role that different models types of models play in knowledge generation and revision.

Understandings About the Nature of Science				
Categories	**K–2**	**3–5**	**Middle School**	**High School**
Scientific Knowledge Is Open to Revision in Light of New Evidence	• Scientific knowledge can change when new information is found.	• Scientific explanations can change based on new evidence.	• Scientific explanations are subject to revision and improvement in light of new evidence. • The certainty and durability of scientific findings vary. • Scientific findings are frequently revised and/or reinterpreted based on new evidence.	• Scientific explanations can be probabilistic. • Most scientific knowledge is quite durable but, in principle, is subject to change based on new evidence and/or reinterpretation of existing evidence. • Scientific argumentation is a mode of logical discourse used to clarify the strength of relationships between ideas and evidence that may result in revision of an explanation.
Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena	• Scientists use drawings, sketches, and models as a way to communicate ideas. • Scientists search for cause and effect relationships to explain natural events.	• Scientific theories are based on a body of evidence and many tests. • Scientific explanations describe the mechanisms for natural events.	• Theories are explanations for observable phenomena. • Scientific theories are based on a body of evidence developed over time. • Laws are regularities or mathematical descriptions of natural phenomena. • A hypothesis is used by scientists as an idea that may contribute important new knowledge for the evaluation of a scientific theory. • The term "theory" as used in science is very different from the common use outside science.	• Theories and laws provide explanations in science, but theories do not with time become laws or facts. • A scientific theory is a substantiated explanation of some aspect of the natural world, based on a body of facts that has been repeatedly confirmed through observation and experiment. The science community validates each theory before it is accepted. If new evidence is discovered that a theory does not accommodate, the theory is generally modified in light of new evidence. • Models, mechanisms, and explanations collectively serve as tools in the development of a scientific theory. • Laws are statements or descriptions of the relationships among observable phenomena. • Scientists often use hypotheses to develop and test theories and explanations.

Figure 9 Learning progression on NOS
(Excerpt reproduced from NGSS Lead States, 2013, Appendix H, p. 5)

The study of proposed models, their limitations, and how they could be revised and improved captures these aspects of NOS in a concrete and pedagogically sound manner. Scientists and science educators agree that science is a way of explaining the natural world. Science in its essence is both a set of practices and a historical process of knowledge accumulation and revision.

Another contributing factor to mapping out the new unit materials was interactions with other teachers in the field. Direct interactions with other teachers either during Professional Learning Community (PLC) in my school or district wide PLCs, or with professors at the University of Delaware during the STEM workshops held in January and June in the past three years added another dimension to the design of the unit. Collaboration with other teachers and professors who hold unique PCKs through their daily interactions with diverse students at the high school and college levels, enriched my personal PCK and provided me with more insight for mapping the unit to better serve students and support learning outcomes. As a result, the new developed unit aims to support teachers PK and PCK.

Knowledge gained from the literature review, teacher questionnaires, and collaborations with experts in the field strongly shaped the unit design. As a result, the new unit is rich in using various models, both traditional and non-traditional, such as model kits, balloons, computer animations, applets, online activities, students' self-created models, and analogies. Even though I received limited suggestions on the sequence of using models in teaching MG, it is apparent that the transition from a two-dimensional to a three-dimensional model is a concern. As a result, special consideration was given to the order in which different models were introduced in each lesson as well as the sequence of the lessons in the developed unit to ensure a smooth transition from two- to three-dimensional geometrical shapes.

Students' Misconceptions

Addressing common students' misconceptions and struggles to understand molecular geometry were taken into consideration in the unit design. In the previous

chapter, “Methodology”, I explained in detail how to use the selected groups of models and introduce them in a classroom in a strategic order to minimize students’ misconceptions. In this section, I provide some examples to show how models can be strategically used to address student misconceptions in learning MG. For example, to help students to better understand the interaction between electrons lone pairs and the bonded electrons, the following were utilized: Lessons V and VI and VSEPR Model Parts I & II, introduced the VSEPR model using CA model, and a four-minute video, to help students visualize the core idea of the VSEPR model “minimizing the repulsion force between electrons (similar electric charges).”

Furthermore, the use of PhET, Colorado University and Ohio State University simulations (CA models), enabled students to either build digital molecules and/or manipulate pre-built molecules by reducing bond angles to observe bond steric energies and visualize how electron lone pairs and bonded electrons bounce back to maximize the distance between similar charges (electrons). Another example is to create a fluid transition from a flat model, (Lewis) to 3D model (VSEPR) and vice versa; at the end of lesson IV, students are asked to critique the limitation of the Lewis model and to revise the model to minimize its disadvantage.

Bringing to awareness the limitations of the Lewis model by evaluating its role in conveying molecular geometry emphasizes the need for a more refined model as explained in the following section; a single model versus a set of models. Moving to lessons V and VI, students examine the VSEPR model, 3D models, using clusters of various models: videos, applets, balloon activity, and a VSEPR geometries chart, which help students to examine the advantage of using VSEPR. In lesson VI, summarizing strategy and formative assessment, students are asked to complete a table

that summarizes the interdependence between the Lewis and the VSEPR models. Furthermore, by the end of the unit, the performance task uses a similar pedagogical approach to bridge both models, Lewis and VSEPR.

Assessment and NGSS Three-Dimensional Learning

Two types of assessments were developed for each lesson, formative and summative. Both types of assessments are aligned with the three-dimensional learning goals of NGSS; Science and Engineering Practices (SEPs), Crosscutting concepts (CCCs), and Disciplinary Core Ideas (DCIs). The assessment piece is a part of doing science where students need to design their own models to express their understanding of the learning target. To maximize the educational benefits and to ensure the elimination or reduction of misconceptions, specific assessments were developed that focus not only on the concept that each model introduces, but also on the model itself, its limitations, and how it could be revised, substituted or added to another model in use. The purpose of the formative assessment tasks are to address students' misconceptions and support teachers in modifying their pedagogical approach as a way of helping their students acquire the needed basic concepts and to meet the diverse needs of students.

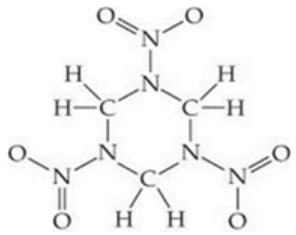
The formative assessment tasks are placed at the end of each lesson and the summative assessment can be found in Appendix G. Both formative and summative assessment tasks address the three dimensions of the NGSS (SEPs, CCCs, and DCIs), to assess not only students' understanding, but also their skills to apply what they have learned in the new context. As mentioned in Chapter 3, the logic model (Figure 3) was used to guide the decision regarding the assessment materials in the teaching

curriculum. The desired outcomes were the focus of the summative assessment tasks. In addition, to encompass the nature of science, students will be assessed on the use of the model itself, its dimensions and its limitations. In addressing the NGSS, the assessment promotes students' created models and analogies. The *Framework for K12 Science Education* (NRC, 2012) specifies that each performance expectation must the SEPs, CCCs, and DCIs appropriate for students of the designated grade level:

> Science assessments will not assess students' understanding of core ideas separately from their abilities to use the practices of science and engineering. They will be assessed together, showing students not only "know" science concepts; but also, students can use their understanding to investigate the natural world through the practices of science inquiry, or solve meaningful problems through the practices of engineering design.(Cited in NGSS Lead States, 2013, Appendix F, p. 1).

For example, at the end of the unit summative assessment (see question 4 in Figure 10), students are introduced to a complex molecule, *cyclotrimethylenetrinitramine* (plastic) to examine the students' ability to apply the Lewis model, resonance concepts, and predict bond strength and molecular polarity.

4. The "plastic" explosive C-4, often used in action movies, contains the molecule *cyclotrimethylenetrinitramine*, which is often called RDX (for Royal Demolition explosive):



a. Complete the Lewis structure for the molecule by adding unshared electron pairs where they are needed.

b. Does the Lewis structure you drew in part a have any resonance structures? If so, how many?

d. Which is the weakest type of bond in the molecule? Defend your answer.

e. Is this molecule polar or non-polar? Provide as many evidence to support your answer.

Figure 10 Cyclotrimethylenetrinitramine (Plastic) Molecule Assessment Task

Furthermore, the performance task titled, Molecular geometry and polarity, measures students' ability of not only "knowing" science concepts, but also, using their understanding to investigate the natural world through the practices of scientific inquiry.

Alignment of lessons objectives, formative assessment and the expectations of the NGSS, is illustrated in Table 7. The alignment Table shows how each lesson and topics maps to the lesson objective(s) and enduring understanding and how those are aligned with the formative assessment to measure students' understanding of the learning objective(s). For each formative assessment question, I explain how it addresses one or more of the NGSS three dimensional learning.

Feedback on the Developed Unit

After developing the unit, it was shared with two groups of experts, six high school and higher education chemistry teachers and five committee members. The comments and feedback I have received from each group shaped the final product of this study. Chemistry educators: I shared the developed unit with experts in teaching chemistry on both levels, high school and college, and they provided me with their views on the unit design, lesson format, and lessons sequences. I received some comments compliment the work and the unit design. For example, one of the responses I received from a colleague was:

> *"I'm so impressed with how you've incorporated so many ways to help students visualize and understand this abstract topic. The unit is thorough, well thought out, and organized in a logical sequence that allows students to build knowledge as they go through the lessons. Your use of POGILs, computer models and simulations, analogies, as well as the traditional ball-and-stick models gives multiple opportunities for students to grasp concepts, addressing all student learning styles. It's almost enough to make me want to have a chance to try it in the classroom!"*

I did not receive any critiques regarding the accuracy of the content, which was the main reason for sharing the unit with chemistry college professors. High school teachers provided positive feedback and showed their desire to implement the new unit in their teaching curriculum as did the college professors.

Committee members: I shared the developed unit with my committee members. Three out of a total five committee members provided me with comprehensive feedback specific to the unit. Committee members' feedback shaped the final design of the unit to address different readers: chemistry teachers,

professional development leaders, and curricular designers. I took into consideration all the solicited feedback and comments from all groups: high school chemistry teachers, college professors, and committee members. Each group provided me with valuable perspectives based on their area of expertise, which provided me with multiple lenses to edit, revise, add, and re-arrange the developed unit.

Unit Development

Overview of Unit Materials

In this section, I provide a descriptive tour of the main features of the teaching unit and how to navigate throughout each lesson. The complete unit along with its educative components is described in detail in Chapter 5. As mentioned in the previous chapters, I utilized the EATS lesson format and POGIL to fit the purpose of the Model-based teaching pedagogical approach.

The MG unit consists of eight lessons. It begins with an introductory section that provides the teacher with the lesson format, EATS, followed by lesson-by-lesson overview to highlight the main ideas in each lesson and to present how the using of MBT and POGIL addresses students' misconception. It also introduces the summative assessment which aligns with the NGSS three dimensions of SEPs, DCIs, and CCCs. In addition, it refers to additional references for the teacher and students' handouts.

Lesson Design

1. Each lesson starts with an introduction of the new topic that highlights the main idea of the lesson. The introduction of each lesson varies; it may

provide basic facts about the new concept(s) or a historical approach with some with some images as in lesson III, the Lewis Model Part I, which starts with a brief biography about Gilbert Newton Lewis (1875-1946) and his memorandum of 1902 showing his model. The lesson may also start with a model as in lesson V, VSEPR Model Part I, or review questions that relate to the previous lesson, especially if the lesson is split into two parts as in the VSEPR model parts I & II. Each lesson is estimated to be taught in a 90 minute block schedule, otherwise it should be taught over two shorter periods (45-50 minutes each)

2. Following the lesson introduction, lesson objectives, and enduring understanding, which make the purpose of the lesson explicit to the teacher and summarizes important ideas that students should understand and maintain beyond the classroom.

3. Essential question(s) should be shared with students and displayed at the beginning of the lesson to give students meaningful ideas of the lesson's purpose. Students should be made aware of the essential questions and work throughout the lesson to encompass answers to those questions. By the end of each lesson, the students' ability to answer the essential questions reflects effective teaching-learning.

4. An activating strategy focuses on how will the teacher activate the lesson or link it to students' prior knowledge, and how the teacher will stimulate students' thinking and draw their attention to the new topic. Activating strategies differ from one lesson to another. For example, in lesson I, EN

periodic trend, the activating strategies vary from asking students about the atomic radius periodic trends (prior knowledge) to an historical approach about the life and accomplishment of Linus Pauling. In lesson IV, The Lewis model part II, the activating strategy used common terms in our daily life “free radicals and antioxidants.”

5. New Vocabulary: Learning the new vocabulary for the lesson helps students toward smooth transition during the lesson activities and keeps them engaged. It reminds the teacher of terms that are new to students and that are necessary to address at the beginning of lesson or during instruction.

6. Teaching strategy: In this unit, the pedagogical approach is student-centric. It is rich in using models (MBT). Each lesson comes with an assemblage of various models: physical, digital, verbal, visual, analogies, CA, or student-created model. Most of the unit lessons include POGIL activities which require students’ collaboration, reading, writing, inquiry, analyzing, and interpretation of data/models.

7. Commentaries: In each lesson, commentaries are provided to ensure clear expectations and provide a rationale for the use of each model, highlight students’ misconceptions, and address how each model targets a specific misconception. Furthermore, the commentaries raise awareness about the limitations of each model and make explicit how and when the model should be presented in classroom. In addition, the commentaries section provides the teachers with various pedagogical approaches and gives the

teacher flexibility to choose what fits his or her class and the students' needs. On another note, the commentaries centerpieces the alignment of NOS, NGSS, and its three dimensions of Science and Engineering Practices (SEPs), Disciplinary Core ideas (DCIs), and Crosscutting Concepts (CCCs).

8. Summarizing strategy: How will students summarize what they learn during the lesson? Some summarizing strategies will be done in groups, online, using digital model, or revise and critique a classic model as in lesson IV, the Lewis Model part II, where students were asked to critique the Lewis model and revise it in a way that minimizes its disadvantages.

9. Formative assessment: There are many forms of formative assessment embedded in each lesson. POGILs are rich in formative assessment questions which provide teachers with instantaneous feedback on students' understanding or any developed misconception. Furthermore, at the end of each lesson there is a list of formative assessment questions aligned with both essential questions and NGSS standards.

10. Summative assessment: By the end of the unit, there are summative assessment questions in two different formats, multiple choice and short free responses, In addition to the Performance task which concludes the target of the teaching unit. Each summative assessment question targets a specific concept as explained in the commentaries areas (boxes). The performance task is aligned with the NGSS three dimensions of SEPs, DCIs, and CCCs.

11. Student handouts: All sources for student handouts are available as attachments by the end of the unit, or via active link to online resources.

12. Active links: Many lessons come with active links for online resources, lesson activities, and CA models, such as applet from the Colorado University (PhET) and the Ohio University and/or videos.

13. Additional resources: By the end of the unit, additional web-sites are provided for teachers as a tool to create assessments or substitute activities for students. In addition, some of the resources can be used as interactive tutorials for students.

The lesson-by-lesson overview can be found in Appendix A while the teaching unit with its entire components is presented in the following chapter (Chapter 5).

Chapter 5

TEACHING UNIT: MOLECULAR GEOMETRY

A Model-based Teaching Approach

This chapter contains the educative curriculum unit pertaining to molecular geometry. The unit provides teachers with an introduction to the unit, background information, and detailed lesson plans that include instructional options that allow them to customize the unit to the needs of their students.

Introduction

Chemistry is a highly abstract discipline that is traditionally taught and learned with the aid of various models. Molecular geometry is among the most challenging and fundamental topics in general chemistry. Students' difficulty with mastering the topic could be explained by the lack of skill to visualize three-dimensional structures and the struggle of students to use logical thinking in solving complex of steps to produce the most valid geometrical structure of molecules.

This unit aims to minimize students' misconceptions through a focus on using model based teaching (MBT). The models selected in the unit's lessons are strategically sequenced to enable students to visualize three-dimensional structures. The MBT and the Process Guided Inquiry Learning (POGIL) approaches are used to support students to develop logical thinking through collaboration in examining models and answering critical thinking questions in sequence which increases in

difficulty and ends up with extended thinking questions. This unit incorporates relevant performance expectations along the 3-dimensional learning emphasized in the Next Generations Science Standards (NGSS) and also addresses nature of science (NOS) goals that are relevant to the content.

The primary goal of this unit is to teach the geometrical shapes of the molecules. The purposes of the teaching materials are to (1) enhance student understanding of molecular geometry through the use of various models, strategically sequenced to enable them to predict and to explain the structure and the behavior of molecules, and to (2) minimize students' misconceptions about molecular geometry.

NGSS Innovations

The National Research Council's (NRC) framework views being proficient in science as both a body of knowledge and an evidence-based, model and theory building enterprise that continually extends, refines, and revises knowledge. In the NGSS, the three dimensions of Science and Engineering Practices (SEPs), Disciplinary Core Ideas (DCIs), and Crosscutting Concepts (CCCs) are crafted into performance expectations that guide the design of formative and summative assessment (The Next Generation Science Standards 2013). Attachment (5), the performance task designed by The Ohio State University "Molecular Geometry and Polarity, is an example of evidence-based assessment of the three distinct dimensions of learning outcomes. The NGSS expectations for students include making connections among all three dimensions. Students are to develop and apply the skills and abilities described in the SEP, as well as learn to make

connections between different DCIs through the CCC to help gain a better understanding of the natural and designed world. For example, the following NGSS standard, structure and properties of matter, (Figure 19) reflects the three dimensions design in a way that shows each dimension individually in a separate column which is color coded. The first column (blue) identifies the SEPs; the middle column (peach), the DCIs; and the last column(green), the CCC. Under each column, there are specifics related to each dimension which guide teacher planning and instruction as well as students' performance expectations.

HS.Structure and Properties of Matter

HS.Structure and Properties of Matter

Students who demonstrate understanding can:

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.** [Clarification Statement: Examples of properties that could be predicted from patterns could include reactivity of metals, types of bonds formed, numbers of bonds formed, and reactions with oxygen.] [Assessment Boundary: Assessment is limited to main group elements. Assessment does not include quantitative understanding of ionization energy beyond relative trends.]

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.** [Clarification Statement: Emphasis is on understanding the strengths of forces between particles, not on naming specific intermolecular forces (such as dipole-dipole). Examples of particles could include ions, atoms, molecules, and networked materials (such as graphite). Examples of bulk properties of substances could include the melting point and boiling point, vapor pressure, and surface tension.] [Assessment Boundary: Assessment does not include Raoult's law calculations of vapor pressure.]

HS-PS1-8. **Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay.** [Clarification Statement: Emphasis is on simple qualitative models, such as pictures or diagrams, and on the scale of energy released in nuclear processes relative to other kinds of transformations.] [Assessment Boundary: Assessment does not include quantitative calculation of energy released. Assessment is limited to alpha, beta, and gamma radioactive decays.]

HS-PS2-6. **Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.*** [Clarification Statement: Emphasis is on the attractive and repulsive forces that determine the functioning of the material. Examples could include why electrically conductive materials are often made of metal, flexible but durable materials are made up of long chained molecules, and pharmaceuticals are designed to interact with specific receptors.] [Assessment Boundary: Assessment is limited to provided molecular structures of specific designed materials.]

The performance expectations above were developed using the following elements from the NRC document *A Framework for K-12 Science Education*:

Science and Engineering Practices

Developing and Using Models

Modeling in 9–12 builds on K–8 and progresses to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds.

- Develop a model based on evidence to illustrate the relationships between systems or between components of a system. (HS-PS1-8)
- Use a model to predict the relationships between systems or between components of a system. (HS-PS1-1)

Planning and Carrying Out Investigations

Planning and carrying out investigations in 9-12 builds on K-8 experiences and progresses to include investigations that provide evidence for and test conceptual, mathematical, physical, and empirical models.

- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly. (HS-PS1-3)

Obtaining, Evaluating, and Communicating Information

Obtaining, evaluating, and communicating information in 9–12 builds on K–8 and progresses to evaluating the validity and reliability of the claims, methods, and designs.

- Communicate scientific and technical information (e.g. about the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically). (HS-PS2-6)

Disciplinary Core Ideas

PS1.A: Structure and Properties of Matter

- Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons. (HS-PS1-1)
- The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states. (HS-PS1-1)
- The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms. (HS-PS1-3),*(secondary to HS-PS2-6)*

PS1.C: Nuclear Processes

- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process. (HS-PS1-8)

PS2.B: Types of Interactions

- 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-PS1-1),(HS-PS1-3),(HS-PS2-6)

Crosscutting Concepts

Patterns

- Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena. (HS-PS1-1),(HS-PS1-3)

Energy and Matter

- In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved. (HS-PS1-8)

Structure and Function

- Investigating or designing new systems or structures requires a detailed examination of the properties of different materials, the structures of different components, and connections of components to reveal its function and/or solve a problem. (HS-PS2-6)

Figure 11 NGSS Standard: Structure and Properties of Matter

Current research suggests that both knowledge (DCIs and CCCs) and practice (SEPs) are necessary for a full understanding of science. The ultimate goal of an NGSS-aligned science education is for students to be able to explain real-world phenomena and to design solutions to problems using their understanding of the DCIs, CCCs, and SEPs. Students also develop their understanding of the DCIs by engaging in the SEPs and applying the CCCs. These three dimensions provide tools that students can assimilate and use to answer questions about the world around them and to solve design problems. (www.nextgenscience.org/three-dimensions).

Model and Modeling in Chemistry

A prominent value of models in science education is their contribution to visualization of complex ideas, processes, and systems (Dori & Barak, 2001). The uses of molecular models enable visualization of complex ideas, processes and systems in chemistry teaching (Peterson, 1970). It is impossible to teach molecular structure and decide the polarity of a molecule without the aid of scientific models. The choice of the type of model has an impact on the mental image that the student creates. The Lewis model, Valence Shell Electron Pair Repulsion theory (VSEPR) model, analogies, ball-stick models, and computer animation models among others all are tools that help students to visualize complex ideas and enable them to predict the behavior of molecules.

Gilbert and Boulter (2000) classified models into four main categories: mental, expressed (verbal), consensus, and teaching. A mental model is a cognitive representation of an object or a phenomenon which can later turn into an expressed model when it is put in action, speech, or writing. A consensus model is an expressed

model that is subject to testing by a social group (scientists or classroom) which opens the door for revisions and modifications.

In chemistry, the submicroscopic representations are invisible and abstract which make these the most difficult for students to comprehend. Students understand submicroscopic representations better through multiple visual models such as Computer Animations (CA), constructed physical models, maps, equations, and analogies. The microscopic level and static particle models, as a teaching pedagogy, are useful in showing the submicroscopic world. Molecular modeling software enables learners to interactively construct ball-and-stick, space-filling, and electron density models even for large molecules. Interactive modeling programs provide opportunities for the construction of molecules from atoms, find the lowest energy geometric structure, measure bond lengths and angles, and manipulate and rotate the model to be viewed from different angles (Dori & Kaberman, 2011).

Strategic Use of Models

Some models successfully represent one or more aspects of a system and help students to predict additional aspects as well. Teachers need to handle models with care because deep understanding of the model and what it presents and what it prevents leads to better teaching and as a result; better understanding. In teaching a model, it is important to make it explicit how the model may represent the system and how it fails to convey other aspects of it. In other words, teachers need to teach not only the model itself but also the use of the mode as a teaching tool.

Teachers try to simplify abstract concepts (such as molecular geometry) to improve student understanding. In the process, however, they may create more

misconceptions. The use of a single model or even a set of models may contribute to students' misconceptions of chemistry. In the Lewis model, students may perceive covalent bonds as static entities in the space between atoms. The idea of drawing dashes and dots may help students to visualize the basic structure of the molecules; however, it may also initiate a misunderstanding of the nature of chemical bonds as well as the dimensions of the geometrical shape.

Typically, the use of a single model may not only simplify the complexity of the bonded atoms, which is one purpose of using models; but, it may also create a flat image of the atomic structure! This is one of the most common misconceptions students hold about atomic structure and the geometrical shapes of molecules. The introduction of the Lewis dot structure model should be followed by the VSEPR model. The use of the VSEPR model may help students to add a third dimension to molecular geometry. It also may help students who have difficulty visualizing a 3D model due to the lack of spatial capacity. Each of the previous models adds dimensions to the geometrical structure as well as limitations.

The use of a CA (Computer Animation) model adds a conceptual and visual dimension to the geometrical structure. Both Lewis and VSEPR models lack representations of the constant movement of electrons. Students come to the conclusion that bonded electrons are static, still line(s) between the central atoms and the terminal ones.

Computer Animation models are sophisticated in the sense that they provide accurate and precise data, visualization and manipulation options. However, students need to learn how to represent their understanding of molecular geometry using an appropriate, graphic depiction mode.

The outcome of this analysis focuses on three main categories (modes) of models that are presented in Chapter four: material (Table 2), visual (Table 3), and digital (Table 4).

Pedagogical approach

The design of the educative curriculum materials for this unit's lessons is structured around a heuristic intended to support teachers to engage students as well as provide teachers with scientific instructional representations (models, diagrams, analogies). In the words of Cochran and colleagues (1993), "Increasingly strong Pedagogical Content Knowledge (PCK) enables teachers to use their understandings to create teaching strategies for teaching specific content in a discipline in ways that enable specific students to construct useful understandings in a given context." The curriculum materials are intended to support teachers' use of PCK in molecular geometry.

The Brandywine School District implements Learning-Focused Solutions (LFS) and an EATS lesson format. The acronym EATS refers to the lesson design which starts with Essential question(s) followed by Activating, Acceleration, Teaching, and Summarizing strategies (Attachment 1). In this curriculum unit, the LFS strategies and the EATS lesson template are merged in designing the molecular geometry unit. In addition, the use of Process Oriented Inquiry Learning (POGIL) and the EATS format are aligned. Each lesson uses set of models to address one or more aspects of the teaching units 'goals termed the enduring understanding in LFS and essential questions component.

This teaching unit uses the conceptual framework of Model-Based Teaching (MBT). In designing the new curriculum materials, some consideration is given to the Nature of Science (NOS) and-in particular- to the tentative nature of scientific theory. Science does not provide absolute truths. The history of science shows that scientists continually look for theories that provide greater explanatory power. The development of scientific theories, at times, is based on inconsistent foundations. Furthermore, scientific knowledge relies heavily, but not entirely, on observation, experimental evidence, and rational arguments (Niaz & Maza, 2011).In some lessons, note the outline of the historical context of multiple models noting how certain models were developed and revised based on the foundation of new scientific knowledge. The focus of this curriculum unit not only targets teaching science; but also is intended and designed to teach about science and to teach how to do science (Justi and Gilbert, 2002). Thus the unit focuses on the concepts of molecular geometry, the knowledge of practices and historical aspects pertaining to them, and how teachers can use these concepts and models to explain and predict related phenomena.

There is a tendency for teachers to use a limited number of models, and seldom emphasize how models are developed, or consider their advantages and limitations (Gilbert, 1997). For this reason, the lessons in this unit employ a diverse set of models: material, visual, digital, and mental models that are intentionally sequenced in such a way so as to minimize students' development of misconceptions, and to improve their understanding of the nature of science.

In order to reach these ultimate goals, the scope and limitations of each selected model, its purpose, its role in teaching molecular geometry and the possible misconceptions it may create, are considered. In addition, inserted textboxes provide

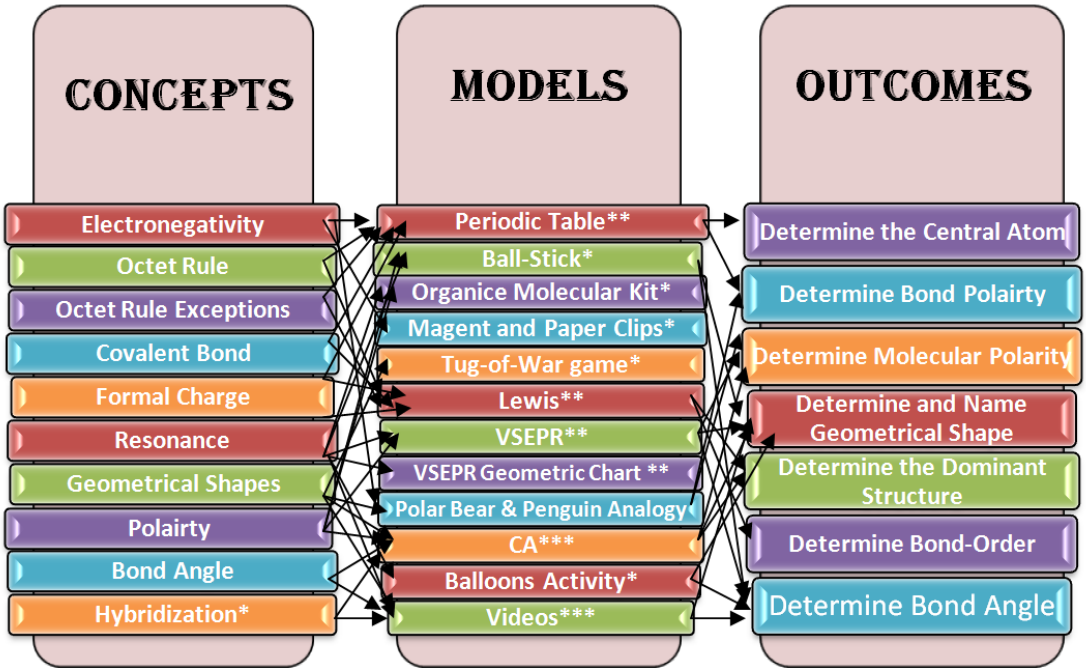
the rationale for how and why the selected models were introduced in a specific order during the unit. Where applicable, the historical context of models is emphasized to address the nature of science.

With respect to the third goal-to learn how to do science- the designed unit aims to enable students to create, express, and test their own models. This is a shared goal between the NOS and the NGSS, because developing and testing models is one of the eight scientific practices upheld by the new standards. According to the NGSS, students should develop, revise, and critique models. Models can be used to summarize data, construct explanations, formulate predictions, justify results, and facilitate communication in science.

The logic model was shared earlier in chapter 2, conceptual framework, represents how models can be used in teaching as mediators between target concepts and learning outcomes. The first section of the logic model summarizes the essential concepts that students need to master in order to successfully construct a valid molecular shape. It illustrates how models mediate the chemistry concepts and result in desired learning. Apparently, some models can serve more than a single concept; while a single concept could be taught through the use of various models. For example, the Lewis model could be used to: calculate the formal charge, fulfill the octet rule, and show all possible resonance structures.

Figure 5, illustrates, a-at-glance, the complexity of the molecular geometry topic and the overlap adoption of various models in teaching molecular geometry. The description of asterisked models can be found in Tables 1-3. Models followed by a single asterisk (*) are listed in Table 1, two asterisks are listed in Table 1, and 2 asterisks are listed in Table 3. In addition, the logic model was used alongside other

criteria to guide decisions regarding the assessment materials that pertain to the curriculum unit. Note: hybridization is not a part of Honors chemistry course (Chemistry 1).



Models Mediate between Concepts and the Outcomes

Teaching with Models

Various types of models have been researched, examined, and deliberately selected to serve the goals of the teaching molecular geometry. Models are sorted in different groups (as can be seen in Tables 1-3) in order to choose the most suitable set of models for the developed curriculum unit. Each model was identified and analyzed against the criteria for scientific models: approximate, productivity (projectability),

visual representation, predictability and flexibility. For each lesson, a select set of models were examined through a comparative analysis to determine the extent to which each model serves its purpose in teaching molecular geometry. In addition, in some lessons, it is noted if a potential model is likely to create misconceptions, and -- if so-- how the model could be revised or supplemented to minimize the misconception outcomes.

In order to reach that optimal goal, various resources were employed such as literature on scientific models and modeling as well as on students' misconceptions in molecular geometry, chemical bonds, and polarity, high school teachers' questionnaire on teaching molecular geometry, and college professors' feedback on the designed educative curriculum.

Assessment

The formative and summative assessments developed for this unit align with the goals of NGSS. The assessment component is a part of doing science where students will need to design their own models and/or revised an existing model to express their understanding of the taught concept. To maximize the educational benefits, and to ensure the elimination or reduction of misconceptions, specific assessments are developed. Those assessments are intended to focus not only on the concept that each model introduces, but also on the model itself, its limitations, and how it could be revised, substituted or used effectively with another model.

Two types of assessments have been developed for the educative curriculum unit: formative and summative assessments. The formative assessment is materialized in various formats:

A. In the middle of each lesson in form of Process Oriented Guided Inquiry Learning (POGIL) activities contain; questions, summarization strategies, building models and revising, developing rules, digital interactive applets, peer reviews, and classroom discussion.
B. At the end of each lesson where the teacher could utilize it as formative assessment to guide the subsequent lesson or as summative assessment by the end of each lesson. In addition, a unit summative assessment is provided to address the main concepts taught in this unit.

The purpose of the formative assessment tasks is to address students' misconceptions and support teachers in modifying their pedagogical approach as a way of helping their students acquire the needed basic concepts and meet the diverse needs of students.

The summative assessment tasks are placed at the end of the unit. The designed summative assessment tasks target NGSS core ideas as well as scientific and engineering practices. These tasks assess not only students' understanding, but also their skills in applying what they have learned in new contexts. The logic model (Figure 3) was used to guide the decision regarding the assessment materials in the teaching curriculum.

The desired learning outcomes are the focus of the summative assessment tasks. In addition, to encompass the nature of science, students could be assessed on the use of model itself, its dimensions and its limitations. To address the NGSS core ideas as well as scientific and engineering practices, the assessment will promote models and analogies created by students. *The Framework for K-12 Science Education*

(NRC, 2012), specifies that each performance expectation must combine a relevant practice of science or engineering with a core disciplinary idea appropriate for students of the designated grade level:

> "*Science assessments will not assess students' understanding of core ideas separately from their abilities to use the practices of science and engineering. They will be assessed together, showing students not only "know" science concepts; but also, students can use their understanding to investigate the natural world through the practices of science inquiry, or solve meaningful problems through the practices of engineering design."*(Cited in NGSS Lead States, 2013, Appendix F, p. 1).

Table 7 presents the alignment of each lesson objective, essential question, formative assessment, and the NGSS three-dimensional learning components: Science and Engineering practices, Crosscutting Concepts, and Disciplinary Core Ideas. Aligning the lessons' objectives with the formative assessment promoted by the NGSS expectations assures the clarity of the teaching objectives for both teacher and students. Furthermore, it fulfills one of the unit design goals to encompass the vision of the NGSS to be proficient in science as both body of knowledge and an evidence-based, model and theory building enterprise that continually extends, refines, and revises knowledge (NRC, 2012).

Table 6 **Alignment of Lesson Objectives, Essential Question, Formative Assessments, and NGSS3D Strands**

Lesson Topic	Lesson Objectives	Essential Questions	Formative assessment	NGSS
Periodic Trend: EN	Use the EN trends to predict the relative EN of atoms. Explain how atomic radius and shielding factor contributes to elements' EN Identify the EN trend throughout periods and groups on the periodic table.	What are the factors that influence elements' EN? How does the periodic table (Model) help to predict the relative EN of atoms?	Which element in each pair has the lower EN? Provide your evidence for each answer. a) Li , N b)Mg, Br c) K, Cs d)Na, I Arrange the following elements in order of increasing attraction for electrons in a bond: a) Antimony, fluorine, indium, selenium b) Francium, gallium, germanium, phosphor, zinc	DCI: Structure and properties of matter CCCs: Patterns SEP: Use models to predict SEP: Using model to predict pattern DCI: Structure and properties of matter CCCs: Patterns
Covalent Bond	Apply the octet rule to atoms that bond covalently. Explain the formation of single, double, and triple covalent bonds. Relate the strength of covalent bonds to bond dissociation energy. Use elements EN to predict the polarity of a covalent bond.	Explain how covalent bonds (single, double, and triple) are formed? How can you identify the bond polarity? Why triple covalent bond is the hardest to break? What type of laboratory evidences are needed to support your answer?	How does the octet rule apply to covalent bonds? How is this different from how it applies to ionic bonds? Why do elements on the same side of the periodic table tend to form covalent bonds? Why do elements on the opposite sides of the periodic table tend to form ionic bonds?	CCC: Compare and contrast, cause and effect. DCI: Structure and properties of matter CCC: Cause and effect DCI: Structure and properties of matter SEP: Using models CCC: Pattern DCI: Types of interactions SEP: Using models, cause and effect.

Lewis Model Part I	Evaluate the use of the Lewis model to predict covalent bonding patterns in molecules. Design basic steps to draw Lewis models. Use the octet rule, valence electrons, and elements' EN pattern to draw a valid Lewis structure for molecules and polyatomic ions.	What are the main steps used in drawing Lewis Structures for molecules and polyatomic ions? How to validate a Lewis structure of molecules and polyatomic ions?	Online 20 self-graded multiples-choices exercise on the Lewis model practice. Ask students to provide their reasoning (in writing) for each choice based on their created set of rules to draw Lewis structure ions and molecules.	DCI: Structure and properties of matter SEP: Developing and using models. Constructing explanations.
Lewis ModelPart II	Explain the three exceptions to the octet rule and identify molecules in which these exceptions occur. Identify the molecules with more than one equivalent Lewis structure. Use the concept of formal charge to identify the dominant Lewis structure.	What are the three exceptions to the octet rule? Provide some example of molecules do not follow the octet rule. Explain why resonance occurs and identify resonance structures. How can one calculate the formal charge of each atom in a structural formula of molecules and thus the overall change of the molecule?	Ask students to work in groups of three, develop two columns note to evaluate the Lewis model; its advantages and disadvantages. And then ask students to design solutions in a way that minimize the disadvantages of the Lewis model (Model V: student-created model). https://www.stolaf.edu/depts/chemistry/courses/toolkits/121/js/lewis/ (Model VI) Use the online applet to draw valid Lewis structures by. The online applet will calculate the FC for each atom to help students to predict the validity of the structure. Use the following link to show students how to calculate the formal charge.www.chem.ucalgary.ca/courses/351/Carey5th/Ch01/ch1-3-2.html The link provides FA questions.	SEP: Critique, evaluate, and revise models. Developing and using models. Constructing explanations and designing solutions. DCI: Structure and properties of matter SEP: Developing and using models. Obtaining, evaluating, and communicating information. Using models, analyzing and interpreting data.

VSEPR Model Part I	1. Use the VSEPR model to predict the geometrical shape of molecules and polyatomic ions. 2. Apply the VSEPR model, bond order, and element EN to determine bonds angle in molecules and polyatomic ions	What is molecular geometry? How is the VSEPR model used to predict the shape of and the bond angles of molecules? What factor(s) affect bond angel? How VSEPR model is used to determine the bond angle in molecules and polyatomic ions?	Use the following worksheet provided to summarize the interdependence between the Lewis and the VSEPR models. Also, the activity works as not only an exit ticket for the lesson but also as a formative assessment for the VSEPR model part I.	SPE: Developing and using models. Constructing explanations. DCI: Structure and properties of matter
VSEPR Model Part II	1. Use the VSEPR model to predict the geometrical shape of molecules and polyatomic ions. 2. Utilize VSEPR model, bond order, and element EN to determine bonds angle in molecules and polyatomic ions	1. How is the VSEPR model used to predict the shape of and the bond angles of molecules? 2. What are the factor(s) that affect the bonding angel? 3. How VSEPR model is used to determine the bond angle in molecules and polyatomic ions?	Use the following seven questions quiz from the Ohio State University. Seven multiple choice questions address, https://undergrad-ed.chemistry.ohio-state.edu/cgi-bin/quiz.pl/quiz/TEST/tut.1	DCI: Structure and properties of matter SEP: Developing and using models. Constructing explanations.
Polarity Part I	1. Predict the polarity of covalent bonds and the polarity of molecules. 2. Compare and contrast polar and nonpolar covalent bond and molecules. 3. Describe the characteristics of polar molecules.	How is EN used to determine bond type& bond polarity? 2. How are Lewis and VSEPR models used to predict the polarity of molecules? 3. What are the factors to consider in predicting the molecular polarity?	a) Determine the geometrical shape. b) Predict the polarity of each molecule. c) Provide adequate evidence that supports your prediction. (16 molecules)	DCI: Structure and properties of matter SEP: Developing and using models. Constructing explanations. Engaging in argument from evidence. CCC: Structure and function

Polarity Part II	1. Predict the polarity of covalent bonds and the polarity of molecules. 2. Compare and contrast polar and nonpolar molecules. 3. Describe the characteristics of polar molecules.	1. How to use Lewis and VSEPR models to predict the polarity of molecules? 2. What are the factors to consider predicting the molecular polarity?	Predict whether these molecules are polar or nonpolar. For each molecule provide valid reasoning(s) for molecular polarity. HBr, SO2, XeF4, NF3, BCl3, H2O, CO2	DCI: Structure and properties of matter SEP: Asking questions and defining problems. Developing and using models. Constructing explanations. Engaging in argument from evidence.
Performance Task	1. Write Lewis structures for molecules. 2. Classify bonds as nonpolar covalent, polar covalent, or ionic based on EN differences. 3. Recognize exceptions to the octet rules; draw accurate representations. 4. Describe 3-D shapes of simple molecules based on VSEPR theory. 5. Predict polarity based on geometry and individual dipole moments.	Activity 1: Drawing Lewis structures Activity 2: VSEPR and predicting MG Activity 3: Molecular Polarity		DCI: Structure and properties of matter Types of interactions SEP: developing and using models. Analyzing and interpreting data. Constructing explanations Obtaining, evaluating, and communicating information CCC: patterns. Structure and function

Lesson Scope and Sequence

Each lesson begins with the lesson topic followed by the goals/objectives of each lesson and the selected group of models for the lesson. Table 7 provides an overview of the lesson sequence and presents what group of models used in each lesson to support the lesson goals to maximize students' understanding of the molecular geometry unit and to minimize the development of misconceptions.

Each lesson is designed for a 90-minute block. If the school's schedule does not follow the 80-90 minutes block setting, one the following options can be followed: 1) Break longer lessons into shorter ones, 2) Use a form of blended learning where students do online activities and save classroom time for argumentation, critique and collaboration, and 3) Follow recommendations provided in each example lesson for different approaches by using shorter videos, fewer activities, alternate between POGILs and worksheets

To the extent possible, teach the lessons in the curriculum unit in the order provided in this document. The recommended sequence is intended to enhance understanding of molecular geometry through the use of various models. The order is strategically organized to enable students to predict and explain both the structure and behavior of molecules and, at the same time, minimize students' misconceptions of molecular geometry concepts. Within each lesson, a variety of models are used to maximize students learning to reach the learning goal.

Table 7 **Lesson Sequence with an Outline of Objectives and Set of Models Pertaining to each Lesson**

Topic/ Sequence	**Goals/Objectives**	**Models**
Lesson I Periodic Trend (EN)	Use the electronegativity trends to predict the relative electronegativities of atoms. Explain how atomic radius and shielding factor contributes to elements' electronegativity (EN) Identify the EN trend throughout periods and groups on the periodic table.	Video I: Linus Pauling (Historical) Video II: Linus Pauling (Vitamin C) Periodic table (Electronegativity chart) Periodic Trend POGIL EN periodic trend graph The magnet and paper clips demo Blank periodic table Dissociation energy table
Lesson II Covalent Bond	Apply the octet rule to atoms that bond covalently. Explain the formation of single, double, and triple covalent bonds. Relate the strength of covalent bonds to bond dissociation energy. Use elements EN to predict the polarity of a covalent bond	The "lunch time" analogy "What is covalent bond" POGIL (three models) Tug of war game analogy (or physical activity outdoor) Covalent bonding animation Dissociation energy table

Lesson III Lewis Model Part I	Evaluate the use of the Lewis model to predict covalent bonding patterns in molecules Use the octet rule, valence electrons, and elements' electronegativity pattern to draw a valid Lewis structure for molecules and polyatomic ions. Design basic steps to draw Lewis models.	Gilbert Newton Lewis's memorandum (1902) Video: Crash course chemistry: Bonding models and Lewis structures **https://www.youtube.com/watch?v=a8LF7J__Eb0IA** "Lewis Structures" POGIL Part A" students to create a list of rules/steps to draw valid Lewis Structures (student-created model) Applet I: Build Lewis structures http://chemsite.lsrhs.net/bonding/images/lewis%20dot%20tutorial.swf Applet II**:** build single, double, and triple covalent bonds. http://phet.colorado.edu/en/simulation/build-a-molecule
Lesson IV Lewis Model Part II	Explain the three exceptions to the octet rule and identify molecules in which these exceptions occur. Identify the molecules with more than one equivalent Lewis structure. Use the concept of formal charge to identify the dominant Lewis structure	Octet rule exceptions: student-created model Digital models, videos, and external links to more digital/animated models http://chemwiki.ucdavis.edu/Theoretical_Chemistry/Chemical_Bonding/Lewis_Theory_of_Bonding/Violations_of_the_Octet_Rule Resonance model of the carbonate ion, CO_3^{-2} The Lewis structures of the sulfate ion SO_4^{-2} Summarizing strategy: (student-created model) Online applet to draw valid Lewis structures by choosing molecules from the drop list https://www.stolaf.edu/depts/chemistry/courses/toolkits/121/js/lewis/ How to calculate a formal charge www.chem.ucalgary.ca/courses/351/Carey5th/Ch01/ch1-3-2.html

Lesson IV VSEPR Model Part I	Use the VSEPR model to predict the geometrical shape of molecules and polyatomic ions. Apply the VSEPR model, bond order, and element electronegativity to determine bonds angle in molecules and polyatomic ions.	Various Lewis and VSEPR models http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch8/vsepr.html TEDEd: George Zaidan and Charles Morton shape our image of molecules: http://ed.ted.com/lessons/what-is-the-shape-of-a-molecule-george-zaidan-and-charles-morton#watch Building Lewis models using molecular kit VSEPR geometries chart.
Lesson VI VSEPR Model Part II	Use the VSEPR model to predict the geometrical shape of molecules and polyatomic ions. Utilize VSEPR model, bond order, and element electronegativity to determine bonds angle in molecules and polyatomic ions	The Ohio State University simulation of molecular geometries https://undergrad-ed.chemistry.ohio-state.edu/VSEPR/ Balloons model (student-created model) Online quiz from Ohio State University. https://undergrad-ed.chemistry.ohio-state.edu/cgi-bin/quiz.pl/quiz/TEST/tut.1
Lesson VII Polarity Part I	Predict the polarity of covalent bonds and the polarity of molecules. Compare and contrast polar and nonpolar covalent bond and molecules. Describe the characteristics of polar molecules.	BF3 Lewis model H2O Lewis model Polar Bears and Penguins Comic/POGIL http://achs.roselleschools.org/UserFiles/Servers/Server_3154010/File/Chakraborty/Penguins-and-Polar-Bears-Comic%20book.pdf Polar, Nonpolar, and Ionic Bonding POIGIL www.myips.org/cms/lib8/IN01906626/Centricity/Domain/8123/**polar**ity_**pogil**.doc

Lesson VIII Polarity Part II	Predict the polarity of covalent bonds and the polarity of molecules. Compare and contrast polar and nonpolar molecules. Describe the characteristics of polar molecules.	Tutorial on molecular polarity and the steps to determine molecular polarity http://www.marin.edu/homepages/ErikDunmire/CHEM105/Concept_Review/Polarity/Polarity.html Crash Course Chemistry #23 https://www.youtube.com/watch?v=PVL24HAesnc "Drops on a Penny" demonstration/lab https://www.teachengineering.org/lessons/view/duk_drops_mary_less "Molecule Polarity" simulation https://phet.colorado.edu/en/simulation/molecule-polarity Molecular polarity guided activity (POGIL Lab) https://phet.colorado.edu/services/download-servlet?filename=%2Factivities%2F3960%2Fphet-contribution-3960-7132.pdf

Lesson I: Periodic Trends: Electronegativity (EN)

Around 1935, an American chemist, Linus Pauling developed a scale to describe electronegativity, a measure of attraction an atom in a molecule has for the bonding electrons it shares with another atom.

Lesson Objectives& Enduring understanding:

1. Use the electronegativity trends to predict the relative electronegativities of atoms.
2. Explain how atomic radius and shielding factor contributes to elements' electronegativity (EN)
3. Identify the EN trend throughout periods and groups on the periodic table.

Essential Questions:

1. What are the factors that influence elements 'electronegativity?
2. How does the periodic table help to predict the relative electronegativities of atoms?

Activating strategies:

Review the previous lesson on atomic radius trend:

1. What is the trend in the atomic radius as you go from the left to right in a row on the periodic table? Explain why?

2. What is the trend in the atomic radius as you go from the top to bottom in a group on the periodic table? Provide a minimum of three pieces of evidence to support your answer.
3. Historical approach (NOS): Use the following 14-minutevideo*(model I)* on the history of chemical bonds and various models of Ernest Rutherford, Neils Bohr, Robert Millikan, and the work of the two times Noble Prize winner, Linus Pauling (Figure 12), to summarize the work and collaborations of scientists 'various models of chemical bonds. https://www.youtube.com/watch?v=atr-OImgwUU

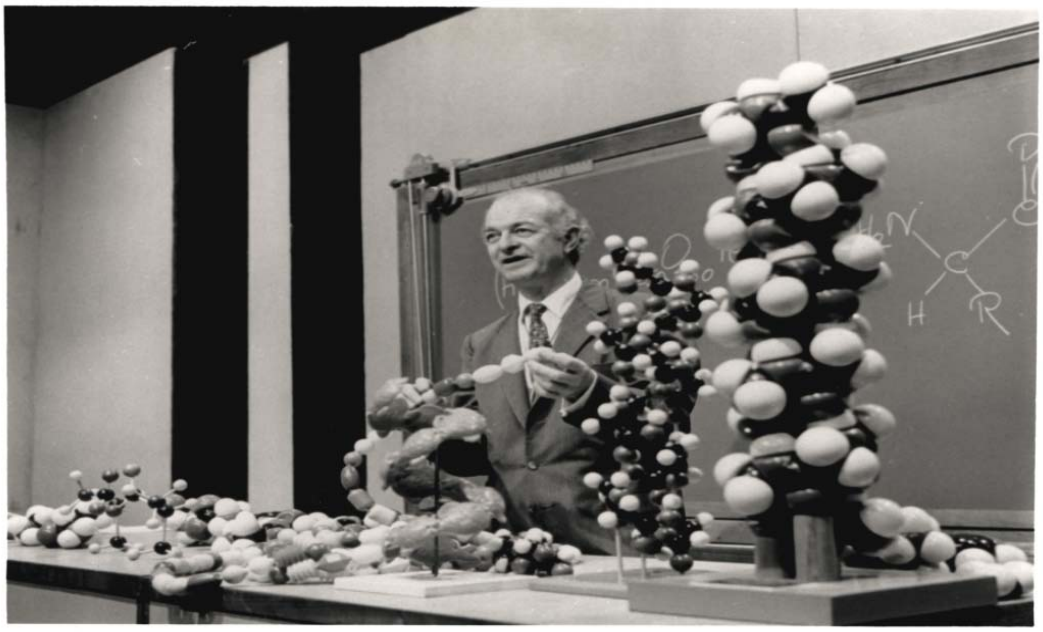


Figure 12 Oregon State University Library. Ava Helen and Linus Pauling

4. Real-life application approach: Use a seven-minute video *(model II)* on Linus Pauling for chemistry real life application (vitamin C and drinking orange juice). The video covers the concepts of EN, covalent bonding, and polar covalent bonds.

   https://www.youtube.com/watch?v=7bOQ0ccY3f4

The teacher can choose between the historical approach and the real-life application approach the choice depends on classroom time limit. If possible, sharing both short videos maximize the benefits for students to apprehend and/or appreciate the nature of science.The recommended video is a short one, 14 minutes to fit with the lesson timeline. However, for more of a historical approach, there are longer documentary videos (around 60minutes)https://www.youtube.com/watch?v=WHzG3nTA27Mthat cover the life of Linus Pauling, some of which include information about his life and achievements which could be assigned as out-of-classroom project.

Another video, 135 minutes, is a long lecture of Dr. Pauling himself (his voice). https://www.youtube.com/watch?v=6w4Kgij-Wlw

NOS: The recommended historical approach reflects the Nature of Science where all scientific knowledge can also be seen to be embedded in a global scientific community. This community has a particular culture, expectations and accumulated knowledge – all of which are essential to increasing scientific knowledge. In addition, it reflects the imperial nature of science. http://sciencelearn.org.nz/Nature-of-Science/Tenets-of-the-nature-of-science

New vocabulary:

Periodic trends, atomic radius, shielding factor, electronegativity (EN)

Teaching strategies:

- Students work in groups of three for 30 minutes on the “Periodic Trend” POGIL (attachment 1) *(model III).*
- Class reconvenes to discuss the students’ answers of the POGIL activity.

- Use the PowerPoint "Periodic trends" with the focus on graph *(model IV)* analysis (Figure 13).

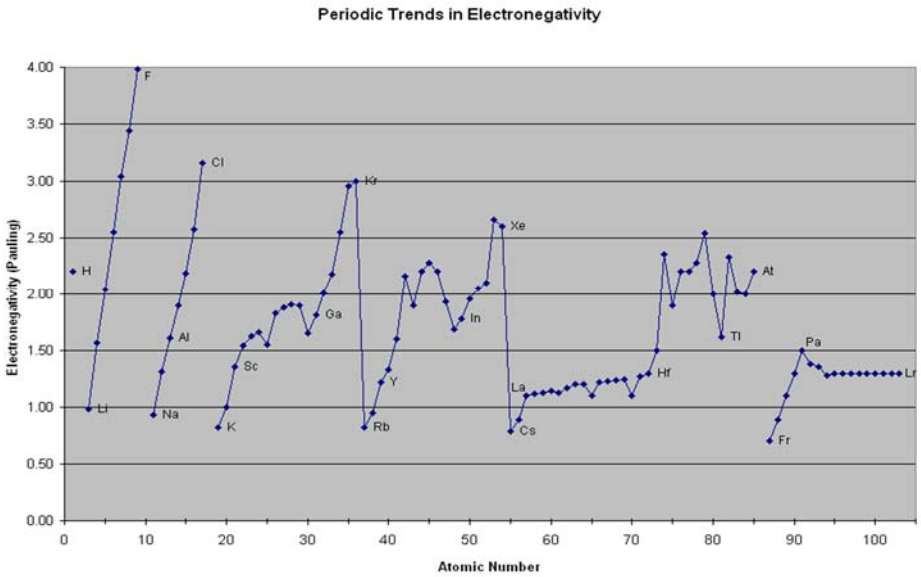


Figure 13 EN Periodic Trend versus Atomic Number

- **The magnet model/demo *(model V)*:** use a strong magnet, paper clips, and several pieces of cardboard to model the force of attraction between the positive nucleus (magnet) and electrons (paper clips). Use several pieces of cardboard to model the shielding factor from the core shells.

Misconception: The teacher should highlight the use of the model, including boththe advantages and limitations. The magnet model may contribute to students' misconceptions of EN. Many students believe EN property measures the force of attraction between the nucleus of an atom and its valence shell electrons. However, EN is a measure of an atom's tendency to pull electrons towards itself while bonded to another atom (bonded electrons). To avoid developing or contributing to students' misconception, the teacher may refer to the paper clips as bonded electrons between two atoms (not valence electrons of a single atom). In addition, the teacher may use specific number of paper clips (2, 4, or 6) to refer to the covalently bonded electrons. The teacher can denote that element neon has no unknown EN. Since no compounds of neon have been prepared yet, its EN has not been measured.

Periodic table model *(model VI)*: use a periodic table with elements electronegativity written (Figure 14) or customize a table from the following web-sites to help students to observe the EN trends within periods and groups.

Figure 14 Periodic Table of Electronegativity Values

http://chem.libretexts.org/Core/Inorganic_Chemistry/Descriptive_Chemistry/Periodic_Trends_of_Elemental_Properties/Periodic_Trends
http://www.sciencegeek.net/tables/tables.shtml
http://sciencenotes.org/printable-periodic-table/

Summarizing strategies and Formative assessment:

- Students developing model (NGSS): Use a blank periodic table (Figure 15) and ask students to draw arrows that model the periodic trends of the atomic radius and EN from the left to right and top to bottom. Ask students to use different colors for each trend. In addition, students should write the reason(s) to explain each pattern. When done, ask the students to scrutinize the relationship between the atomic radius and EN.

*Blank periodic table (Figure 15): http://science.widener.edu/~svanbram/ptable_1.pdf

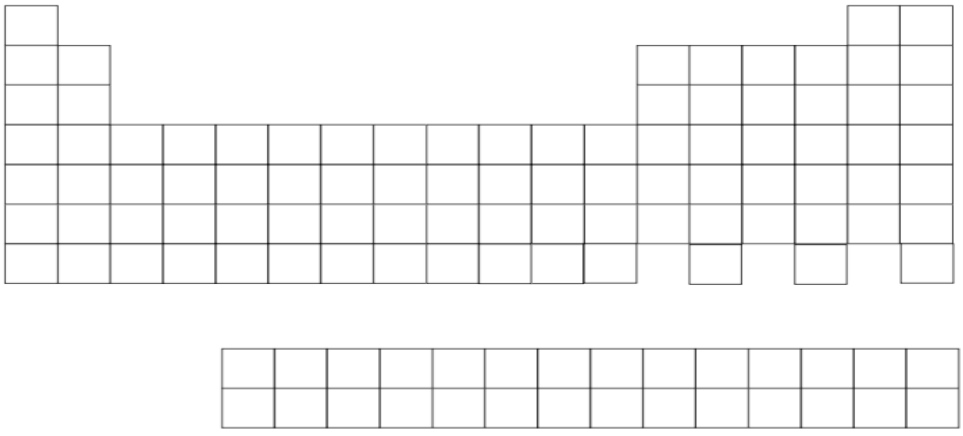


Figure 15 Blank Periodic Table

- Extended thinking:

  Ask students to predict the diagonal trend of the atomic radius and EN on the periodic table.

Formative assessment:

1. Which element in each pair has the lower electronegativity? Provide your evidence for each answer.

a) Li , N

b) Mg, Br

c) K, Cs

d) Na, I

2. Arrange the following elements in order of increasing attraction for electrons in a bond

a) Antimony, fluorine, indium, selenium

b) Francium, gallium, germanium, phosphor, zinc

Each question in the formative assessment addresses a learning target:
Question 1:

a) Li, EN trend across a period, increases left to right.
b) Mg, EN trend across a period and group, increases left to right and bottom to top.
c) Cs, EN trend in a group, decreases top to bottom.
d) Na, EN with two factors in effect, which trend has the major effect, atomic radius versus shielding factor.

Question 2:

a) In, At, Se, F
b) Fr, Zn, Ga, Ge, P

NGSS: Students may use electronegativity chart (model) to answer this question. The chart (model) help students to observe two factors in effect; moving across a period and down within a group. Students should use argument to explain which factor is dominant when comparing elements' electronegativities.

Lesson II: Covalent Bond

Atoms can combine to achieve an octet of valence electrons by sharing electrons. A covalent bond is a chemical bond that involves the sharing of valence electrons between atoms. In a covalent bond, the shared electrons are considered to be part of the complete outer energy level of both atoms involved. Covalent bonding occurs when elements are relatively close to each other in EN among the nonmetals element. Depending on the number of shared electrons; single, double, and triple covalent bonds are formed to create a molecule.

Lesson Objectives & Enduring Understanding:

1. Apply the octet rule to atoms that bond covalently.
2. Explain the formation of single, double, and triple covalent bonds.
3. Relate the strength of covalent bonds to bond dissociation energy.
4. Use elements EN to predict the polarity of a covalent bond.

Essential Questions:

1. Explain how covalent bonds (single, double, and triple) are formed.
2. How can you identify the molecular polarity?
3. Why is the triple covalent bond the hardest to break? What type of laboratory evidence is needed to support your answer?

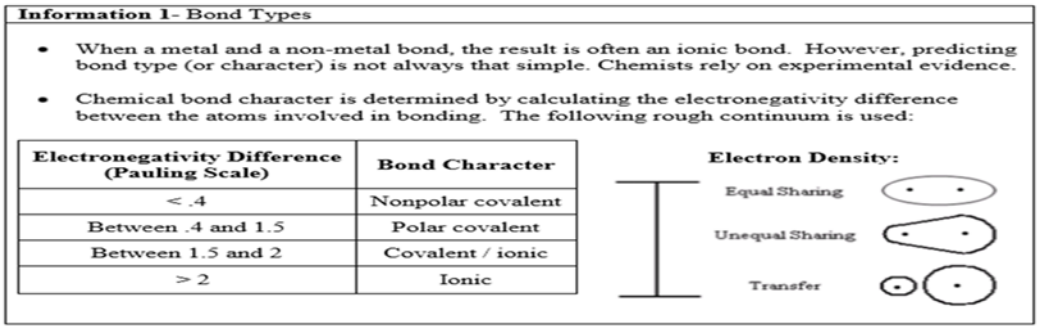
Activating strategies:

Review the previous lesson on the EN trend predict trend:

1. Use the EN periodic trends to predict which element tends to lose electrons and which tends to gain electrons. Provide evidence to support your answer.
2. Which are the most and the least electronegative elements on the periodic table?

Teaching strategies:

- Use the "Lunch time" analogy *(model I)* to introduce the topic of covalent bonding.
- Students work in groups of three for 30 minutes on the "What is a covalent bond" POGIL (Figure 16).Students will examine three different models:
  1- Pauling scale (Figure of electronegativities and model of different types of chemical bonds (diagram of electron density) *(model II).*



Information 1- Bond Types

- When a metal and a non-metal bond, the result is often an ionic bond. However, predicting bond type (or character) is not always that simple. Chemists rely on experimental evidence.
- Chemical bond character is determined by calculating the electronegativity difference between the atoms involved in bonding. The following rough continuum is used:

Electronegativity Difference (Pauling Scale)	Bond Character
< .4	Nonpolar covalent
Between .4 and 1.5	Polar covalent
Between 1.5 and 2	Covalent / ionic
> 2	Ionic

Figure 16 Pauling Scale of Electronegativity

2- Electrons orbital diagram of two fluorine atoms (Figure 17) and the formation of a single covalent bond illustrated by the Lewis dot diagram *(model III).*

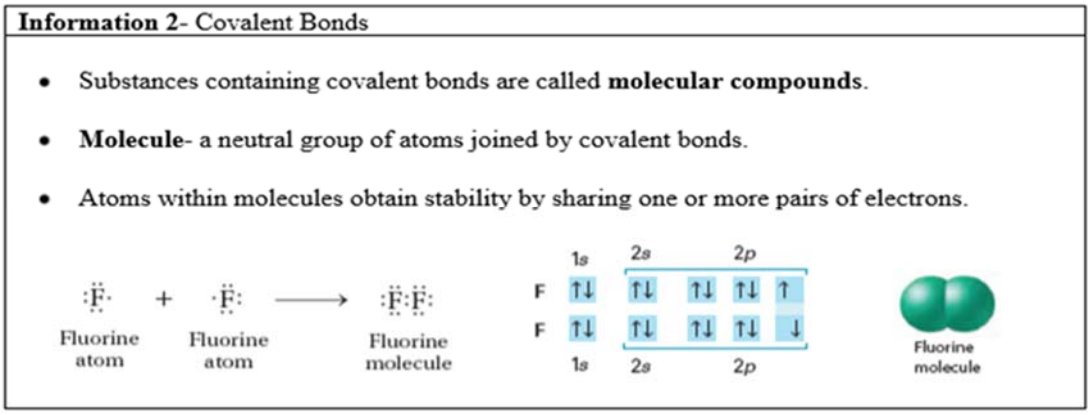


Figure 17 Electrons Orbital Diagram of Two Fluorine Atoms

3- The formation of a water molecule from two hydrogen atoms and an oxygen atom (Figure 18).

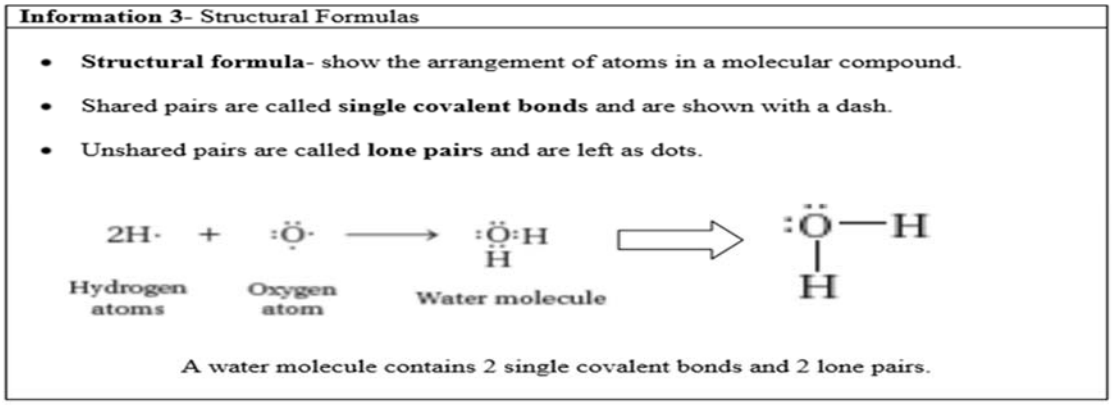


Figure 18 A Model of Formation of Water Molecule

- Class reconvenes to discuss students' answers to the POGIL activity *(model IV).*
- Use the "Tug of war game" analogy *(model V)* to explain the nature of the covalent bond.

Analogy1: "Lunch time" *A nonpolar covalent bond*: trading one half of your sandwich for one half of your friend's sandwich (electrons are shared equally between the atoms).*A polar covalent bond*: Your friend giving you most of his lunch for a bite of your lunch(unequal sharing of electrons).*A coordinate covalent bond*: a person sits next to you and eats from your lunch (one atom contributing both of its electrons to the shared pair, while the other atom contributes nothing).

Analogy 2: "Tug of war game" (Figure 19) A covalent bond forms when two atoms share a pair of electrons, but what does "share" mean? A covalent bond is like a "tug of war game" that can't be won by either team, yet neither side gives up trying to win.

Figure 19 Tug of War Game

New vocabulary:

Covalent bond, polar covalent, nonpolar covalent, coordinate covalent, electrons lone pairs, dissociation energy, single covalent bond, doubles covalent bond, and triple covalent bonds.

Both "Lunch time" and "Tug of war" analogies use daily life experiences:

1- Imagining eating lunch at the school cafeteria helps students to differentiate between the three types of covalent bonding: nonpolar, polar and coordinate covalent. The sandwich (food) represents the number of shared electrons while the two students represent the bonded atoms.

2- Tug of war game: students can go to the school gym or an open area and use a rope and play "tug of war." The teacher uses the game to represent two different modes of covalent bonding, nonpolar and polar. Two teams of the same strength where the ribbon stays in the middle despite both teams are pulling in opposite directions, represent the nonpolar covalent bond. When one team is stronger (still not winning) pulls the ribbon towards their team, it represents a polar covalent bonding where electrons are shared unequally.

Misconception: The first analogy helps students to understand the sharing aspect of the covalent bonding. However, the analogy fails to represent the pulling forces from the two nuclei of the bonded atoms (unless students are fighting for food). To complement the lunch time analogy, the second analogy is used to illustrate the pulling force felt by the bonded electrons due to the force of attraction between each nucleus and the bonded electrons.

- **Animation *(model VI)***:

Use the two-minute video on "Ionic and covalent bonding animation" to help students to distinguish between ionic and covalent bonding.

https://www.youtube.com/watch?v=QqjcCvzWwww

The short video provides a simple animation of the formation of an ionic bond between a sodium atom and a chlorine atom versus the formation of a covalent bond between an oxygen atom and two hydrogen atoms to produce a water molecule. The animation illustrates the difference between chemical bonds based on the difference in electronegativities of the bonded atoms. In addition, the teacher can help students to use key terms to differentiate between different types of chemical bonds, electrons transfer (ionic bonding) and electron share (covalent bonding).

Summarizing strategies:

1. Predict the type of bond, bond order, and the nature of bond (polar, nonpolar) for the following molecules (Provide your reasoning(s):
   a) O_2 (double covalent bond)
   b) N_2 (triple covalent bond)
   c) HF (a single polar covalent bond)
   d) Place the molecules in order, low to high, based on the bond dissociation energy. Explain your answer.

Formative assessment:

1- How does the octet rule apply to covalent bonds? How is this different from how it applies to ionic bonds?

2- Why do elements on the same side of the periodic table tend to form covalent bonds?

3- Why do elements on the opposite sides of the periodic table tend to form ionic bonds?

Misconception: Students may predict the nitrogen molecule has the highest dissociation energies due to the triple covalent bonding.However, the teacher should discuss the nature of the bond, polar versus nonpolar and guide students to predict how it affects the rate of dissociation energy of the bond. Both nitrogen and oxygen molecules have nonpolar covalent bonds. On the other hand, HF has a polar covalent bond. Students may predict which factor has the most effect, polarity or bond order, and therefore predict the order of the dissociation energy of the three molecules.Later on, the teacher providesstudents witha dissociation energy table*(model VII)* for data analysis to confirm or refute their predictions.

TABLE 7.1 Average Bond Dissociation Energies, *D* (kJ/mol)[a]

H—H	436[a]	C—H	410	N—H	390	O—H	460	F—F	159[a]
H—C	410	C—C	350	N—C	300	O—C	350	Cl—Cl	243[a]
H—F	570[a]	C—F	450	N—F	270	O—F	180	Br—Br	193[a]
H—Cl	432[a]	C—Cl	330	N—Cl	200	O—Cl	200	I—I	151[a]
H—Br	366[a]	C—Br	270	N—Br	240	O—Br	210	S—F	310
H—I	298[a]	C—I	240	N—I	—	O—I	220	S—Cl	250
H—N	390	C—N	300	N—N	240	O—N	200	S—Br	210
H—O	460	C—O	350	N—O	200	O—O	180	S—S	225
H—S	340	C—S	260	N—S	—	O—S	—		
Multiple covalent bonds[b]									
C=C	611	C≡C	835	C=O	732	O=O	498[a]	N≡N	945[a]

[a] Exact value

Dissociation Energy Table

https://usflearn.instructure.com/courses/986898/files/31116394

Different approach:
The teacher provides students with the dissociation energies table and asks students to locate the dissociation energies for N_2, O_2 and HF and to explain why HF molecule has higher dissociation energy than the O_2molecule. Student should refer to fluorine high EN (from the previous lesson) and how it affects the strength of the covalent bond.

NGSS: both pedagogical approaches help students to apply, predict, build connections, and use data to provide evidence for their claim/prediction. The first approach requires more classroom time than the latter

Lesson III: The Lewis Model Part I

In 1916 Gilbert Newton Lewis (1875–1946) published his seminal paper suggesting that a chemical bond is a pair of electrons shared by two atoms. In 1902, while Lewis was trying to explain valence to his students, he depicted atoms as constructed of a concentric series of cubes with electrons at each corner. This "cubic atom" explained the eight groups in the periodic table and represented his idea that chemical bonds are formed by electron transference to give each atom a complete set of eight outer electrons (an "octet"). Lewis's theory of chemical bonding continued to evolve and, in 1916, he published his seminal article suggesting that a chemical bond is a pair of electrons shared by two atoms. Subsequently elaborated on this idea and introduced the term covalent bond*.) For cases where no sharing was involved, Lewis in 1923 redefined an acid as any atom or molecule with an incomplete octet that was thus capable of accepting electrons from another atom; bases were, of course, electron donors.*

(www.chemheritage.org/historical-profile/gilbert-newton-lewis). *(Model I)*

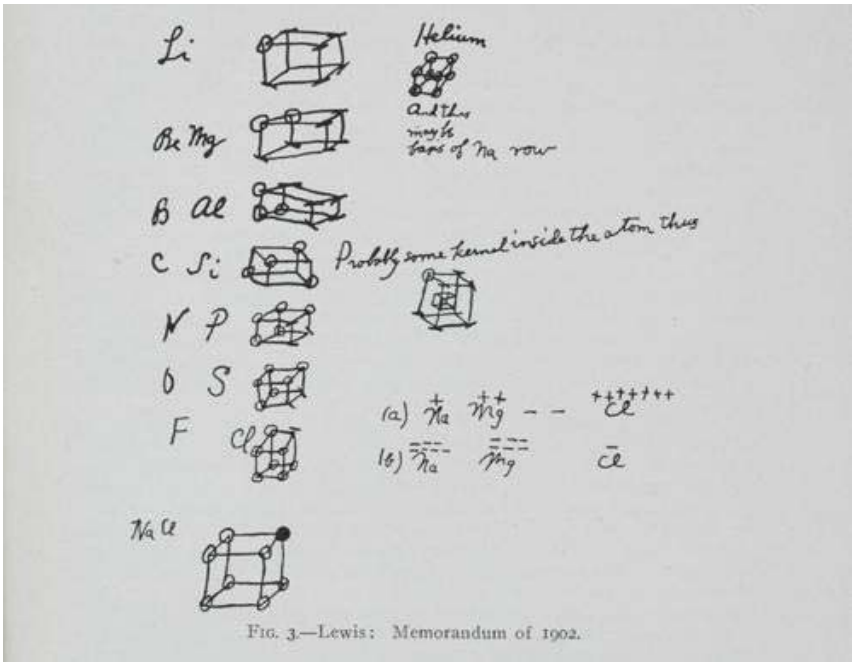


FIG. 3.—Lewis: Memorandum of 1902.

Gilbert Newton Lewis's memorandum of 1902 showing his speculations about the role of electrons in atomic structure from Valence and the Structure of Atoms and Molecules *(1923), p. 29.CHF Collections.*

A Lewis Structure is a representation of covalent molecules (or polyatomic ions) where all the valence electrons are shown distributed about the bonded atoms as either shared electron pairs (bond pairs) or unshared electron pairs (lone pairs). A shared pair of electrons is represented as a short line (a single bond). Sometimes atoms can share two pairs of electrons, represented by two short lines (a double bond). Atoms can even share three pairs of electrons, represented by three short lines (a triple bond). Pairs of dots are used to represent lone pair electrons. (www.smc.edu/projects/28/Chemistry_10_Experiments/Ch10_Molecular_Shapes.pdf)

Lesson Objectives& Enduring understanding:

1. Evaluate the use of the Lewis model to predict covalent bonding patterns in molecules
2. Design basic steps to draw Lewis models.
3. Use the octet rule, valence electrons, and elements' electronegativity pattern to draw a valid Lewis structure for molecules and polyatomic ions.

Essential Questions:

1. What are the main steps used in drawing Lewis Structures for molecules and polyatomic ions?
2. How to validate a Lewis structure of molecules and polyatomic ions?

New vocabulary:

Structural formula, Lewis model, electrons lone pairs, bonded electrons.

Activating strategy:

Review the previous lesson on the covalent bond:

1. What is the structural formula for water molecule, H_2O?
2. Use Crash course chemistry: Bonding models and Lewis structures

   (Model II)

   https://www.youtube.com/watch?v=a8LF7JEb0IA

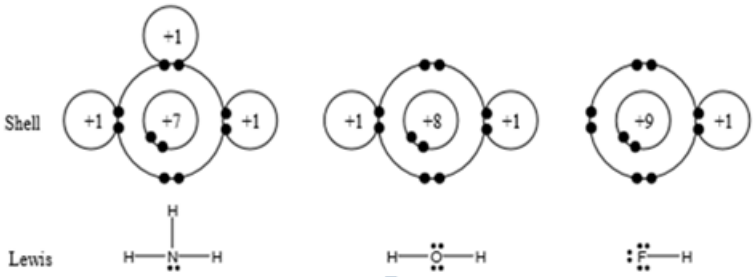
NOS: It is recommended the teacher introduces the historical work of Gilbert Newton Lewis (1875-1946) and how he depicted atoms as series of cubes which may stimulate a discussion about the shape of an atom: is it spherical, cubical, flat, three dimensions, or what? The history of the Lewis model reflects the NOS; the history of science shows that scientists continually look for theories that provide greater explanatory power and the development of scientific theories, at times is based on inconsistent foundations.

NGSS: The eleven minute video "Bonding models and Lewis structures" reviews the differences between the ionic and the covalent bonds. The video does not only explain the use of the model in molecular geometry, but it also explains the model itself and its limitations, which the teacher should emphasize throughout the unit. The video introduces the concept of Lewis modeling with some visual aids of simple molecules, which may help students to proceed easily through the later activity, "Lewis Structures" POGIL.

Teaching strategies:

1. Students work in groups of three on the "Lewis Structures" POGIL Part A (attachment 3) *(model III*), for 45 minutes. When done, ask students to create a list of rules/steps to draw valid Lewis Structures for molecules and polyatomic ions *(model 1V: student-self created model).*

2. Class reconvenes to discuss students' answers to the POGIL activity.
3. Share students' created rules/steps *(Model IV)* (NGSS: students creating models) to draw valid Lewis structures (you may use google.doc) and guide students to refine their steps and place them in order. After the class, agree on the set of rules/steps, ask students to use their own created rules to draw a Lewis structure of the following molecules; CH_4, CO_2, NH_3, HCN, and H_2CO.



Electrons' Energy Levels and the Lewis Model

NGSS: Students may struggle with where to place the electron lone pair of the NH_3 molecule or which atom should be placed in the middle (centric atom) and which are terminals. Additionally, students may struggle to draw the last two molecules (HCN, and H_2CO) because it contains three different atoms. The teacher should share the students' work and ask students to revise/add steps (NGSS: students revise their own models) to address the placement of electrons lone pairs and the concept of the central atom versus terminals atoms. The teacher may link the concept of EN to the Lewis structure model by discussing why the central atom should be the least EN and how to locate it on the periodic table (to the left and down on the periodic table) following the EN periodic trend (CCCs).
The above molecules do not contain any exception to the octet rule which will be addressed in the Lewis structure model part II.

NGSS: The first two figures were introduced in the previous lessons of the Lewis dot structure of element and covalent bonding. Examining the same models again in this POGIL activity helps students to connect various concepts and to conceptualize the 3D structure of molecules (CCCs).

Energy Levels and Lewis representations:
Misconception: This figure creates a link between the valence shells electrons and covalent bonds in a molecule. Most of Lewis models focus on the bonded electrons and the lone pairs in isolation of the valence shell. As a result, students create a misconception of a static covalent bond, solid dashes and dots (representation of bonds and electrons). The use of the above model provides a better illustration of the Lewis model tominimize the misconception of the static covalent bond. For the best use of this model, the teacher should emphasize the constant motion of electrons and refer to covalent bonding as higher electrons density (the probability of electron spending more time)between the nuclei of the bonded atoms. In addition to the POGIL models, the use of animation of covalent bonding provides another visual aid to students which help them to conceptualize the sharing concept of covalent bonding among valence shells electrons.

Applet I*(model V)*:

http://chemsite.lsrhs.net/bonding/images/lewis%20dot%20tutorial.swf

Use applet to build Lewis structures' molecules. The applet provides students with a chance to build different types of molecules using single bonds. However, if the molecule includes double or triple bonds, it is pre-structured (Figure 20).

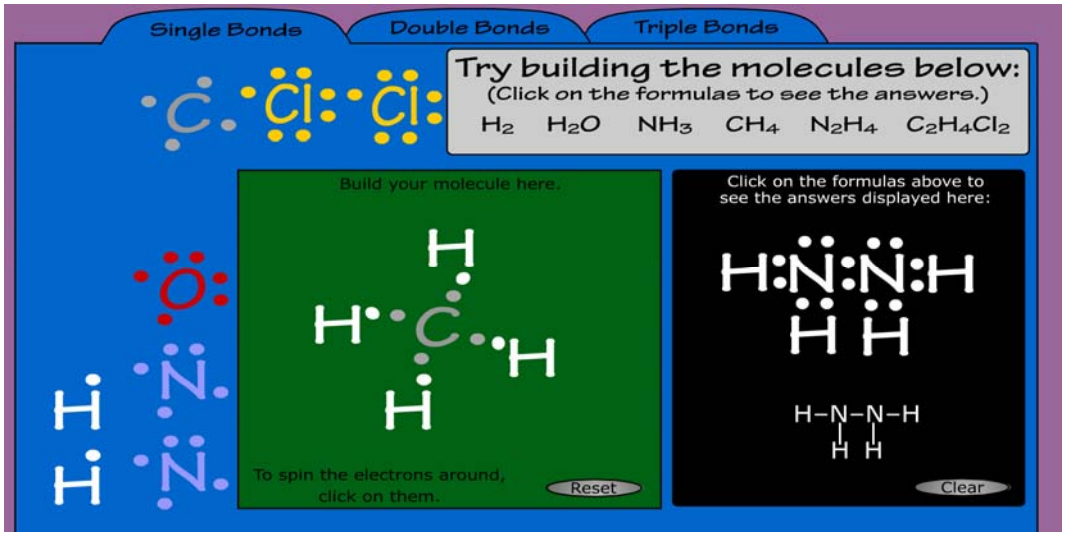


Figure 20 Building Lewis Models Applet

Students try to build their own molecules by dragging different atoms, position them and click on electrons to rotate electron lone pairs. When done, the student clicks on the 2nd window to see the correct answer (self-check learning). Students should compare their work to the pre-build molecules and critique their work and review accordingly.

The use of applet and the flexibility of adding and rotating different atoms and electrons provide students with a visual tool (model) to manipulate atoms in building valid Lewis structures. In addition, the use of technology and animation is an addition to the new generation of learners who use technology on daily basis. The joy and ease of applied technology in chemistry classroom supports learning and provides students with visual aid of the sub-microscopic level of matter.

Applet II *(model VI)*:

http://phet.colorado.edu/en/simulation/build-a-molecule

The PhET web-site provides another applet similar to the previous one with the ability to build single, double, and triple covalent bonds. In this applet (Figure 21), students can add electron lone pairs, rotate the molecules and show bond angles. The website provides a teacher guide and students detailed step by step of how to use the applet to build various molecules using a PBL approach (see attached).

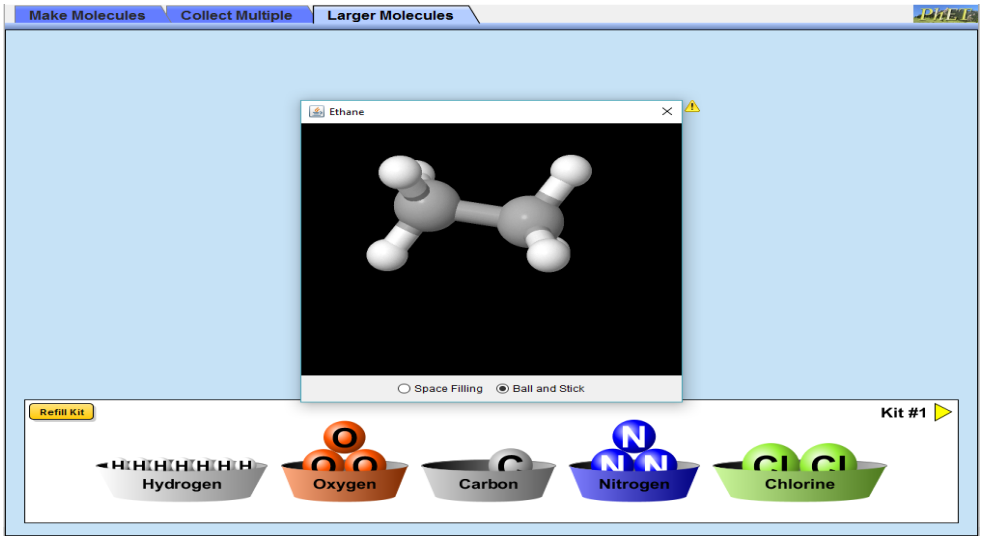


Figure 21 Colorado University, PhET Applet

NGSS: Each model contributes to a better understanding of a specific aspect molecular geometry; however, it brings its limitations.
Misconception: The use of multiple animations/applets provides students with various avenues to minimize the misconceptions of the static molecules, electrons, and bonds. The teacher is the best judge to decide which the best pedagogical approach is for his or her students. The lesson plan provides various types of activities that serve the same purpose; however, the teacher PCK guides the choice of which activity is the best fit for the students' needs.

Summarizing strategies & Formative assessment

Online 20 self-graded multiples-choices exercise on the Lewis model practice. It is a useful tool to be used either in groups or individually (depends on technology in classroom). Students to provide their reasoning (in writing) for each choice based on their created set of rules to draw Lewis structure ions and molecules.

http://www.sciencegeek.net/Chemistry/taters/Unit3LewisStructures.htm

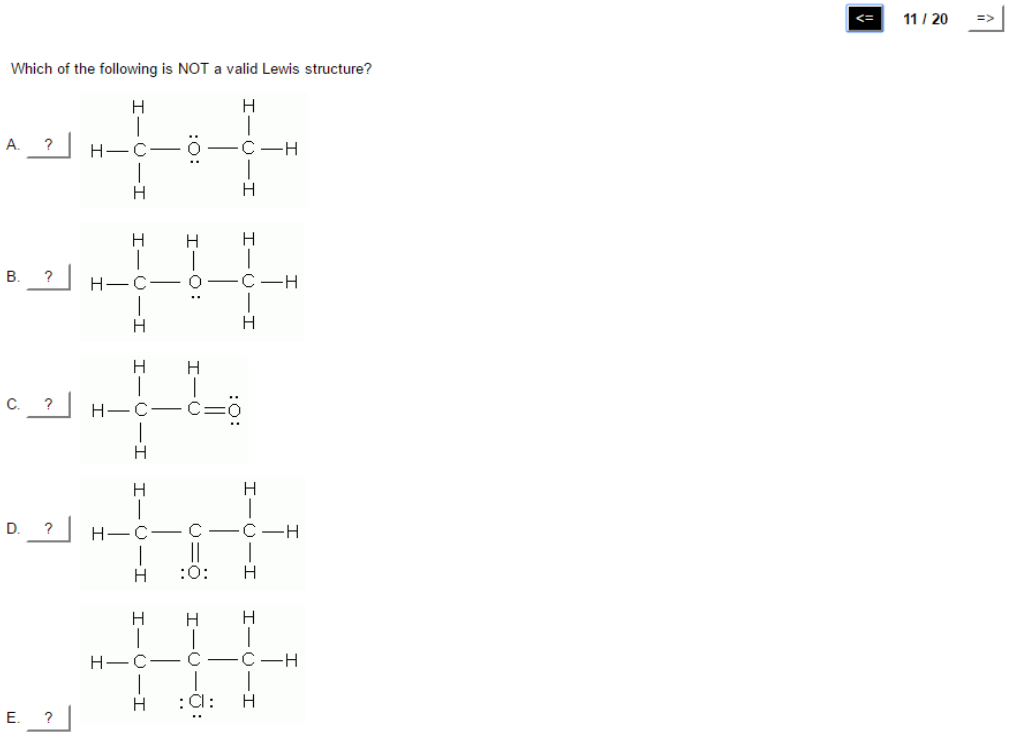


Figure 22 Online “Lewis Structures” POGIL Part A

Questions 11 (Figure 22): an example of the self -graded multiples-choices exercise on the Lewis model practice.

Lesson IV: The Lewis Model Part II

One of the most useful molecular models is the structural formula, which uses letter symbols and bonds to show relative positions of atoms. Using the same sequence of atoms, it is possible to have more than one valid Lewis structure. Resonance is a condition that occurs when more than one valid Lewis structure can be written for a molecule of the ion. The two more valid Lewis structures that represent a single molecule or ion are often referred to as a resonance structure. In resonance structures, only the position of the electron pairs differs, never the atom's position.

Lesson Objectives& Enduring understanding:

1. Explain the three exceptions to the octet rule and identify molecules in which these exceptions occur.
2. Identify the molecules with more than one equivalent Lewis structure.
3. Use the concept of formal charge to identify the dominant Lewis structure.

Essential Questions:

1. What are the three exceptions to the octet rule? Provide some example of molecules do not follow the octet rule.
2. Explain why resonance occurs and identify resonance structures.
3. How can one calculate the formal charge of each atom in a structural formula of molecules and thus the overall change of the molecule?

Activating strategy:

Ask students to share their knowledge on: What are free radicals? Antioxidants? And why is it important to consume food rich in antioxidants

"In recent years, there has been a great deal of attention toward the field of free radical chemistry. Free radicals reactive oxygen species and reactive nitrogen species are generated by our body by various endogenous systems, exposure to different physiochemical conditions or pathological states. A balance between free radicals and antioxidants is necessary for proper physiological function. If free radicals overwhelm the body's ability to regulate them, a condition known as oxidative stress ensues. Free radicals thus adversely alter lipids, proteins, and DNA and trigger a number of human diseases. The vitamins C and E are thought to protect the body against the destructive effects of free radicals. Antioxidants neutralize free radicals by donating one of their own electrons, ending the electron-"stealing" reaction. The antioxidant nutrients themselves do not become free radicals by donating an electron because they are stable in either form. They act as scavengers, helping to prevent cell and tissue damage that could lead to cellular damage and disease."
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3249911/(Lobo et al., 2010).

http://www.healthchecksystems.com/antioxid.htm

http://www.rice.edu/~jenky/sports/antiox.html

New vocabulary:

Structural formula, resonance, formal charge (FC)

Teaching strategies:

Octet rule exceptions: *(Model I: student-created model)*

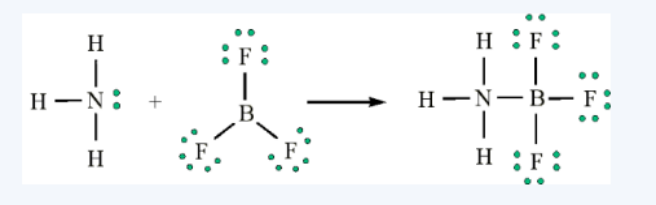
Ask students to draw Lewis structure of the following molecules BH_3, PCl_5, and NO_2

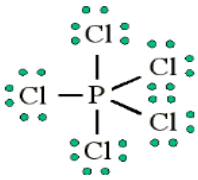
NGSS: For the activating strategy, teacher may use the provided links for more information or ask students to look up some information online on free radicals and antioxidants
Students will struggle to apply the octet rules for the above molecules. However, the teacher should ask students to try the best scenario to draw the molecules. After providing group work time, the teacher share students' trials (Model I: student-created model) to structure the three molecules and ask students to:

1- Provide their rationale behind their structures.
2- Explain why they failed to follow the octet rule in the structures of those molecules.
3- As a result, teacher may ask students to revise their rules list for drawing the Lewis structure and add the three exceptions to the rules to the previous list (Lewis model part I).

The teacher may use the following rhyme to make it easier for students to remember the three exceptions for the Octet rule exceptions: "too many, too few, and odd"

- When there are too few valence electrons (BH_3, BF_3)
- When there are too many valence electrons (expanded octet) (PCl_5, XeF_6)
- When there is an odd number of valence electrons (NO, NO_2)





http://chemwiki.ucdavis.edu/Theoretical_Chemistry/Chemical_Bonding/Lewis_Theory_of_Bonding/Violations_of_the_Octet_Rule

In addition to the above rhyme, the teacher can use the same source (link above) which is rich in digital models, videos, and external links to summarize the octet rules

exceptions and to provide students with tutorial tool to use either inside or outside the classroom *(Model II).*

NGSS: In the NGSS, the three dimensions of Science and Engineering Practices (SEPs), Disciplinary Core Ideas (DCIs), and Crosscutting Concepts (CCCs) are crafted into performance expectations that guided the design of the activation strategy "Free radical" in conjunction with the exceptions to the octet rules in drawing the Lewis model. The SEPs, designing the antioxidants area is based on the DCIs of molecular geometry, the octet rule, exceptions to the octet rules, and the Lewis model, which all are weaved together to reflect the CCCs. The NGSS expectations for students include making connections among all three dimensions. Students develop and apply the skills and abilities described in the SEP, as well as learn to make connections between different DCIs through the CCC to help gain a better understanding of the natural and designed world. Current research suggests that both knowledge (DCIs and CCCs) and practice (SEPs) are necessary for a full understanding of science. (www.nextgenscience.org/three-dimensions).

1. **Resonance**

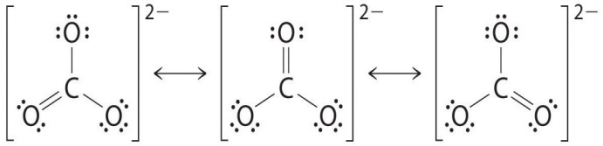
When more than one Lewis structure can be drawn, the molecule or ion is said to have resonance. The individual Lewis structures are termed contributing resonance structures. Resonance is a common feature of many molecules. Which one of these structures is the correct one? How could we tell?

http://www.chem.ucla.edu/harding/tutorials/resonance/draw_res_str.html

Resonance model of the carbonate ion, CO_3^{-2} *(Model III)*

Ask students to draw the Lewis model of the carbonate ion CO_3^{-2}. Compare student's models of Lewis structures of the CO_3^{-2}ion (Figure 23) and ask students which one of

these three structures is the correct one? What are the differences between the three structures?



[A] [B] [C]

Figure 23 Resonance Model of the Carbonate Ion, CO_3^{-2}

NGSS: The teacher may share different models for the carbonate ions and ask students to identify the differences between the three different models. Students will refer to the different locations of the double bond versus the single bonds and the number of electron lone pairs on each oxygen atom. The teacher may explain the validity of the three different models and provide more laboratory measurements (data driven based-evidence) to guide students to understand the nature the resonance. If structure **A** was correct, laboratory measurements would show one shorter bond (the carbon-oxygen double bond) and two longer bonds (the carbon-oxygen single bonds). Measurement of structures **B** and **C** would give the same results as well. As it turns out, laboratory measurements show that all three bonds are equal and between single and double bond length. This suggests that none of the Lewis structures we have drawn are correct. It further suggests that the actual structure has three equal carbon-oxygen bonds that are intermediate between single and double bonds.

Misconception: Using laboratory measurement as evidence (NGSS) will lead to better understanding of the dynamic nature of the covalent bonding and minimize the misconceptions of the Lewis model, which uses dashes and dots to represent bonded and lone pairs of electrons. Based on the course level, the teacher may expand the lesson to cover the topic of bond orders.

2. **Formal Charge (FC)**

To calculate the formal charge of an atom, take the valence number of the atom and subtract the number of bonds and the number of non-bonding electrons. Accepted FC should fall between (-1, 0, 1).

The Lewis structures of the sulfate ion SO_4^{-2} (Figure 24) *(model (IV)* :

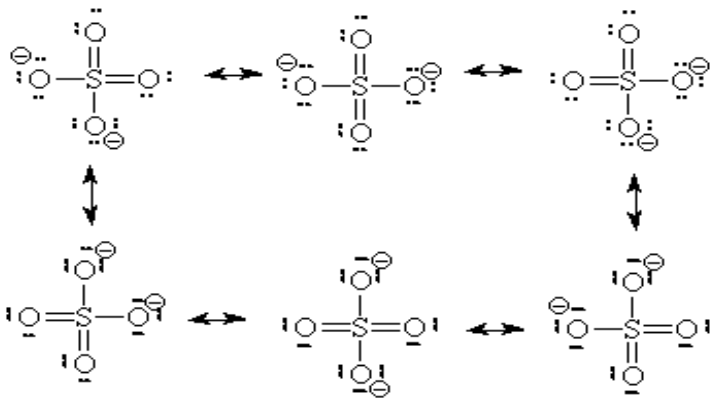


Figure 24 The Sulfate Ion SO_4^{-2}

Ask students to draw as many as possible Lewis models of the sulfate ions. Share the students' work and start to introduce the concept of Formal Charge (FC) and how to calculate it for each atom.

The following link provides notes, directions, and examples (tutorial)

http://chemwiki.ucdavis.edu/Theoretical_Chemistry/Chemical_Bonding/Lewis_Theory_of_Bonding

NOS: Students will create many Lewis models of the sulfate ion, which shows the need for another tool to validate each model. Introducing the concept of FC will provide students with a tool to examine their models, revise accordingly, and provide the most valid model based on the octet rule, expanded octet (starting from the third row on the periodic table), resonance, and the FC.

NGSS: The above design is solely inquiry-based and helps students not only to create their own models, but also to examine the models and revise them accordingly. The activity is guided step by step from students: creating and revising rules, adding new rules, examining models, learning new concepts, and revising models and validating them.

Summarizing strategies & Formative assessment:

1. Ask students to work in groups of three, create two columns note to critique the Lewis model; its advantages and disadvantages. And then ask students to revise the Lewis model in a way that minimize its disadvantages (Model V: student-created model)
2. https://www.stolaf.edu/depts/chemistry/courses/toolkits/121/js/lewis/ (Model VI)

   The online applet to draw valid Lewis structures by choosing molecules from the drop list and add covalent bonds and/or electrons lone pairs. The online applet will calculate the formal charge for each atom to help students to predict the validity of the structure.
3. How to calculate formal charge and self-scored assessment (Model VII).

Use the following link to show students how to calculate the formal charge of each atom in the molecule. In addition, the link provides formative assessment questions to provide the teacher with immediate feedback on students' performance.

www.chem.ucalgary.ca/courses/351/Carey5th/Ch01/ch1-3-2.html

Lesson V: Valence-Shell Electron-Pair Repulsion (VSEPR) Model Part I

The VSEPR theory assumes that each atom in a molecule will achieve a geometry that minimizes the repulsion between electrons in the valence shell of that atom. The five compounds shown *(Model I)* in Figure 25 can be used to demonstrate how the VSEPR theory can be applied to simple molecules.

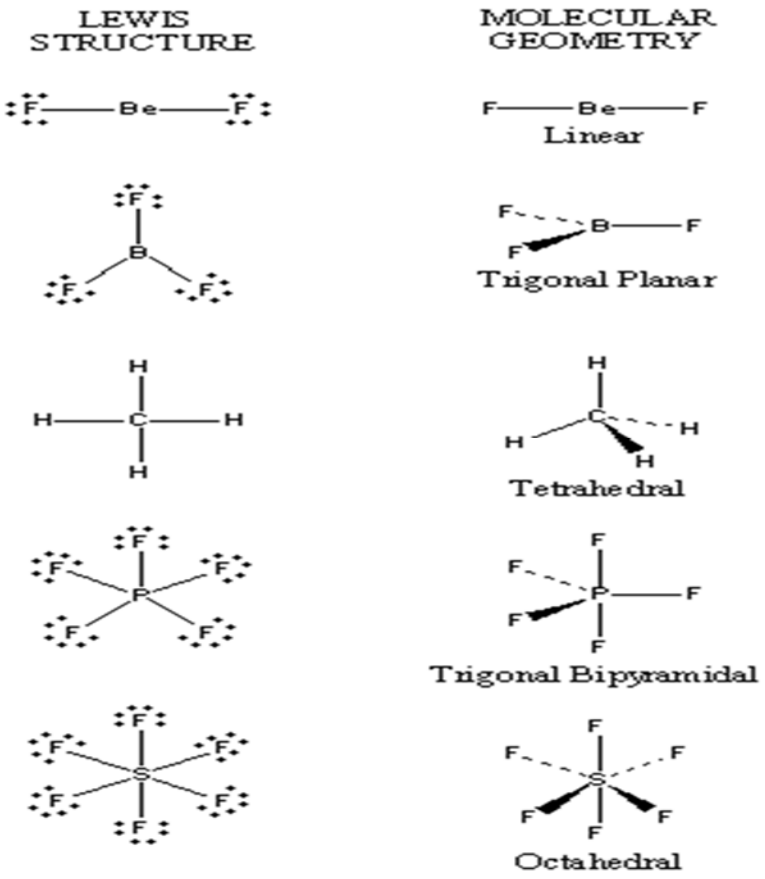


Figure 25 Lewis Model versus VSEPR Model

http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch8/vsepr.html

Lesson Objectives& Enduring understanding:

1. Use the VSEPR model to predict the geometrical shape of molecules and polyatomic ions.
2. Apply the VSEPR model, bond order, and element electronegativity to determine bonds angle in molecules and polyatomic ions

Essential Questions:

1. What is molecular geometry?
2. How is the VSEPR model used to predict the shape of and the bond angles of molecules?
3. What factor(s) affect bond angel?
4. How VSEPR model is used to determine the bond angle in molecules and polyatomic ions?

Activating strategy:

A molecule is nearly all empty space, apart from the extremely dense nuclei of its atoms and the clouds of electrons that bond them together. When that molecule forms, it arranges itself to maximize attraction of opposite charges and minimize repulsion of unlike.

TEDEd: George Zaidan and Charles Morton shape our image of molecules *(Model II)*:

http://ed.ted.com/lessons/what-is-the-shape-of-a-molecule-george-zaidan-and-charles-morton#watch

The four minute video introduces the shape of molecules in a simplified way to introduce the VSEPR model where atoms are arranged to maximize the attraction of opposite charges and minimize the repulsion of the like charges. The discovery of methane gas is used to conclude the shape of the methane molecule where all hydrogen atoms have to bond to the central carbon atom. Maximizing the distance between bonds (negative charges) leads to the shape of tetrahedral (bond angle 109.5^0). The video also introduces the shape of some simple molecules such as H_2O, NH_3, CO_2 and ClF_3.

New vocabulary:

Valence-Shell Electron-Pair Repulsion (VSEPR), molecular geometry, bond angle, linear, bent, Trigonal planar, Tetrahederal, Trigonal pyramidal, Trigonal bipyramidal, seesaw, T-shape,Octaheral, equatorial, and axial.

Teaching strategies:

VSEPR Geometries *(Models III& IV)*:

1. Ask students to use the Lewis lab from the previous lesson (Building Lewis models using molecular kit), provide students with a chart (Model IV) of VSEPR geometries (Figure 26) and ask students to name (describe) the shape of each molecule.

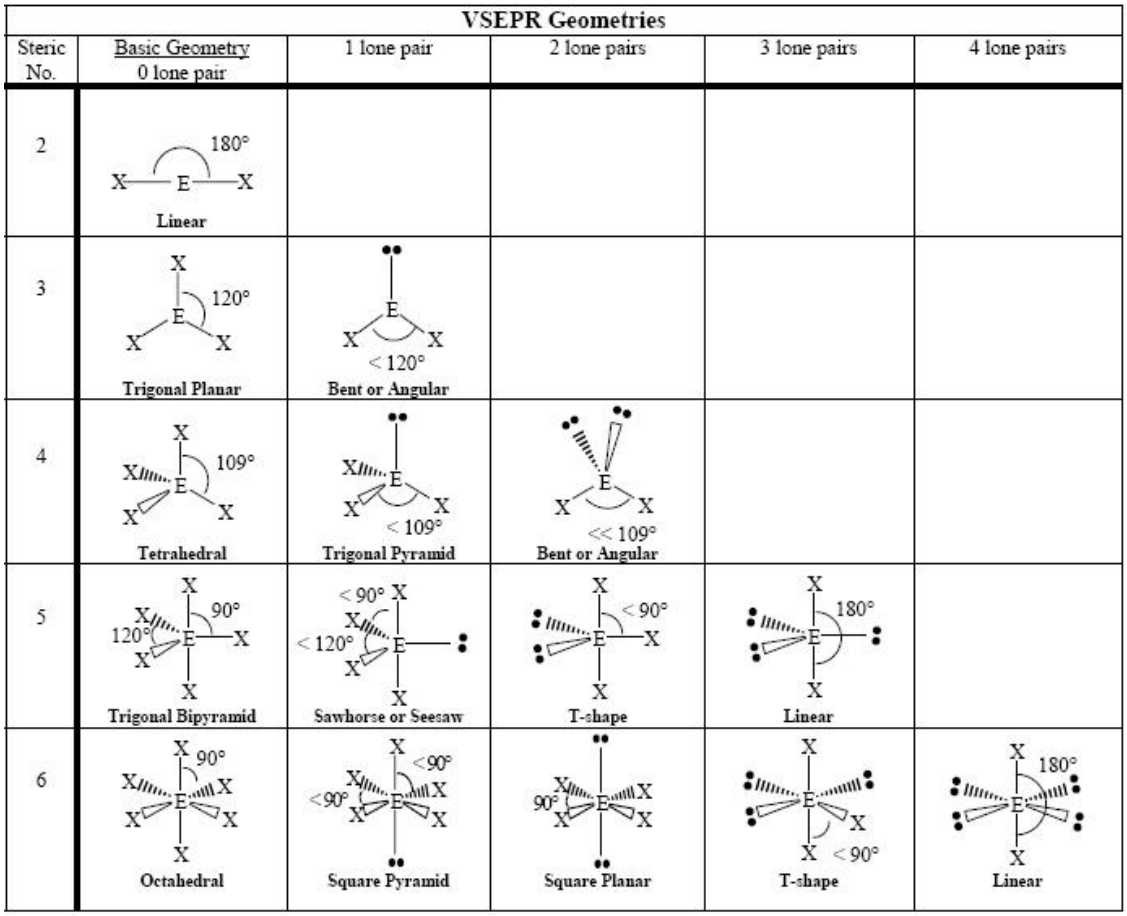


Figure 26 VSEPR Geometries Chart

https://figures.boundless.com/10397/full/vsepr-geometries.png

2. In a two columned note, ask students to compare the Lewis model to the VSEPR model, including commonalities and differences. In addition, ask students to come up with a list of rules to determine the geometrical shapes of molecules and poly atomic ions. Use the students' notes to create a list of rules for using the VSEPR model (Model V: student-created model).

The rules for using the VSEPR model to predict molecular structure are:

1. Determine the Lewis structure for the molecule.
2. For molecules with resonance structures, use any of the structures to predict the molecular geometry.
3. Sum the electron pairs around the central atom.
4. In counting pairs, count each multiple bond as one single effective pair.
5. The arrangement of the pairs is determined by minimizing electron pair repulsions.
6. Lone pairs require more space than bonding pairs. Choose an arrangement that gives the lone pairs as much room as possible. Recognize that the lone pairs may produce a slight distortion of the structure at angles less than 120^{o}.

NGSS: The teacher follows the same pedagogical approach (PCK) as in the previous lesson, "Lewis model II, "where students created their list of rules to structure molecules and ions (students created model).

NOS: The comparison between Lewis and VSEPR models is a smooth transition from a 2D model to a 3D one. In addition, it helps students to emphasize the importance of the use of multiple models. The use of a VSEPR model illustrates the limitations of the Lewis model as a flat representation which later affects molecular polarity. However, the VSEPR model is based on the Lewis model; students have to start with the Lewis model to understandVSEPR model and predict molecular geometries.

NGSS: The use of the Lewis lab model from the previous lesson with the new added VSEPR geometries chart contributes to the CCCs and help students to conceptualize the main idea of molecular geometries, which is an intermediate step to decide molecular polarity.

Simulation (Model VI):

3. Use the following simulation from the Colorado University "molecule shapes" (Figure 27). http://phet.colorado.edu/en/simulation/molecule-shapes

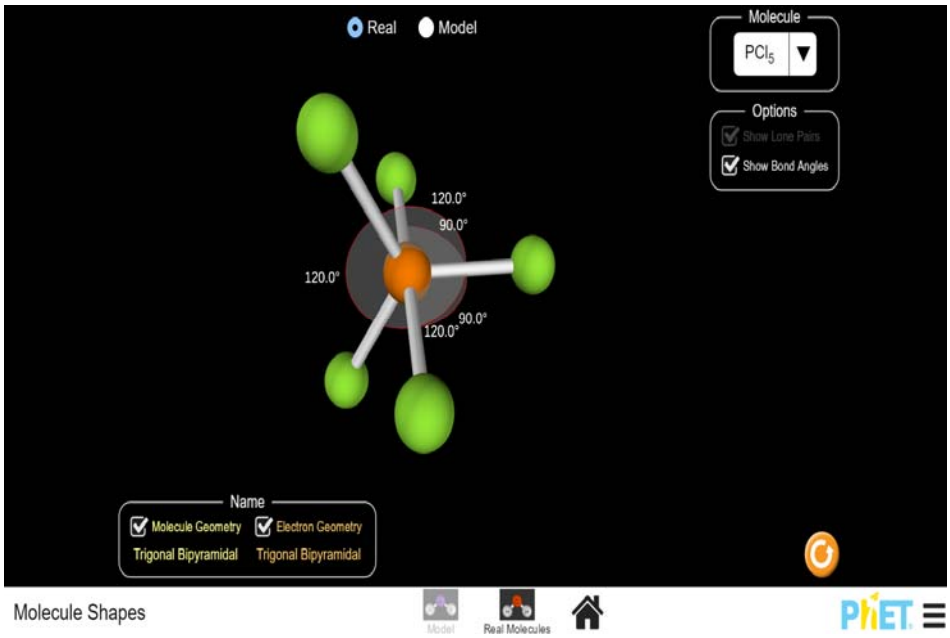


Figure 27 Colorado University: PhET Applet

The simulations provide students with the tool to build different molecules; double, and triple bonds. In addition, students can add an option to show the bond angles and the name of the molecular geometry. The simulation allows students to rotate each molecule 360 degree in three dimensions for better visualization of different bond angles (ex: 90.0 and 120.0). In addition, students can examine real molecules (click on real molecules icon).

Ask students to use the Lewis lab model and the PhET simulation to build each molecule using the simulation and figure out the bond angles and the molecule geometrical shape. Students have the option to look up the molecules (from the lab) under the real molecules option on the PhET simulation or to build it using the model option.

NOS: The PhET simulation provides the average bond angles. The teacher should point out this limitation of the PhET simulation model. For example, with awater molecule, the bond angle should be 104.5^0 instead of 109^0. Teachers should point out how electron lone pair has a bigger electron domain than bonded electron pair, thus it reduces the bonding angle H-O-H to be less than $109^0(104.5^0)$. On the other hand, the Ohio University simulations (provided in VSEPR Model Part II) provides more accurate bond angles, though the software, Jmol, may be a challenge for some students to use. The use of more than a single model provides students with various learning tools, and more data which reflect the nature of scienceas accurate and precise.

Summarizing strategy &Formative assessment:

Students use the following worksheet to summarize the interdependence between the Lewis and the VSEPR models. Also, the activity works as not only an exit ticket for the lesson but also as a formative/and or summative assessment for the VSEPR model part I.

Formula	Lewis Structure	Molecular Geometry
HBr		
NH_3		
SO_4^{-2}		
NO_3^{-1}		
PH_3		
XeF_6		
ICl_4^{-1}		

Lesson VI: Valence-Shell Electron-Pair Repulsion (VSEPR) Model II

Lesson Objectives& Enduring understanding:

1. Use the VSEPR model to predict the geometrical shape of molecules and polyatomic ions.
2. Utilize VSEPR model, bond order, and element electronegativity to determine bonds angle in molecules and polyatomic ions

Essential Questions:

1. How is the VSEPR model used to predict the shape of and the bond angles of molecules?
2. What are the factor(s) that affect the bonding angel?
3. How VSEPR model is used to determine the bond angle in molecules and polyatomic ions?

Activating strategy:

Ask students to use the VSEPR geometries chart from the previous lesson to provide an example (molecule or polyatomic ion) for each geometrical shape.

NGSS: In the previous lesson, VSEPR Model Part I, students used the VSEPR geometries chart to identify the geometrical shapes of molecules and polyatomic ions. In the activating strategy, students need to identify molecules and polyatomic ions which take certain geometrical shape based on the number of atoms, electrons lone pairs, and bond order which create a link between the Lewis model, the VSEPR model, bond angel, and real molecules in our daily life. The approach supports the CCC. In addition, moving back and forth between Lewis and VSEPR models contributes to students' mastery of the learning target concept.

Simulation *(Model I):*

The Ohio State University website provides another useful simulation (Figure 28) of molecular geometries. The molecules are pre-built and rotate automatically. The website provides a tutorial on how to use the Jmol applet in addition to a link on how to draw Lewis model, calculate the formal charge, resonance, and bond polarity. The Ohio University website provides more accurate bonding angels in comparison to the PhET web-site. https://undergrad-ed.chemistry.ohio-state.edu/VSEPR/

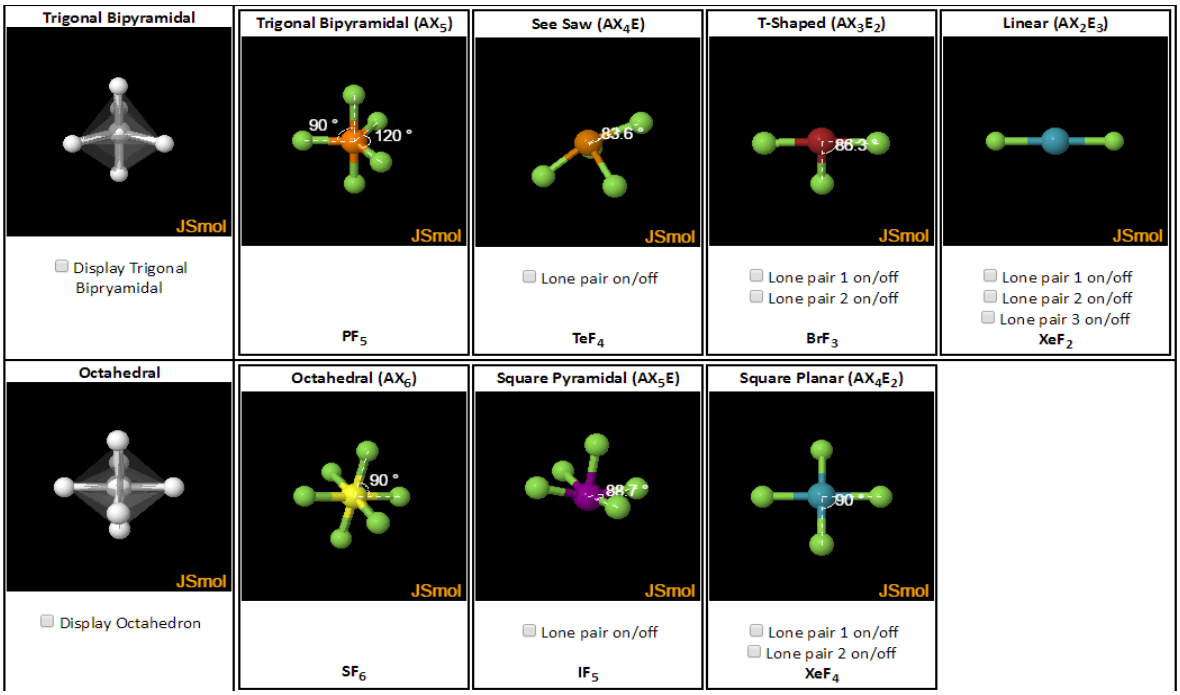


Figure 28 An example from the Ohio State University Jmol applet

NGSS: Many students struggle to visualize the molecules in 3D. The use of the VSEPR geometries chart helps students with spatial capacity while other students struggle. The use of the simulation in 3D helps students to rotate molecules and to visualize different angles for different molecular geometries. Some geometrical shapes are a challenge to visualize due to the existence of two different types of bonding angles. For example, the Trigonal Bipyramid shape includes two different bonding angles, 120^0 equatorial and 90^0 axial. In 3D simulations, students can rotate the molecule to observe each angle in a single dimension at the time, x, y, or z (students may need to rotate the molecules multiple times to see both angles simultaneously). The use of multiple models (e.g., Lewis, VSEPR, 2D, 3D, movie, and simulations) provide students with various avenues to support their spatial capacity.

Balloons model (Model II: student-created model):

Provide each student (or group of students) with six big balloons. Ask students to inflate the balloons and then tie them tightly at the center (Figure 29). Different number of balloons and various sizes are used to demonstrate different geometrical shapes (bigger balloons for electron lone pairs and smaller ones for bonded electron pairs).

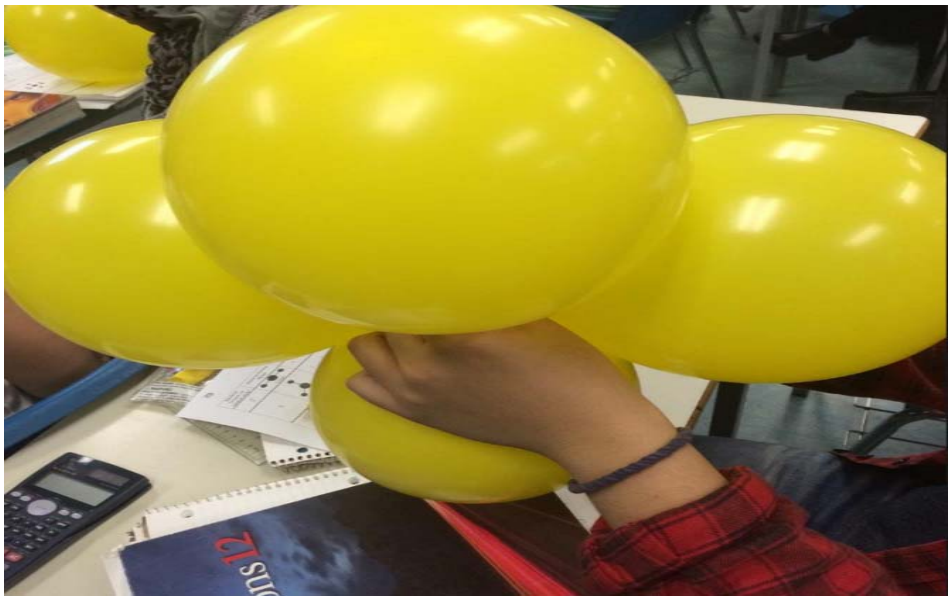


Figure 29 The Balloon Model Activity

Ask students to shake the six tied balloons and observe the resultant geometrical shape. Students may use the VSEPR geometries chart (from VSEPR Part I) and/or the teacher may project the PhET simulation on the screen (if available). After students identify the first shape, ask students to pop one balloon at the time and shake the model again to observe the resultant geometrical shape. Continue to pop one balloon at the time until you end up with only two. Ask students to use their fist as the central atom to observe a linear shape with bonded angle of 180 degrees.

Misconception: The balloons activity presents not only a tangible model but also brings joy to the chemistry classroom. The model helps students in an amusing way to observe the entire balloon as electrons' cloud. The previous models included the simulation failed to represent the electron cloud in a tangible way to show how similar charges repel each other's. The teacher should point out how the entire body of each balloon represents the electron cloud. The model helps students to observe how the balloons by nature take the positions to minimize the repulsion force and stay far apart as possible. The use of the balloons model (enactive/analog), the VSEPR geometries chart (iconic), and the PhET simulations (CA) simultaneously bring all senses together to a single activity. The presentations of various types of model complement each other and minimize students' misconceptions due to the limitations of the use of a single model.

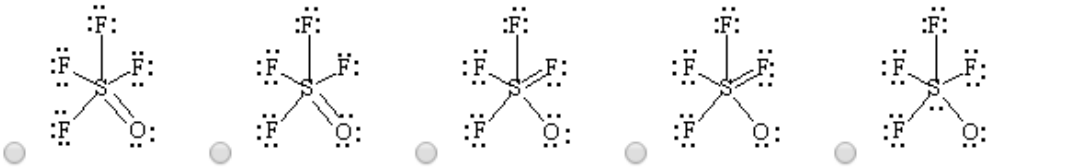
Summarizing strategy &Formative assessment *(Model III)*:

Use the following seven questions quiz from the Ohio State University. Seven multiple choice questions on the VSEPR model (Figure 30).

https://undergrad-ed.chemistry.ohio-state.edu/cgi-bin/quiz.pl/quiz/TEST/tut.1

Question 5

Identify the best Lewis diagram for SF_4O.



Submit Answer | Clear Answer

Previous Question | Next Question

Figure 30 Question 5: Identify the Best Lewis Diagram for SF_4O

The quiz provides students with seven consecutive questions on the VSEPR model. The interactive quiz provides students with feedback for each answer. In addition, it provides tutorial tool to explain the correct answer and provide hints for each wrong answer.Each question provides a summary of one concept of the Lewis and VSEPR models: counting the total number of VE, octet rule, formal charge, central atom, and bond angle. The difficulty of the questions increases throughout the short quiz however, it summarizes the rules for: calculating the total number of valence electrons, the Lewis model, resonance structures, formal charge and geometrical shapes for molecules and polyatomic ions.
The teachers can usethis quiz as either a formative assessment or as a home-study tool for students. The quiz summarizes the Lewis and VSEPR models in a nice smooth transition from a simple question such as counting the total number of valence electrons to predict the location of fluorine atom on the structure, axial or equatorial. The teacher may use each question to summarize/re-teach each concept based on the students responses (formative assessment). In addition, the teacher may ask students to provide the rationale for their answers to address any misconceptions students may have.

Lesson VII: Molecular Polarity Part I

Bond polarities arise from bonds between atoms of different electronegativity. When we have more complex molecules, we must consider the possibility of *molecular polarities* that arise from the sums of all of the individual bond polarities. To do full justice to this discussion, we really need to consider the concept of vectors (mathematical quantities that have both direction and magnitude). A molecule can possess polar bonds and still be nonpolar. If the polar bonds are evenly (or symmetrically) distributed, the bond dipoles cancel and do not create a molecular dipole. For example, the three bonds in a molecule of BF_3 *(Model I)* are significantly polar, but they are symmetrically arranged around the central boron atom. No side of the molecule has more negative or positive charge than another side, and so the molecule is nonpolar (Figure 31) http://chemistry.bd.psu.edu/jircitano/polar.html

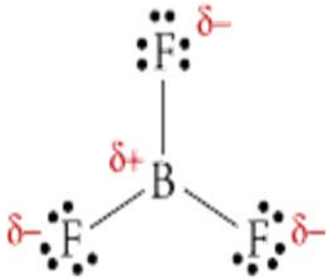


Figure 31 Structure of the Boron Trifluoride (BF_3) Molecule

A water molecule (Model II) is polar for two reasons:

1. Its O-H bonds are significantly polar
2. The geometrical shape is bent due to the existence of the electron lone pair, which makes the distribution of those polar bonds asymmetrical (see Figure 32). The side of the water molecule containing the most electronegative oxygen atom is partially negative, and the side of the molecule containing the least electronegative hydrogen atoms is partially positive.

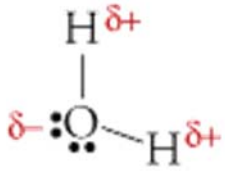


Figure 32 Polarity of the H_2O Molecule

Lesson Objectives& Enduring understanding:

1. Predict the polarity of covalent bonds and the polarity of molecules.
2. Compare and contrast polar and nonpolar covalent bond and molecules.
3. Describe the characteristics of polar molecules.

Essential Questions:

1. How is electronegativity used to determine bond type and bond polarity?
2. How are Lewis and VSEPR models used to predict the polarity of molecules?
3. What are the factors to consider in predicting the molecular polarity?

Activating strategy:

Did you ever wonder how molecules of a substance stay close together? Why does water form droplets or support things on its surface? Electrons may be distributed evenly or unevenly throughout a molecule, which creates partial charges at different parts of the molecule. These partial charges on one molecule often interact with the partial charges of a neighboring molecule. In this activity you will learn how to determine molecular polarity and placement of partial charges molecules.

New vocabulary:

Polar covalent, nonpolar covalent, symmetric, asymmetric, and dipole moment.

Teaching strategies:

1. Polar Bears and Penguins Comic & POGIL: ***(****Model III: iconic/analogy)*

   (Attachment 4)

http://achs.roselleschools.org/UserFiles/Servers/Server_3154010/File/Chakraborty/Penguins-and-Polar-Bears-Comic%20book.pdf

A shorter version of the same POGIL

http://www.pleasanton.k12.ca.us/avhsweb/simmsp/SelfdirectedUnits/Unit4ChemicalBondsandCompounds/Polar%20Bears%20and%20Penguins.pdf

POGIL answers
http://schools.alcdsb.on.ca/hcss/teacherpages/wallekat/sch3u/Fall%202013%20Notes/Unit%201-%20Matter,%20Periodic%20Trends,%20Bonding/Day%2015-%20Polar%20Bear%20Answers.pdf

NGSS: First, students may read the comic individually and then work in groups of three to answer the POGIL questions. After class reconvenes, students provide not only their answers to the POGIL questionsbut alsorationalize their answers. The comic introduces bond polarity based on the difference in electronegativity between the bonded atoms. The teacher should refer to the EN trends and provide students with an EN periodic table to link bond polarity to atomic EN (CCCs). In addition, the teacher may spend some time asking students to figure out the similarities between the iceberg in the comic and the periodic table, including the size of the animals, locations, shapes, active versus non-active animals, etc. The comic provides another avenue for students' cognitive learning of bond polarity based on differences in strength between Polar bears and Penguins. The comic could be classified under two types of models, iconic and analogy.

2. "Polar, Nonpolar, and Ionic Bonding" POGIL *(Model IV).* www.myips.org/cms/lib8/IN01906626/Centricity/Domain/8123/polarity_pogil.doc

NGSS: The teacher follows the same pedagogical approach with POGIL (as above). The advancement of this POGIL is how it connects all the related concepts (CCCs). First, the POGIL starts with the basic information on EN. Second, the POGIL uses graphic models to introduce bond polarity, and polar versus nonpolar bonds. Finally, the POGIL uses the two preceding concepts to introduce the topic of molecular polarity, which includes Lewis models of some common molecules: BF_3, H_2O, CO_2, and CCl_4. Each section is followed by critical thinking questions appropriate for the target concept.

Summarizing strategy & Formative assessment:

The following assessment is modified from:

(http://people.cornellcollege.edu/cstrong/courses/vsepr_practice1.htm)

For each of the following molecule or ions:

a) Determine the geometrical shape.

b) Predict the polarity of each molecule.

c) Provide adequate evidence that supports your prediction.

1. SO_2
2. CCl_4
3. $CHCl_3$
4. XeF_6
5. CO_3^{2-}
6. NH_3
7. SO_4^{2-}
8. I_3
9. BF_3
10. SF_3^+
11. XeF_2
12. BrF_5
13. XeF_4
14. SeF
15. ClF_3
16. SeF_6

Answers:

1. bent, polar (slightly)
2. tetrahedral, non-polar
3. tetrahedral, polar
4. Octahedral polar
5. trigonal planar *
6. trigonal pyramidal, polar
7. tetrahedral *
8. linear, non-polar
9. trigonal planar, non-polar
10. trigonal pyramidal **
11. linear, non-polar
12. square pyramid, polar
13. square planar, non-polar
14. see-saw, polar
15. t-shaped, polar
16. octahedral, non-polar

* Would be non-polar if it were a neutral molecule, but we don't generally talk about ions as being polar or non-polar

** Would be slightly polar if it were a neutral molecule

NGSS: The above assessment is modified from The Cornell College. Students are asked to provide evidence for their predictions on molecular polarity. For students to predict molecular polarity: they have to structure the Lewis model, VSEPR model, consider bonded and non-bonded electron pairs, electron' domains, bond order, and elements' electronegativities (CCCs).

Misconception: The assessment features some molecules share the same molecular geometry however, some are polar and some are nonpolar. For example; $CCl_4$and $CHCl_3$, both molecules attain the same molecular geometry, tetrahedral, however CCl_4 is a nonpolar molecule while $CHCl_3$ is a polar one. Those questions address students' misconception of certain molecular geometries being always polar or nonpolar for example: some students believe the geometrical shape "tetrahedral" always results in a polar molecule. Others may believe the existence of electron lone pairs on the central atom leads to a polar molecule. For example, the triiodide ion, I_3, is a *nonpolar molecule* even though it contains electron lone pairs on the central atom in comparison to the XeF_6 molecule which is a *polar molecule* due to the existence of electron lone pair on the central atom.

Lesson VIII: Molecular Polarity Part II "like dissolve like"

The charge distribution (known as polarity) of a molecule is one of the most important factors in understanding many of the physical properties of the substance. Determining whether a molecule is polar or nonpolar requires a multi-step analysis, as outlined below. We will use water (H_2O), carbon dioxide (CO_2), and formaldehyde (H_2CO) as examples for this tutorial.

http://www.marin.edu/homepages/ErikDunmire/CHEM105/Concept_Review/Polarity/Polarity.html

The web-site provides a tutorial on molecular polarity and the steps required to determine if a molecule is polar or nonpolar *(Model I).*

Lesson Objectives& Enduring understanding:

1. Predict the polarity of covalent bonds and the polarity of molecules.
2. Compare and contrast polar and nonpolar molecules.
3. Describe the characteristics of polar molecules.

Essential Questions:

1. How to use Lewis and VSEPR models to predict the polarity of molecules?
2. What are the factors to consider for predicting the molecular polarity?

Activating strategy:

Ask students to work in groups of two to answer the following questions:

1. Why don't oil and water mix?
2. How does a rain coat repeal water?

Polar & Non-Polar Molecules: ten minutes Crash Course Chemistry #23 *(Model II).*https://www.youtube.com/watch?v=PVL24HAesnc

Misconception: Using the Chemistry Crash course video to summarize the previous lesson "Polarity Part I" and provide students with a chance to ask questions and comment on the video based on what they learned in the previous lesson. This approach provides the teacher with feedback on any gaps or misconceptions that students may have or developed before moving on with molecular polarity. In addition, the teacher may check the homework from the previous lesson after watching the video to address any misconceptions.

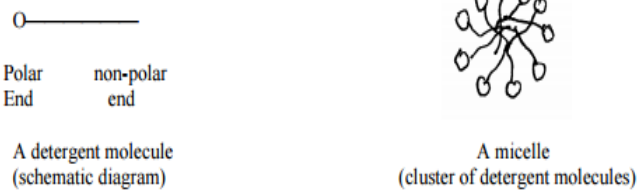
New vocabulary:

Polar molecule, nonpolar molecule, symmetric, asymmetric, and dipole moment.

Teaching strategies:

"Drops on a Penny" demonstration/lab *(Model III)*:

https://www.teachengineering.org/lessons/view/duk_drops_mary_less



Detergent molecule

Water drops on a penny

Based on the available time, the teacher can utilize the "Drops on a penny" provided by (*Curriculum for K-12 teachers - www.teachengineering.org*) *as* a demonstration or assign it as a lab for students' group-work. This demo/lab demonstrates the Intermolecular Force (IMF) among molecules of different solutions/liquids. The use of different molecules, such as water, ethyl alcohol, water detergent solution, mineral spirits or hexane (nonpolar molecule) illustrates the IMF among molecules. Based on the IMF among molecules, due to molecular polarity, students count the number of drops each penny can hold.

The use of “Drops on a penny” either in a demonstration or a lab format helps students to connect the macroscopic and sub-microscopic levels of chemistry. The teacher provides students with a chance to inquire why certain liquids/solutions stick together (hold many drops), while others do not. Students need to use their understanding of molecular polarity to draw a conclusion on why each penny holds a different number of drops. For example, why water molecules stick together and provide the highest number of drops versus other molecules, such as hexane (nonpolar molecules), which hold only one drop.

NGSS: In general, students tend to provide observations rather than rationales behind certain phenomenon. Thus, the teacher should encourage students to provide valid reasoning backed up with evidence from what they just learned on molecular polarity to explain their observations (using argumentation in science). The teacher has the flexibility to utilize the above activity in any format that fits his or her students’ needs and time availability: demo, lab, mini-lab, mix of demo and lab.

Simulation *(Model IV)*:

Use the following PhET simulation from the Colorado University “molecule Polarity” https://phet.colorado.edu/en/simulation/molecule-polarity. This simulation demonstrates two atoms, three atoms, or real molecules. Students can change the electronegativity of each atom (slider)add/remove an electric field, rotating molecules (Figure 33), changing bonding angles, view bond dipole, molecular dipole, and partial charges. The web-site provides molecular polarity guided activity *(Model V)* with a teacher guide and a clicker activity. Students need to use the simulation to answer the guided inquiry activity question (POGIL lab).

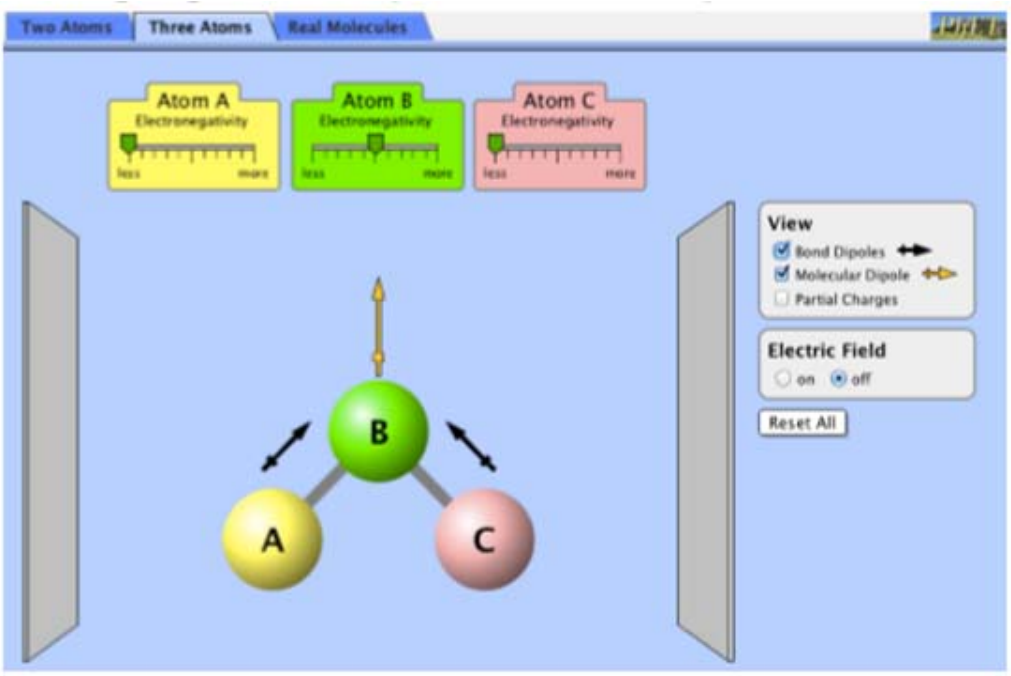


Figure 33 Three atoms molecules, Electronegativity Slider, and an Electric Field

The above PhET website is loaded with various types of models and it consolidates models with the guided inquiry approach (POGIL). The teacher can employ the provided activities in substantial ways; lab, demonstration, POGIL, individual or group work, formative or summative assessments, and/or blended learning. The multiple approaches maximize students' benefits of the learning target(s). Images and interactive simulations enable students to visualize bonds and molecular polarities which assist them to bridge the bonds polarity to the molecular polarity.

NGSS: The addition or animation of electric fields helps students to conceptualize the behavior of certain molecules based on its polarity and identify it as a physical property (CCCs). Students observe that bond angles affect the dipole moment and the overall net charge of certain molecules. The ability to manipulate the molecules' bonding angles and elements' electronegativities exemplifies the role of models in helping students to observe, interact, and predict molecular properties (polarity). The above simulation illustrates an entertaining inquiry learning approach.

NOS: It reflects another aspect of model-based teaching as well as the nature of science where students *do science;* observe, collect data, control variables, and draw conclusion based on scientific evidence and empirical data. In addition, it builds strong connection among the three facets of chemistry; macroscopic, sub-microscopic and symbolic.

Summarizing strategy& Formative assessment:

1. Predict whether these molecules are polar or nonpolar.

2. For each molecule provide valid reasoning(s) for molecular polarity.

HBr, SO_2, XeF_4, NF_3, BCl_3, H_2O, CO_2

NGSS: The above molecules contain polar molecules: HBr, NF_3 SO_2, andH_2O and nonpolar molecules: XeF_4, BCl_3, and CO_2 which come in various molecular geometries. For each molecule: students need to draw the Lewis model, followed by the VSEPR model, determine bond angles, electrons lone pairs, bond order, use EN data, apply mathematical rules, and then decide the polarity of each molecule. Students may use periodic table, EN chart, VSEPR geometries chart, PhET simulations, Ohio universe simulation, and any other format of digital or physical models.

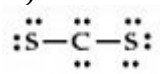
This multiple steps process requires high level of thinking, mastery of various concepts, applying various models, and utilizes some data (element's electronegativity) which summarize the entire unit of teaching molecular geometry.

Summative Assessment

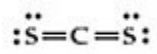
Part I: Multiple choices (modified from Basic Chemistry, Timberlake 5e & ACS)

1. Which of the following is the correct electron-dot structure for CS_2?

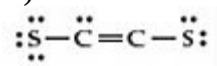
A)



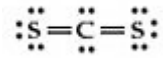
B)



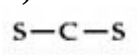
C)



D)



E)



2) The number of lone pairs in the water molecule is _____.

A) 8 B) 2

C) 1 D) 3

3. The NO_3^- ion is an example of a polyatomic ion with _____.

A) resonance structures B) triple bonds

C) a linear shape D) a nonpolar bond

4. The shape of the polyatomic ammonium ion, NH_4^+ is _____.

A) linear B) trigonal pyramidal

C) trigonal planar D) tetrahedral

5. The shape of the ammonia molecule is _____.

A) linear B) square

C) trigonal pyramidal D) hexagonal

6. Hydrogen sulfide, H_2S, has a shape similar to _____.

A) carbondioxide B) carbonmonoxide

C) hydrogen chloride D) water

7. Which of the following substances contains a nonpolar bond?

A) H_2O B) NaCl

C) NH_3 D) N_2

8. Which of the following elements has the lowest electronegativity?

A) Li B) C

C) N D) O

9. A polar covalent bond is found in which of these compounds?

A) H_2O B) F_2

C) NaCl D) H_2

10. A molecule is said to be polar if it

A) has a north and south pole.

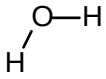
B) has a symmetrical electron distribution.

C) exhibits a polar spin under certain conditions.

D) exhibits a partial positive charge at one end and a partial negative charge at the other.

11. Which of these is a nonpolar molecule with one or more polar bonds?

A) H—Cl C) H—H

B) F—Be—F D) 

12. Which formula represents a nonpolar molecule?

A) HCl B)CF_4

B) NH_3 D)H_2S

First: Multiple Choice sections:
Each question measures students understanding of a specific concept(s) in the molecular geometry unit:

1. The octet rule and formal charges

2. Calculate total number of valence electron, and draw valid Lewis model.

3. Resonance structure and bond polarity

4. The VSEPR model and geometrical shapes.

5. Question # 4 targets the geometrical shape of the ammonium ion, NH_4^+ while question #5 targets the shape of the ammonia (NH_3) molecule. The similarity in names is a distracter. Students should distinguish between the positive charge carried by the cation (one less electron), number of hydrogen atoms (4 and 3), and existence of lone pair on the latter molecule.

6. Geometrical shape similarities based on number of bonded atoms and the location of each atom on the periodic table. Both, sulfur and oxygen are located in the same group, 6A (16), on the periodic table.

7. Bond polarity based on different in electronegativities between the bonded atoms.

8. Decide EN based on the location on the periodic table (EN periodic trend).

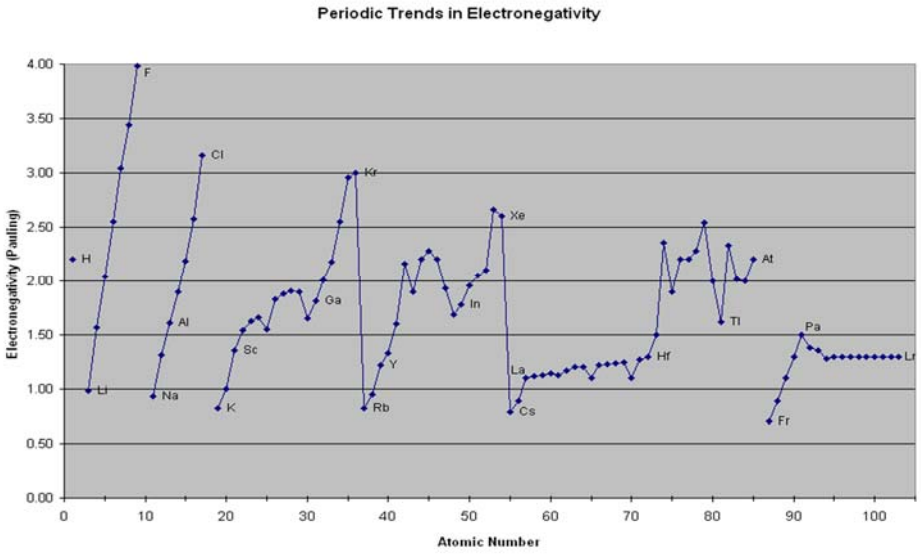
9. Bond polarity based on EN differences, big difference in electronegativities results in ionic compound (electron transfer instead of electrons share), and familiarity with water as the most abundant molecule on earth.

10. The reason for bond polarity (EN differences between the bonded atoms)

11. Differentiates between bond polarity and molecular polarity

12. Decide molecular polarity based on: bond polarity, geometrical shape, and the existence of electron lone pairs on the central atom.

Part II: Free responses



1. The above graph shows the relationship between atomic number and EN:

   a. Why the EN increases from Na to Cl, and from Li to F?

   b. Both Xe and Kr are noble gases, why Kr has higher EN than Xe?

   c. F has the highest EN while Fr has the least,

   Use argument to explain the big difference in EN

   betweenthetwoelementsandconcludehowcanyou use the data

NGSS: Questions 1 examine students' ability to interpret graph's data. Students need to rationalize the increasing in EN from Na to Cl and from Li to F based on their understanding of the EN periodic trend within groups and periods on the periodic table. The ability to interpret the graph expresses students understanding of how shielding factor and atomic radius contribute to the EN values (why Kr has higher EN than XE). Based on students understanding of the first two parts, a and b, students should be able to create a pattern for EN trend not only across groups and periods but also a diagonal trend from F to Fr. Data interpretation and creating argumentation that provides rationale for each EN trend reflect mastery in using model(s) to generate and analyze data to make valid and reliable scientific claims or determine an optima design solution.

2. Use the Lewis & VSEPR models to draw the dominant structure of the following molecules. Include any applicable resonance structures as well.

   a. Indicate the formal charge of each atom in the molecule.

   b. Name the molecular geometry

   c. Indicate the angles between the central atom and the terminal ones.

   d. Indicate if the molecule or ion is polar or nonpolar, defend your answer.

SO_2Cl_2	$XeF_2O_4^{2-}$
H_2CO	NO_3^{-1}
NO_2^{-1}	SF_4O

NGSS: Question 2: examines student's ability to apply two models; Lewis and VSEPR. Students should be able to:

a. Calculate the total number of valence electrons, taking in account the charge of the polyatomic ions.
b. Identify the least electronegative atom and place it in the center of the molecules Predict the existence of resonance as in NO_3^{-1} molecule.
c. Predict the molecular geometry based on bond order, electron lone pairs, bond angels, and elements' EN.
d. Predict molecular polarity based on all the above criteria.

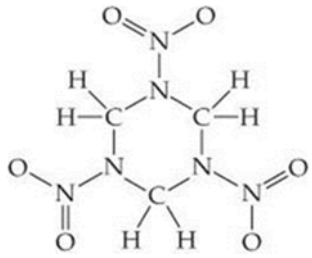
Answering question 2 reflect a mastery of applying both Lewis and VSEPR models to predict molecular polarity. Students have to provide evidence for their predictions which align with the NGSS "compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles".

3. Draw the Lewis structures for each of the following molecules or ions. Which do not obey the octet rule? (Brown Lemay AP Chemistry).

a. NO b. BF_3 c. ICl_2^- d. XeF_4

Question 3 examines how students deliberate their understanding of the octet rules exceptions to distinguish which exception apply to which molecule. NO has an odd number of valence electrons while BF_3 has less than a total of eight valence electrons. On the other hand, both; ICl_2^- and XeF_4 express expanded octet (more than eight electrons around the central atom.

4. The "plastic" explosive C-4, often used in action movies, contains the molecule *cyclotrimethylenetrinitramine*, which is often called RDX (for Royal Demolition explosive):



a. Complete the Lewis structure for the molecule by adding unshared electron pairs where they are needed.

b. Does the Lewis structure you drew in part a have any resonance structures? If so, how many?

c. Which is the weakest type of bond in the molecule? Defend your answer.

d. Is this molecule polar or non-polar? Provide as many evidence to support your answer.

Question 4 provides student with a pre-structured real molecule “plastic”. Students did not learn how to structure such a complicated molecule however; they should be able to apply what they have learned in a new situation. The question begins by asking students to complete the structure by adding the missing electron lone pairs and then examine students’ understanding of resonance structures. Part c, examines students’ ability to predict bond strength based on the differences in the bonded atoms’ electronegativities value and bond order. Finally, part d, addresses students ability not only to predict molecular polarity but also to provide evidence-based answers for their prediction.

Additional materials

Teacher References and Student Study Guide

The expansion of the use of technology creates a new challenge to keep track of new educational digital resources. Some of which provide tutorials, animations, videos, interactive applets, pre-designed labs, and various forms of assessment. It is the teacher’s decision to select what types of resources are suitable for students and for the learning setting. I am providing an example of a useful online resource which is rich in the use of models and can be utilized in many ways to support students’ learning.

http://chem.libretexts.org/Textbook_Maps/General_Chemistry_Textbook_Maps/Map%3A_Chemistry_(OpenSTAX)/07%3A_Chemical_Bonding_and_Molecular_Geometry/7.6%3A_Molecular_Structure_and_Polarity

The www.chem.libretexts.org provides a great tool for formative and summative assessment.
It is a richresources for teachers (and students) to select assessment items that help diverse learners.
The website has a tutorial and is rich in models (charts, tables, 3D images, simulations, etc).
It starts with VSEPR theory with a table of each geometrical shape in both the Lewis model and the VSEPR model format.
It is explicit about the order of electron-pair repulsions from greatest to least as: lone pair-lone pair > lone pair-bonding pair > bonding pair-bonding pair.
In addition, the website does not only provide many examples with answers supported by 3D images but also links to other useful website such as the PhET simulation from Colorado University.
It covers the concepts of molecular polarity, dipole moment, and properties of polar molecules.
At the end of the page there are key concepts, summary and glossary.

Attachment 1: Periodic Trend POGIL

Chapter 6

REFLECTION

The goal of this Executive Exposition Paper was to design educative curriculum materials for teaching molecular geometry, using a Model-based Teaching approach, in order to minimize misconceptions, and help students to develop a deeper understanding of geometrical shapes and its applications in chemistry. The curriculum design process aimed to ensure that the base curriculum materials are accurate, complete, and coherent in terms of content and effective in terms of pedagogy (Davis & Krajcik, 2005).

We often think of using models as an instant solution to many difficulties that students face in learning chemistry principles. I used to believe, as many other teachers in the field do, that the more models I used, the better my teaching would be. I used to think that specific models convey certain concepts or easily facilitate an idea without realizing that such an advanced educational tool can contribute to students' misconceptions. Working on developing this unit enhanced my thinking and helped me develop more effective teaching pedagogy. During classroom discussions, I started to spend more time reflecting on students' answers and investigating their way of thinking in order to identify how they developed certain misconceptions. This provided valuable information for developing more effective teaching methods.

Students tend to ask which model is actually the true representation of reality, which reflects students' misconceptions on models and modeling in the science classroom. The developed unit is a small step in re-aligning curriculum, pedagogical

approach, and the expectations of the NGSS to better serve students to meet the ultimate goal of being true learners.

Limitations of the Study and Opportunities for Evaluation and Reflective Practice

Collaboration with other experts in the field, either from chemistry or education, facilitated the development of the teaching unit. Developing the unit went through consecutive phases as follows:

Phase I: A joyful journey of conducting a thorough research on models and modeling in teaching MG. It was a challenging task to develop an analytical framework to examine each model and how it should be strategically introduce in classroom. This journey made me aware of different perspectives of scientific models. As mentioned in Chapter 2, I came across various classifications of models based on models definitions, applications, properties, and types. Another challenge was selecting which groups of models that best serve the purpose of developing the MG unit and in which order should be introduce them in classroom.

Phase II: Started by attaining teachers input by sharing a four-question questionnaire via e-mail with a group of high school chemistry teachers who teach in the Tri-State area and two local college chemistry professors. The questionnaire addressed three main areas in teaching molecular geometry: models used by teachers (Q. 1), students' misconceptions (Q. 2), and the most and least effective pedagogical approaches (Q. 3 & 4).

1 - What models, animations, or resources do you typically use to teach the topic of molecular geometry?

2- What do your students typically find most challenging when learning this topic?

3- What instructional tools have you used that you found most effective in addressing these learning difficulties? please describe why?

4- What instructional tools/ approaches have you used that you found to be least effective in addressing learning challenges? Please describe why?

I received back a total of eight responses. Seven high school teachers and one college professor provided their input. I found a vast area of agreement from teachers' input on students' misconceptions, which aligned with the literature review I conducted. Both teachers input and the literature reviews helped me narrow down the list of students misconceptions that should be addressed while designing the new unit.

Phase I: I used the information provided by teachers along with research findings from the literature on MBT, misconceptions and models in the domain of molecular geometry to design the first complete draft of the molecular geometry unit.

Phase II: I shared the developed molecular geometry unit with experts in the field of chemistry education, two levels, high school and college, to ensure the accuracy of Content Knowledge (CK) and the quality of the Pedagogical Content Knowledge (PCK).

Phase III: After receiving feedback from high school teachers and college professors, confirming the accuracy of the content and acceptance of the lesson sequence, I shared the developed unit with my committee members. Their input

shaped the paper to be more coherent and readable by those who are not chemistry experts or novice science teachers.

To add a descriptive Performance Task (PT) to the developed unit, I consulted an expert in the field. I communicated with the Associate Director of the Professional Development Center for Education at the University of Delaware who collaborates with the Brandywine School District (BSD) on developing and implementing performance tasks in science curricula. She recommended the PT created by Dr. Ted M. Clark and Dr. Patrick Woodward at The Ohio State University. After examining the PT, I found it to be an appropriate fit for the unit because it summarizes the entire work using not only a similar pedagogical approach, MBT, but also employing similar resources such as the PhET website.

Since the author of the PT employed similar resources to those used in the developed unit, I took a further step and communicated with the author of the PT, Dr. Clark, from Ohio State University who was excited to see a work on using models in teaching chemistry as well as the implementation of his PT in the newly developed unit.

Collaborating and working with experts in the field, whether in science or curriculum design, allowed me to envision my thoughts and shape my ideas in a way that is reflected in the quality of the product of this Executive Exposition Paper. It helped me to see the scope and intensity of work required to develop a single unit in teaching chemistry.

Limitations

Even though great care was vested into designing the teaching unit, there are some limitations to the study. The study focused mainly on the teaching aspect and the implementation of specific pedagogical approaches. Taking into consideration a learning approach would add another dimension to the study that should be considered in future research. Collecting data on students using models in learning molecular geometry could be done by using student questionnaires, interviews, and data analysis of formative assessments after the use of each model and summative assessment at the end of the unit. Furthermore, conducting a pilot study on using specific assemblage of models in teaching molecular geometry could be an extension to this study. In designing the unit, I used my teaching experience in addition to the expertise of other high school teachers and college professors. The literature reviews on teaching molecular geometry, students' misconceptions, and models and modeling informed and guided the unit development, but implementing and evaluating the implementation of the unit can provide evidence regarding the effectiveness of the unit in achieving the intended learning outcomes.

Leadership and Extension Opportunities

The process that led to the development of the educative curriculum unit produced in this study (See Figure 34) serves as a model for redesigning other instructional units in science disciplines. Furthermore, it supports the State of Delaware's ongoing work to align science curricula with the NGSS expectations. In this regard, the newly designed unit may support not only the Brandywine School District (BSD) teachers but also other teachers across the state of Delaware in using a

similar pedagogical approach. In addition, the new unit which is provides multiple opportunities to engage in model based teaching, can be used as a part of the BSD district initiative for blended-learning. The district has expanded the use of a Schoology platform and is working diligently on the use of pre-built courses, which is going alongside with the expanded use of technology across the district.

The educative curriculum materials produced in this study provide readily available resources for other teachers to use in their chemistry courses, or help them redesign their lessons to meet the ultimate goals of the NGSS. The use of the MBT pedagogical approach in teaching molecular geometry may guide other teachers to create a similar pedagogical approach in other units and expand the use of models and modeling practices in other science courses.

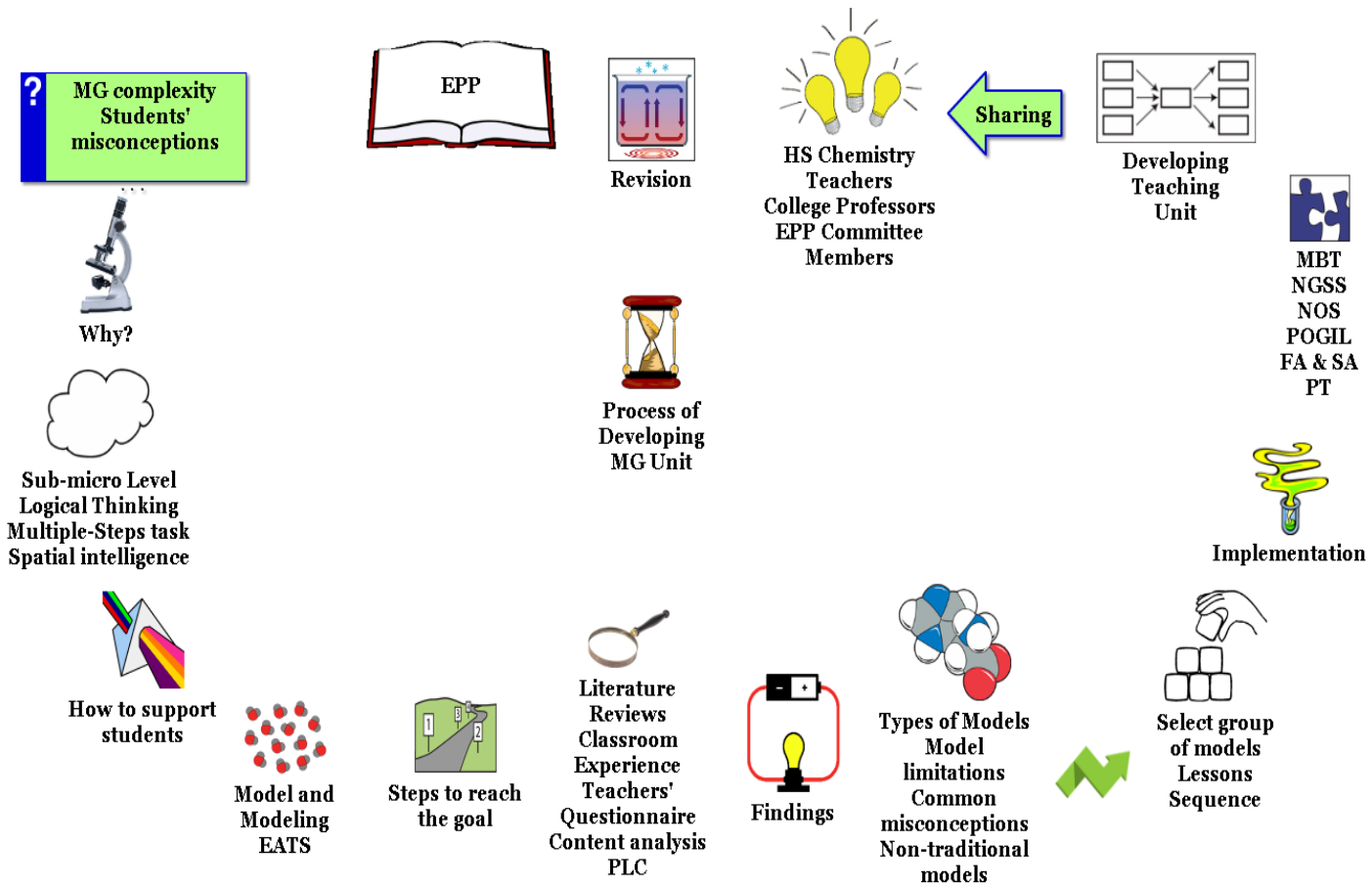


Figure 34 Process of Developing Molecular Geometry Unit

This unit can serve as a model in Professional Development (PD) to show teachers how lesson plans can be revamped to encompass the expectations of the NGSS, the Nature of Science, and Model-Based Teaching. Lesson samples from the unit can be provided to teachers to analyze and discuss. During the PD, teachers could be asked to use their PCK to identify how each lesson pedagogical approach can serve as a tool to minimize students' misconceptions and meet the lesson objectives. The PD developers and leaders can utilize Tables 1-3 to demonstrate how participants can use a research-based approach to analyzing models. This process can be followed by teachers who wish to follow a similar approach in order to investigate different types of models, model limitations, select target groups of models, and how to introduce selected models in classroom in relation to the same or other content areas. Furthermore, PD leaders should make it explicit how the lesson design emphasizes student development and use of models as promoted in the NGSS. Table 7 (Chapter 5) provides an example of how teachers can align lesson objectives, essential questions and formative assessment tasks to the 3D components of NGSS.

Lessons Learned

Developing the teaching unit was an eye opener for me; it expanded my horizon on how students apprehend science concepts. From a teacher's perspective, the scientific concepts are clear, and the models are great tools to simplify complex phenomena and help students to observe the unseen (sub-microscopic level). Furthermore, the expanded use of advanced technology provided us with tools we never had in the past or even imagined could exist. However, a closer look examining how students discern the information reflects different views. A model by itself,

regardless of whether it is a classic model or a high technology one, is not enough to deliver a new concept. A thorough investigation of each model used in this unit in light of students' misconceptions improved my understanding of the use of models in teaching chemistry. Each model brings its advantages and its limitations. Furthermore, the use of a specific model in isolation of other models may contribute more to students' misconceptions instead of minimizing them. Another aspect concerning using models in instruction, is not only which model to use and which to avoid, it is when and how each model should be presented in the classroom and in which sequence.

I also learned to appreciate the role of teaching the historical models, how they were introduced, developed, and revised in science. Understanding the model itself, what it presents and what it eliminates, cultivated my pedagogy to help my students appreciate the role of models and thus appreciate the nature of science. The way we talk about models in class is a question for future investigation. We should teach students that scientists developed these models as ways of making sense of a range of physical and chemical properties and to predict materials behavior. As the limitations of the models were identified, they were developed, replaced, or supplemented (Taber, 2010).

Another lesson I learned is that even if students know how to do something, it does not mean they have learned it! Students can follow sets of rules to construct the Lewis or the VSEPR models; however, this does not mean students comprehend how the Lewis of the VSEPR models work. It is just a step in a complex process. Many students can handle a single task, but not many can master multiple, complex tasks. The complexity of predicting molecular geometry and polarity requires mastering

various concepts in addition to the use logical thinking to reach that sophisticated level of predicting, evaluating, and foremost applying what is learned in a new situation.

I believe that the opportunity to design this unit provided me with a new lens to read the NGSS. In aligning educational programs to the NGSS, the goal of instruction is not for students to memorize content. Content becomes meaningful to students when they see its usefulness — when they need it to answer a question. Therefore, in programs aligned to the NGSS, an important component of instruction is to pique students' curiosity to help them see a need for the content.

The performance expectations of the NGSS in general and the Science and Engineering Practices (SEPs) in particular, reflect the expectations of a true learner. They set the parameter to test students' abilities to understand instead of following a scheme or sets of rules! A true learner should be able to develop and apply the skills he or she acquired in new situations. Furthermore, a true learner should be able to design, evaluate, develop, and predict based on data analysis and the use of authentic scientific methods. The ultimate goal of an NGSS-aligned science education is for students to be able to explain real-world phenomena and to design solutions to problems using their understanding of the DCIs, CCCs, and SEPs.

Future Research and Extension Possibilities

Teachers' perceptions are important; if science teachers do not have the core understanding of the nature and role of models in the development of a discipline, they will not be able to incorporate them properly in their teaching (Barnea & Dori, 1996).

For future research, having a field observation plan with student input in the form of surveys, questionnaires, short quizzes, and/or interviews will bring enrichment to future unit revision and design.

The use of Schoology, Blackboard, Sakai and other technology platforms used by educational institutions are vastly growing to make learning accessible and suitable for a new generation of digital learners. Having a digital version of the developed unit will amplify the benefits for diverse learners as well as may serve as a critical piece for blended learning.

Another element for future research is the relationship between science and mathematical knowledge. In this aspect, several questions present themselves. How much geometry knowledge is involved in teaching molecular geometry? How can teachers support students' development of spatial reasoning skills? Does students' lack of math skills contribute to their understanding of the molecular geometry topic? And how can chemistry and math teachers align their curricula to meet the expectations of the NGSS? I believe that there is currently work being done on aligning math and science for engineering practices, however more work needs to be done along the lines of using mathematical concepts to support learning of scientific core ideas such as those encountered in the topic of molecular geometry. Figure 35 shows commonalities among science, math and English language arts. It underscores the importance of models and modeling practices in science and mathematics particularly in the area of developing and using models.

Furthermore, constructing viable arguments, engaging in arguments from evidence, is a common area among the three disciplines which can be further strengthened in the developed unit. It opens the door for reinforcing writing and

reading in science. Many students excel in reading and writing for ELA but struggle to write a science paper. Writing for science is different from writing for English language class. The strategic use of ELA in a scientific context presents another dimension for interdisciplinary teaching and learning among the three fields of Science, Mathematics, and ELA. As a result, it contributes to better implementation of the STEM teaching in school programs

The new unit can provide opportunities to discuss with mathematics and English language arts teachers ways for forging stronger connections and alignments across the curriculum. Furthermore, this opens the door for further research on how models in science and mathematics can be taught synergistically to support conceptual understanding in both domains.

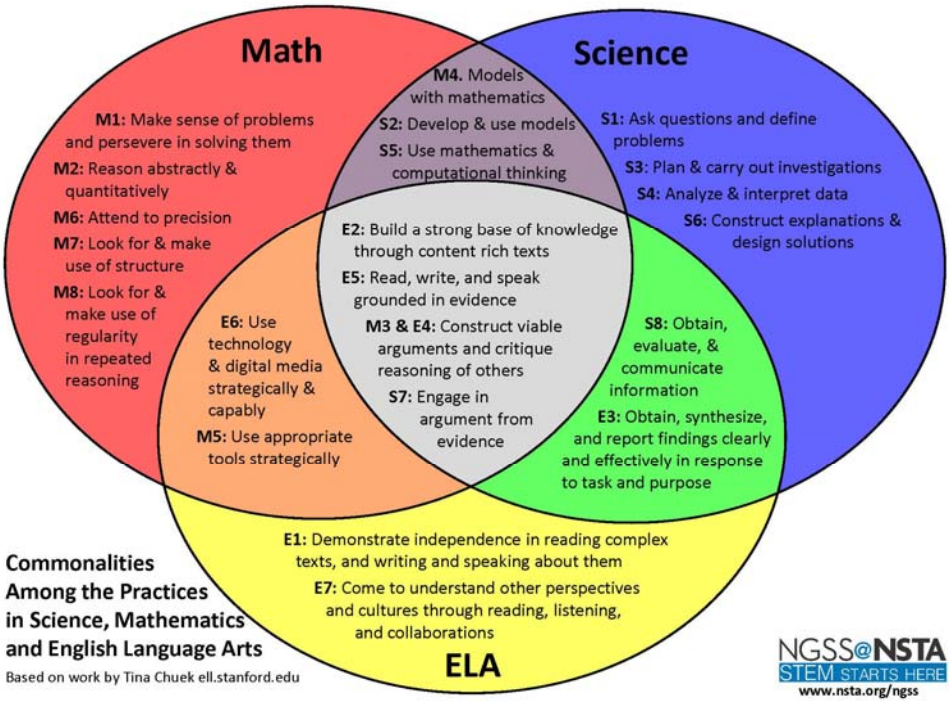


Figure 35 Commonalities among the practices in science, math and ELA (reprinted from http://nstahosted.org)

Conclusion

The design of the new educative curriculum materials employed many elements of evidence-based practices in science education. The principles used to guide and shape the development of the unit are applicable to different topics in chemistry as well as other subject areas. The unit is coherently designed to provide teachers, who appreciate continuing to be long-life learners, with concrete means to support student learning in the chemistry classroom. The process of completing this work has inspired me as a teacher and polished my work in the classroom. Collaborating with other educators, regardless of their area of expertise or their location on the world map, was a great advantage in doing this project. The benefits of

using this unit will be expanded to other areas of the content I teach. It is an uninterrupted work of self-reflection aimed to improving my pedagogy and my students' learning.

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Appendix A

Lesson by Lesson Overview

Lesson I: Periodic Trend: Electronegativity

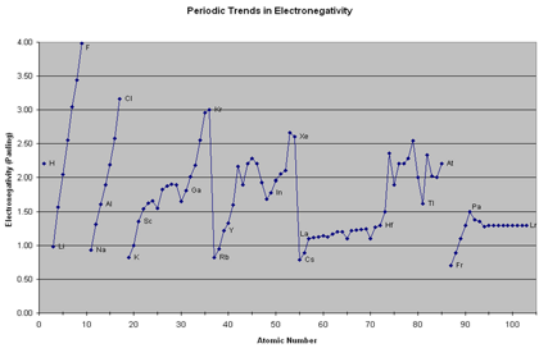
The electronegativity periodic trend is the first lesson in the Molecular Geometry (MG) unit. This lesson could be either a part of the periodic table unit or MG unit. Since chemical bonding and periodic table units precede the MG unit, students come to class with basic prior knowledge on the periodic table. The lesson covers elements' electronegativity property and aims to help students to draw a pattern, periodic trend, moving across periods and groups on the periodic table and observing the change in EN values.

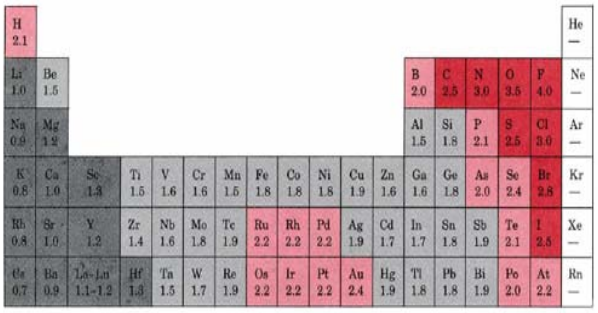
The lesson starts with examining students' prior knowledge on the atomic radius periodic trend as a foundation for learning the EN periodic trend. Factors affecting the atomic radius such as, the number of energy levels and shielding factors, are applicable to the new concept, EN trend, as well. After bridging the new lesson to students' prior knowledge, a historical approach is used to stimulate students' interest to learn the new concept. A short video is used to introduce the work of Linus Pauling on EN and vitamin C molecule, a real life application that helps students connect classroom activities to real life applications/phenomena. The recommended historical approach reflects the Nature of Science (NOS) where all scientific knowledge can also

be seen to be embedded in a global scientific community. This community has a particular culture, expectations, and accumulated knowledge – all of which are essential to increasing scientific knowledge.

Next, students move from a real life application to collaborate for 30 minutes, working in groups of three, on the "Periodic Trend" POGIL, studying a model on the periodic table and provide reasoning for why the EN values of elements changes moving across periods and groups on the periodic table. When done, the class reconvenes for class discussion. In addition to the POGIL, the teacher will use two data samples; a graph of EN periodic trend versus atomic number and a table of element electronegativity values (V36).

Figure 36 EN Trend vs Atomic Number & Periodic Table of EN Values





Students are asked to analyze both, the graph and the table data to provide rationale for each peak on the graph and explain why EN increases across periods and decreases down across groups (NGSS Lead States, 2013).

To help students understand how shielding factor affects elements EN value, teacher use a magnet, cardboard, and paper clips to demonstrate the contributions of

shielding factor and atomic radius (thickness of the cardboard) to the elements' EN values.

By the end of the lesson, to summarize the learning target, students create their periodic trends model (student-created model) using a blank periodic table to scrutinize the relationship between the atomic number and EN (NGSS Lead States, 2013).

Lesson II: Covalent Bond

The lesson starts with reviewing the previous lesson, EN periodic trend, by asking students to predict which element tends to lose and which tends to gain electrons based on its EN value. Asking students to make such a prediction and provide reasoning for their answers helps them connect the EN and covalent bonding topics and explore how the EN value contributes to the nature of the chemical bonds.

For diverse learners, the teacher uses a mental model, lunch time analogy, to help students understand the three different types of covalent bonding, and the tug of war analogy (Figure 37) to clarify the difference between polar and nonpolar covalent bonds.

Figure 37 The Tug-of-War Game Analogy

In the tug of war game, two teams of the same strength where the ribbon stays in the middle despite the fact that both teams pulling in opposite directions, represent the nonpolar covalent bond. When one team is stronger (still not winning) pulls the ribbon towards their team, it represents a polar covalent bonding where electrons are shared unequally. Both analogies of polar and nonpolar covalent bonds address students' misconception of a static bond. Students believe the covalent bond is static since it is represented by solid a dash(s).Playing the game enables students to feel the opposite pull forces from each side on the static ribbon.

After linking students' previous knowledge to the new concept, covalent bonding, and providing two mental models (analogies) students collaborate in groups of three to analyze the three different models using "What is covalent bond" POGIL. The models in the POGIL introduce students to the sub-micro level of covalent

bonding electrons share and help them to visualize how each atom contributes to the bond (Figure 38).

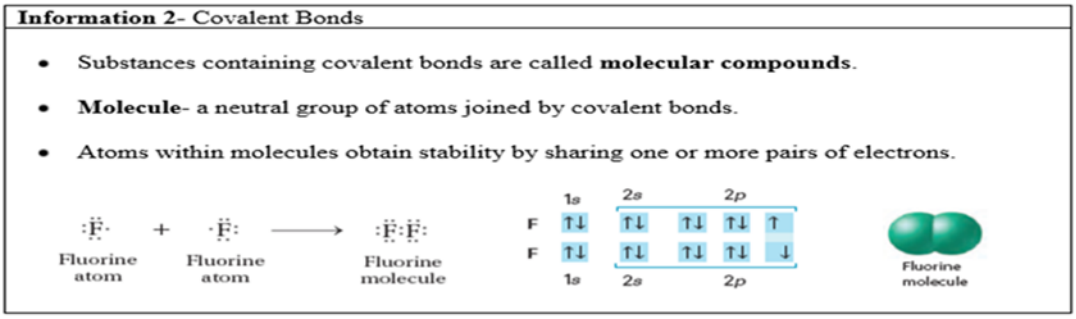


Figure 38 Covalent Bond Model

The teacher has the choice based on students' abilities to introduce first the analogy "the lunch time", followed by the POGIL models, and then move back to the second analogy, "the tug of war game" , or reverse the order and use the POGIL first before the analogies. Since the order of introducing the analogies and the POGIL models is not a contributing factor to students' misconception, the teacher has the flexibility to start with an analogy as a real-life application to engage students in learning the new concept, or for kinesthetic learners, students may go first outdoor for a short tug-of-war game and then move to class to work on the POGIL models. If students are totally engaged and focused, the teacher may introduce the POGIL first and then continue with the lesson as mentioned above.

For Visual-Spatial learners, the teacher uses a two minute animation on ionic and covalent bonding to emphasis the relationship between EN and the type of chemical bond.

The exit ticket (summarizing strategy) for the lesson is predicting the type of bond for certain molecules such as O_2, N_2, and HF and placing them in order, low to high, based on the bond dissociation energy. Students will need to use a dissociation energy chart (model) to answer the question and provide rationale for their answers based on data analysis (NGSS).

Lesson III: The Lewis Model Part I

Since the concept of the Lewis model is intense and rich in class activities and the use of various models, the topic spans two lessons divided into two equal sections, part I and part II.

The lesson follows similar approaches to the previous two lessons; a historical approach (lesson one) and connecting students' prior knowledge to the new concept (lessons one and two). In the previous lesson, covalent bond, students examined visual models in "What is a covalent bond" POGIL; the models; bond types, covalent bond (Figure 39), and structural formulas introduced students to basic structure of simple molecules, such as H_2O and F_2. Lesson three starts by asking students to draw the structural formula of water molecule, H_2O.

After going over simple molecular structure, H_2O, the teacher uses an eleven-minute video on “Bonding models and Lewis structures” to differentiate between different types of chemical bonds and learn about the history of the Lewis model.

After watching the video, the teacher displays an image of the Lewis’ memorandum of 1902 showing his speculations about the role of electrons in atoms structure from valance and structure of atoms and molecules (Figure 39).

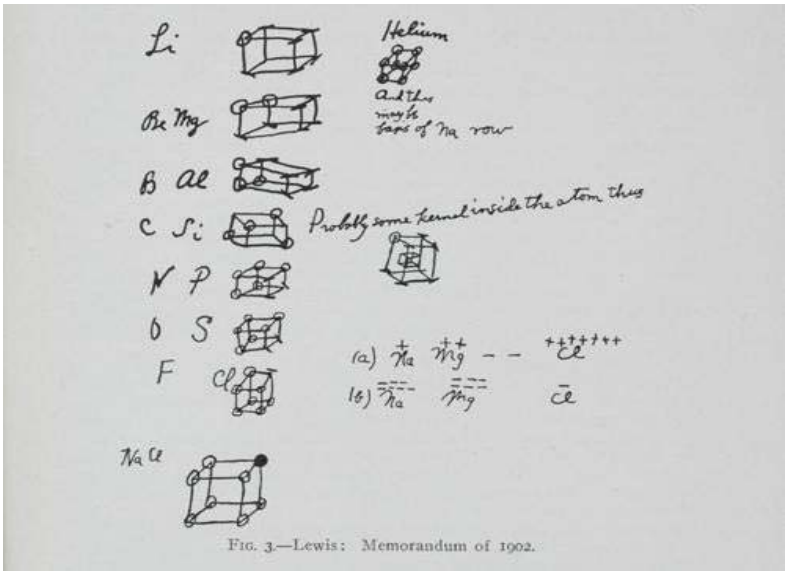


FIG. 3.—Lewis: Memorandum of 1902.

Figure 39 Gilbert Newton Lewis’s Memorandum of 1902

It is recommended that the teacher introduces the historical work of Gilbert Newton Lewis (1875-1946) and how he depicted atoms as series of cubes, which may stimulate a discussion about the shape of an atom: is it spherical, cubical, flat, three dimensions, or what? The history of the Lewis model reflects the NOS; the history of

science shows that scientists continually look for theories that provide greater explanatory power and the development of scientific theories, at times is based on inconsistent foundations.

An alternative approach:

The teacher can use solely an historical approach, by sharing the Lewis' memorandum with students followed by the video from crash-course, which covers the history of the Lewis model as well. The first approach helps to make the linkage between the two lessons; covalent bond and the Lewis model, explicit. In contrast, the alternative approach could be more interesting to visual learners or those who have more interest in history (NOS) to keep them engaged. Both approaches are justifiable since the teacher will use all of lesson elements and just revise the order, which has no negative effect for this lesson.

After using the historical approach and connecting the new lesson to the old ones, students collaborate for 45 minutes in groups of three to examine the "Lewis structures" POGIL, part A (Figure 40)

Figure 1: Shell and Lewis Representations of Selected Compounds

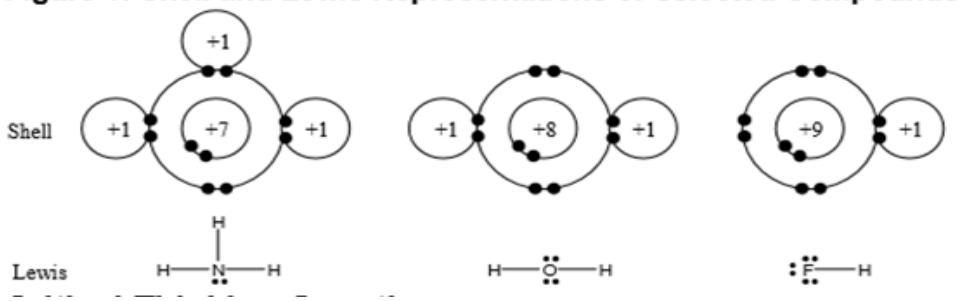


Figure 40 Shell and Lewis Representation of Selected Compounds

The models in the Lewis POGIL enable students to create a connection between atoms' shells and covalent bonding. Many students struggle to make a connection between valence electrons, covalent bonding, energy levels, and the location of element on the periodic table. Most of Lewis models focus on the bonded electrons and the lone pairs in isolation of the valence shell. As a result, students create a misconception of a static covalent bond, solid dashes and dots (representation of bonds and electrons). The use of the above model provides a better illustration of the Lewis model to minimize the misconception of the static covalent bond. For the best use of this model, the teacher should emphasize the constant motion of electrons and refer to covalent bonding as higher electron density (the probability of electron spending more time) between the nuclei of the bonded atoms.

In addition to the POGIL models, the teacher uses an animation of covalent bonding which provides another visual aid to students and helps them to conceptualize the sharing concept of covalent bonding among valence shells electrons.

The following activity is a student-created modeling activity and it is more suitable for logical-mathematical learners, students will create rules/steps to draw valid Lewis structures of simple molecules; CH_4, CO_2, NH_3, HCN, and H_2CO.The class will move from the student-created models to interactive model (suitable for visual learners) using the applet from:

http://chemsite.lsrhs.net/bonding/images/lewis%20dot%20tutorial.swf where

students can build their own molecules by dragging different atoms, positioning them and click on electrons to rotate them. Another applet is available from the Colorado University (PhET) http://phet.colorado.edu/en/simulation/build-a-molecule Similar to the previous applet, students can build their molecules with more lavish tools where students can change bond orders; single, double, and triple.

The teacher will summarize the lesson by asking students to take a short online self-graded multiple-choice exercise on the Lewis model. The use of applet and the flexibility of adding and rotating different atoms and electrons provide students with a visual tool (model) to manipulate atoms in building valid Lewis structures. In addition, the use of technology and animation is an effective way to connect with the new generation of learners who use technology on daily basis. The joy and ease of applied technology in chemistry classroom supports learning and provides students with tools that help them visualize the sub-microscopic level of matter.

Because the Lewis model lessons provide rich opportunities to use multiple models, the teacher has the freedom to choose which model or set of models is the best fit for students. The flexibility here relates only to choosing among online models since skipping the POGIL activity may contribute to student misconceptions. More flexibility is possible through using blended learning where some work can be assigned to do online at home or in class by splitting the class into two groups, each group works on a different applet, and then share their experience on using the digital model with the rest of the class. The lesson design is not rigid but provides flexible instructional supports for diverse learners.

Lesson IV: The Lewis Model Part II

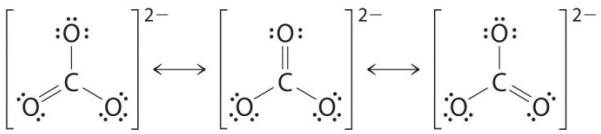
The Lewis model Part II is a natural extension to the previous lesson, Lewis Part I, since both lessons address different areas of the same topic. The activating strategy for this lesson is a real-life application, free radicals and antioxidants. The teacher starts by asking students: What are free radicals? Antioxidants? And why is it important to consume food rich in antioxidants? The use of the real-life application approach helps students to connect classroom chemistry to their daily life. If time is limited or as out-of-classroom activity, the teacher can assign a basic research on what are free radicals.

After having students engage in a discussion, the teacher asks students to draw Lewis structure of the following molecules: BH_3, PCl_5, and NO_2. Students will struggle to apply the octet rule for the above molecules. However, the teacher should ask students to try the best scenario to draw the molecules. After providing group work time, the teacher shares students' trials (student-created models) to structure the three molecules (NGSS approach). The teacher should ask students to provide their rationale behind their structures and explain why they failed to follow the octet rule in the structures of those molecules (limitations of the octet rule). As a result, the teacher may ask students to revise their rules listed for drawing the Lewis structure.

In this approach, the teacher is a facilitator of a learning community where students create their own models. Students will struggle since none of the above

molecules follow the octet rules but are exceptions. In the NGSS, the three dimensions of Science and Engineering Practices (SEPs), Disciplinary Core Ideas (DCIs), and Crosscutting Concepts (CCCs) are crafted into performance expectations that guided the design of the activation strategy "Free radical" in conjunction with the exceptions to the octet rules in drawing the Lewis model. The SEPs, designing the antioxidants area is based on the DCIs of molecular geometry, the octet rule, exceptions to the octet rules, and the Lewis model, which all are weaved together to reflect the CCCs. The NGSS expectations for students include making connections among all three dimensions. Students develop and apply the skills and abilities described in the SEP, as well as learn to make connections between different DCIs through the CCC to help gain a better understanding of the natural and designed world. (www.nextgenscience.org/three-dimensions).

After creating a list for the octet rule exceptions the class moves to another aspect of the Lewis model, resonance. The teacher asks students to draw the Lewis model of the carbonate ion CO_3^{-2} (Figure 41), compare students' models and asks students which one of the three structures is the correct one; and what are the differences between the three structures?



[A] [B] [C]

Figure 41 The Carbonate Ion, CO_3^{-2}

Students may refer to the different locations of the double bond versus the single bonds and the number of electron lone pairs on each oxygen atom. The teacher may explain the validity of the three different models and provide more laboratory measurements to guide students to understand the nature the resonance. If structure **A** was correct, laboratory measurements would show one shorter bond (the carbon-oxygen double bond) and two longer bonds (the carbon-oxygen single bonds). Measurement of structures **B** and **C** would give the same results as well. As it turns out, laboratory measurements show that all three bonds are equal and between single and double bond length. This suggests that none of the Lewis structures they have drawn are correct. It further suggests that the actual structure has three equal carbon-oxygen bonds that are intermediate between single and double bonds. Using laboratory measurement as evidence (NOS) will lead to better understanding of the dynamic nature of the covalent bonding and minimize the misconceptions of the Lewis model, which uses dashes and dots to represent bonded and lone pairs of electrons. Based on the course level, the teacher may expand the lesson to cover the topic of bond orders.

The last section of this lesson is the Formal Charge (FC) concept. Following the same previous pedagogical approach, students will continue to create more models; teacher should ask students to draw as many as possible Lewis models of the sulfate ions, SO_4^{2-}. Share students' work and start to introduce the concept of Formal Charge (FC) and how to calculate it for each atom.

The exit ticket for this lesson consists of creating a two-column note to critique the Lewis model; its advantages and disadvantages. Students are also asked to revise the Lewis model in a way that minimize its disadvantages, student-created model (NGSS).

Lesson V: Valence-Shell Electron-Pair Repulsion (VSEPR) Model Part I

The lesson begins with a visual model, a four-minute video, presents the shape of molecules in a simplified way to introduce the VSEPR model where atoms are arranged to maximize the attraction of opposite charges and minimize the repulsion of the like charges. The discovery of methane gas is used to conclude that the shape of the methane molecule where all hydrogen atoms have to bond to the central carbon atom. Maximizing the distance between bonds (negative charges) leads to the shape of tetrahedral (bond angle 109.5^0). The video also introduces the shape of some simple molecules such as H_2O, NH_3, CO_2, and ClF_3. The video includes molecules that are familiar to students and essential for survival such as water, carbon dioxide, and ammonia.

To create a link between the Lewis model and the new model, VSEPR, provide students with VSEPR geometries chart and ask students to name the geometrical shapes of molecules they build in the previous two lessons. When done, in a two-column note, ask students to compare the Lewis model to the VSEPR model, including commonalities and differences. In addition, ask students to come up with a list of rulesto determine the geometrical shapes of molecules and polyatomic ions. Use the students' notes to create a list of rules for using the VSEPR model (student-created

model).The teacher follows the same pedagogical approach (PCK) as in the previous lesson, “Lewis model II,” where students created their list of rules to structure molecules and ions (students created model). The comparison between Lewis and VSEPR models is a smooth transition from a 2D model to a 3D one. In addition, it helps students to emphasize the importance of the use of multiple models. The use of a VSEPR model illustrates the limitations of the Lewis model as a flat representation which later affects molecular polarity. However, the VSEPR model is based on the Lewis model; students have to start with the Lewis model to understand the VSEPR model and predict molecular geometries.

Moving from using paper-and-pencil to a digital model, simulation, use the following simulation from the Colorado University “molecule shapes” http://phet.colorado.edu/en/simulation/molecule-shapes. For digital learners, using simulations provide them with tools to build different molecules with double and triple bonds. In addition, students can add an option to show the bond angles and the name of the molecular geometry. The simulation allows students to rotate each molecule 360 degree in three dimensions for better visualization of different bond angles (e.g. 90.0 and 120.0). In addition, students can examine real molecules by clicking on real molecules icon.

Even though the digital models bring sophisticated tools to teach MG they still have their limitations. The PhET simulation provides the average bond angles. The teacher should note this limitation of the PhET simulation model. For example, water molecule, the bond angle should be 104.5^0 instead of 109^0. Teachers should point out

how electron lone pair has a bigger electron domain than bonded electron pair, thus it reduces the bonding angle H-O-H to be less than 109^0(104.5^0). In contrast, the Ohio University simulations (provided in VSEPR Model Part II) provide more accurate bond angles though the software, Jmol, may be a challenge for some students to use. The use of more than a single model provides students with various learning tools, and more data which reflect the Nature of Science as accurate and precise.

The summarizing strategy takes a form of linking the Lewis model to the VSEPR model by noting the interdependence between the two models in a table.

Lesson VI: Valence-Shell Electron-Pair Repulsion (VSEPR) Model Part II

In the previous lesson, VSEPR Model Part I, students used the VSEPR geometries chart to identify the geometrical shapes of molecules and polyatomic ions. In the activating strategy, students identify molecules and polyatomic ions which take certain geometrical shapes based on the number of atoms, electrons lone pairs, and bond order which create a link between the Lewis model, the VSEPR model, bond angel, and real molecules in our daily life. Moving back and forth between the Lewis and VSEPR models contributes to students' mastery of the target concept as well as emphasis on the nature of science as a scientific enterprise.

In this lesson, students will use the simulations for the Ohio State University website on molecular geometry. The website provides a tutorial on how to use the Jmol applet in addition to a link on how to draw Lewis model, calculate the formal

charge, resonance, and bond polarity. The Ohio University website provides more accurate bonding angels in comparison to the PhET web-site.

Many students struggle to visualize the molecules in 3D. The use of the VSEPR geometries chart helps students with spatial capacity while other students struggle. The use of the simulation in 3D helps students to rotate molecules and to visualize different angles for different molecular geometries. Some geometrical shapes are a challenge to visualize due to the existence of two different types of bonding angles. For example, the Trigonal Bipyramid shape includes two different bonding angles, 120^0 equatorial and 90^0 axial. In 3D simulations, students can rotate the molecule to observe each angle in a single dimension at the time, x, y, or z (students may need to rotate the molecules multiple times to see both angles simultaneously). The use of multiple models (e.g., Lewis, VSEPR, 2D, 3D, movie, and simulations) provide students with various avenues to support their spatial capacity.

For kinesthetic learners and to bring joy to chemistry classroom while learning a very complex concept, MG, students will create their models using balloons. The teacher provides students (or group of students) with six big balloons and asks students to inflate the balloons, and then tie them tightly at the center. Different number of balloons and various sizes are used to demonstrate different geometrical shapes (bigger balloons for electron lone pairs and smaller ones for bonded electron pairs).

The teacher should ask students to shake the six tied balloons and observe the resultant geometrical shape. Students may use the VSEPR geometries chart (from

VSEPR Part I) and/or the teacher may project the PhET simulation on the screen (if available). After students identify the first shape, ask students to pop one balloon at the time and shake the model again to observe the resultant geometrical shape. Continue to pop one balloon at the time until you end up with only two. It is recommended that the teacher use ear-plugs during this activity (that is what I do). Ask students to use their fist as the central atom to observe a linear shape with bonded angle of 180 degrees.

The model helps students in an amusing way to observe the entire balloon as an electron cloud. The previous models included the simulation failed to represent the electron cloud in a tangible way to show how similar charges repel each other. The teacher should point out how the entire body of each balloon represents the electron cloud which addresses students' misconception of electron as small dot or static entity. This misconception is a product of using a single model or multiple models without addressing the limitations of each. The model helps students to observe how the balloons by nature take the positions to minimize the repulsion force and stay far apart as possible. The use of the balloons model (enactive/analog), the VSEPR geometries chart (iconic), and the PhET simulations (CA) simultaneously bring multiple human senses together to a single activity. The various models presented in this lesson complement each other and minimize students' misconceptions that are likely to arise when using a single model.

As an exit ticket for this lesson, students should answer seven multiple choice questions as an online quiz from the Ohio State University website.

https://undergrad-ed.chemistry.ohio-state.edu/cgi-bin/quiz.pl/quiz/TEST/tut.1

The quiz provides students with seven consecutive questions on the VSEPR model. The interactive quiz provides students with feedback for each answer. In addition, it provides tutorial tool to explain the correct answer and provide hints for each wrong answer. Each question provides a summary of one concept of the Lewis and VSEPR models: Counting the total number of VE, octet rule, formal charge, central atom, and bond angle. The difficulty of the questions increases throughout the short quiz however, it summarizes the rules for: calculating the total number of valence electrons, the Lewis model, resonance structures, formal charge and geometrical shapes for molecules and polyatomic ions.

The teachers can use this quiz as either a formative assessment or as a home-study tool for students. The quiz summarizes the Lewis and VSEPR models in a nice smooth transition from a simple question such as counting the total number of valence electrons to predict the location of fluorine atom on the structure, axial or equatorial. The teacher may use each question to summarize/re-teach each concept based on the students responses (formative assessment). In addition, the teacher may ask students to provide the rationale for their answers to address any misconceptions students may have.

Lesson VII: Molecular Polarity Part I

In this lesson, the teacher starts by asking students about real-world phenomena: Did you ever wonder how molecules of a substance stay close together?

Why does water form droplets or support things on its surface? The teacher uses the answer to the above questions as an introduction to molecular polarity concept and then uses the “Polar bears and penguins” POGIL (Figure 42).

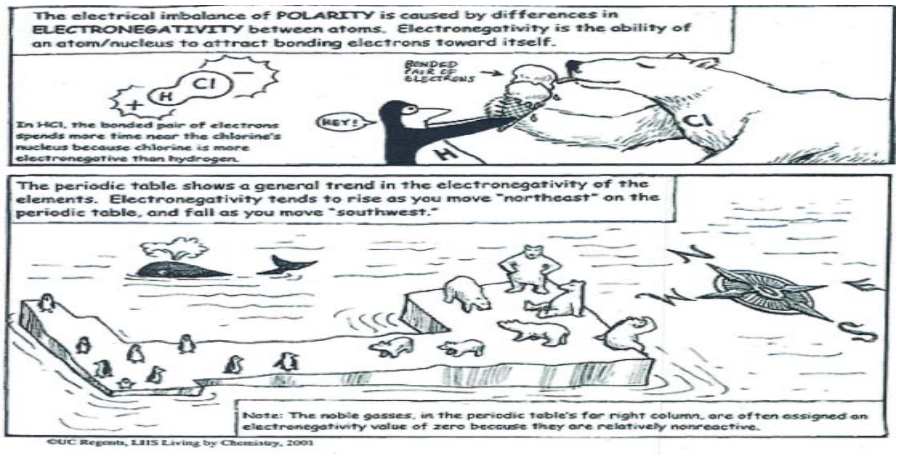


Figure 42 “Polar Bears and Penguins” POGIL

First, students may read the comic individually and then work in groups of three to answer the POGIL questions. After class reconvenes, students provide not only their answers to the POGIL questions but also rationalize their answers. The comic introduces bond polarity based on the difference in electronegativity between the bonded atoms. The teacher should refer to the EN trends and provide students with an EN periodic table to link bond polarity to atomic EN (CCCs). In addition, the teacher may spend some time asking students to figure out the similarities between the iceberg in the comic and the periodic table, including the size of the animals, locations, shapes, active versus non-active animals, etc. The comic provides another avenue for students’ cognitive learning of bond polarity based on differences in

strength between Polar bears and Penguins. The comic could be classified under two types of models: iconic and analog.

Moving from POGIL 1, Polar bears and penguins, to POGIL 2 “Polar, nonpolar, and ionic bonding”, the teacher follows the same pedagogical approach with POGIL (as above). The advantage of this POGIL is in how it connects all the related concepts (CCCs). First, the POGIL starts with the basic information on EN using the elements’ EN values (Figure 43)

1 **H** 2.20											2 **He** —
3 **Li** 0.97	4 **Be** 1.47				5 **B** 2.01	6 **C** 2.50	7 **N** 3.07	8 **O** 3.50	9 **F** 4.10	10 **Ne** —
11 **Na** 1.01	12 **Mg** 1.23				13 **Al** 1.47	14 **Si** 1.74	15 **P** 2.06	16 **S** 2.44	17 **Cl** 2.83	18 **Ar** —
19 **K** 0.91	20 **Ca** 1.04				31 **Ga** 1.82	32 **Ge** 2.02	33 **As** 2.20	34 **Se** 2.48	35 **Br** 2.74	36 **Kr** —

Figure 43 EN Using Elements’ EN Values

Second, the POGIL uses graphic models to introduce bond polarity, and polar versus nonpolar bonds (Figure 44).

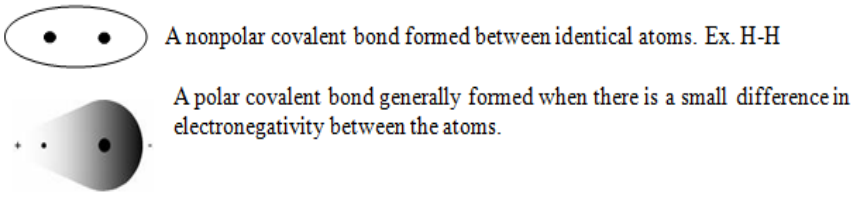


Figure 44 Bond Polarity

Finally, the POGIL uses the two preceding concepts to introduce the topic of molecular polarity, which includes Lewis models of some common molecules: BF_3, H_2O, CO_2, and CCl_4 (Figure 45).

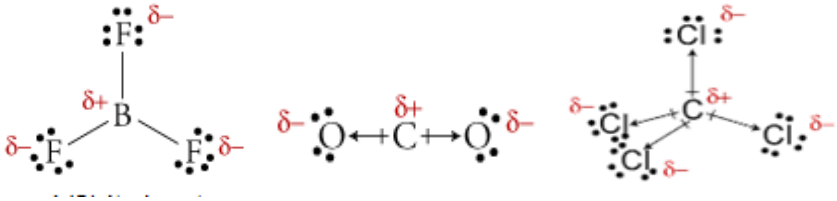


Figure 45 BF_3 CO_2 CCl_4

Each section is followed by critical thinking questions appropriate for the target concept. For the summarizing strategy students are provided with a list of 16 molecules and asked to each molecule to do the following:

a. Determine the geometrical shape.

b. Predict the polarity of each molecule.

c. Provide enough evidence that support your prediction.

Students are asked to provide evidence for their predictions on molecular polarity. For students to predict molecular polarity they have to; structure the Lewis model, VSEPR model, consider bonded and non-bonded electron pairs, electron' domains, bond order, and elements' electronegativities. The assessment features some molecules that share the same molecular geometry. However, some are polar and some are nonpolar. For example both $CCl_4$and $CHCl_3$ molecules attain the same molecular geometry, tetrahedral, however CCl_4 is a nonpolar molecule while $CHCl_3$ is

a polar one. Those questions address students' misconception of certain molecular geometries being always polar or nonpolar. For example, some students believe the geometrical shape "tetrahedral" always results in a polar molecule. Others may believe the existence of electron lone pairs on the central atom leads to a polar molecule. For example, the triiodide ion, I_3, is a *nonpolar molecule* even though it contains electron lone pairs on the central atom in comparison to the XeF_6 molecule which is a *polar molecule* due to the existence of electron lone pair on the central atom.

Lesson VIII: Molecular Polarity Part II "like dissolve like"

Following the same approach from the previous lesson, Polarity Part I, the teacher asks students to work in groups of two to answer the following questions:

3. Why don't oil and water mix?
4. How does a rain coat repeal water?

The most common answer students provide to question one comes from their prior knowledge from 9^{th} grade and middle school science classes, oil is less dense the water. Teacher should use this opportunity to teach students how to address the question properly. Since the question did not ask why oil float on the top but asked why oil and water do not mix, so density is not the reason in this case. Moving forward, teacher can re-direct students to provide answers based on what they learn in polarity lesson one or at least consider polarity as a factor.

After stimulating students' thinking to find answer for the two questions, use the chemistry crash-course video to summarize the previous lesson "Polarity Part I"

and provide students with a chance to ask questions and comment on the video based on what they learned in the previous lesson. This approach provides the teacher with feedback on any gaps or misconceptions that students may have developed before moving on with molecular polarity. In addition, the teacher may check the homework from the previous lesson after watching the video to address any misconceptions.

Based on available class time, the teacher can utilize the “Drops on a penny” activity https://www.teachengineering.org/lessons/view/duk_drops_mary_lessas a demonstration or assign it as a lab for students’ group work. This demo/lab demonstrates the Intermolecular Force (IMF) among molecules of different solutions/liquids. The use of different molecules, such as water, ethyl alcohol, water detergent solution, mineral spirits or hexane (nonpolar molecule) illustrates the IMF among molecules. Based on the IMF among molecules, due to molecular polarity, students count the number of drops each penny can hold.

The use of “Drops on a penny” either in a demonstration or a lab format helps students to connect the macroscopic and sub-microscopic levels of chemistry (the triplet). The teacher provides students with a chance to inquire why certain liquids/solutions stick together (hold many drops), while others do not. Students need to use their understanding of molecular polarity to draw a conclusion on why each penny holds a different number of drops. For example, why water molecules stick together and provide the highest number of drops versus other molecules, such as hexane (nonpolar molecules), which hold only one drop. In general, students tend to provide observations rather than rationales behind certain phenomenon. Thus, the

teacher should encourage students to provide valid reasoning(s) backed up with evidence from what they just learned on molecular polarity to explain their observations (using argumentation in science). The teacher has the flexibility to utilize the above activity in any format that fits his or her students' needs and time availability: demo, lab, mini-lab, mix of demo and lab based on the class time limits.

Following the demo (macroscopic level) the teacher uses the following PhET simulation from the Colorado University "molecule Polarity"

https://phet.colorado.edu/en/simulation/molecule-polarity

The simulation demonstrates two atoms, three atoms or real molecules (sub-microscopic level). Students can change the electronegativity of each atom (slider),add/remove an electric field, rotating molecules, changing bonding angles, view bond dipole, molecular dipole, and partial charges. The web-site provides molecular polarity guided activity *(Model V)* with a teacher guide and a clicker activity. Students need to use the simulation to answer the guided inquiry activity question (POGIL lab).

The PhET website is rich in using various types of models and it consolidates models in the format of guided inquiry approach (POGIL). The teacher can employ the provided activities in substantial ways; lab, demonstration, POGIL, individual or group work, formative, and/or blended learning. The multiple approaches maximize students' benefits of the learning target(s). Images and interactive simulations enable students to visualize bonds and molecular polarities which assist them to bridge the bonds polarity to the molecular polarity. The addition or emanation of electric fields

helps students to conceptualize the behavior of certain molecules based on its polarity and identify it as a physical property (CCCs). Students observe that bond angles affect the dipole moment and the overall net charge of certain molecules. The ability to manipulate the molecules' bonding angles and elements' electronegativity exemplifies the role of models in helping students to observe, interact, and predict molecular properties (polarity). The above simulation illustrates an entertaining inquiry learning approach. It reflects another aspect of model-based teaching as well as the nature of science where students *do science;* observe, collect data, control variables, and draw conclusions based on scientific evidence and empirical data. In addition, it builds strong connection among the three facets of chemistry; macroscopic, sub-microscopic and symbolic.

Alternative Approach:

To fit classroom time, the teacher can use the previous inquiry guided lab from the PhET website, challenging problems (last page), as a formative assessment, it also could be assigned as homework.

The lesson concludes with an exit ticket as summarizing strategy where students need to answer the following questions:

1. Predict whether these molecules are polar or nonpolar.
2. For each molecule provide valid reasoning(s) for molecular polarity.

HBr, SO_2, XeF_4, NF_3, BCl_3, H_2O, CO_2

The above molecules contain polar molecules: HBr, NF_3 SO_2, andH_2O and nonpolar molecules: XeF_4, BCl_3, and CO_2 which come in various molecular

geometries. For each molecule, students need to draw the Lewis model, followed by the VSEPR model, determine bond angles, electrons lone pairs, bond order, use EN data, apply mathematical rules, and then decide the polarity of each molecule. Students may use periodic table, EN chart, VSEPR geometries chart, PhET simulations, Ohio State University simulation, and any other format of digital or physical models.

This multiple steps process requires high level of thinking, mastery of various concepts, applying various models, and utilizes some data (element's electronegativity) which summarize the entire unit of molecular geometry.

Summative assessment

By the end of the unit, there are summative assessment questions in two different formats, multiple choice and short free responses. In addition, there is a performance task which addresses the learning goals of the MG unit. Each summative assessment question targets a specific concept as explained in the commentaries (textboxes). The performance task is aligned with the NGSS three dimensions of SEPs, DCIs, and CCCs.

Teacher References and Students' Study Guide

In addition to all the provided references and teacher' resources, there are many useful websites where teachers can utilize to benefit their students. The expansion of the use of technology creates a new challenge to keep tracking of the

new educational digital resources. Some of which provide tutorials, animations, videos, interactive applets, pre-designed labs, and various forms of assessment. It is the teachers' decision to select what types of resources are suitable for their students and the learning setting. The following online resource is rich in the use of models and can be utilized in many ways to support student learning.

http://chem.libretexts.org/Textbook_Maps/General_Chemistry_Textbook_Maps/Map%3A_Chemistry_(OpenSTAX)/07%3A_Chemical_Bonding_and_Molecular_Geometry/7.6%3A_Molecular_Structure_and_Polarity

The www.chem.libretexts.org provides a great tool for formative and summative assessment. It is a rich source for teachers (and students) to select assessment items that help diverse learners. The website is tutorial and rich in models (charts, tables, 3D images, simulations, etc). It starts with VSEPR theory with a table of each geometrical shape in both the Lewis model and the VSEPR model format.
It is explicit about the order of electron-pair repulsions from greatest to least as: lone pair-lone pair > lone pair-bonding pair > bonding pair-bonding pair.
In addition, the website does not only provide many examples with answers supported by 3D images but also links to other useful website such as the PhET simulation from Colorado University. It covers the concepts of molecular polarity, dipole moment, and properties of polar molecules. At the end of the page there are key concepts, summary and glossary.

Appendix B

EATS LESSON TEMPLATE

ESSENTIAL QUESTION: What is the MOST important concepts or skills? With key questions if necessary.	
Activating Strategy: How will you activate your lesson or link to prior knowledge? (Examples: KWL, work maps, Word splash, etc.) AND/OR	
ACCELERATION STRATEGIES: (Focus on content maps and key vocabulary for next lessons)	
TEACHING STRATEGIES: What instructional strategies will you use in your lesson? (Examples: graphic organizer, distributed guided practice, distributed summarizing, collaborative pairs)	
SUMMARIZING STRATEGIES: How will students summarize what they are learning during the lesson and at the end? (Examples: Ticket out the Door, 3-2-1, etc. Answer the EQ)	
RE-TEACHING FOCUS AND STRATEGY (if necessary)	

Appendix C

PERIODIC TREND POGIL

Periodic Trends

Can the properties of an element be predicted using a periodic table?

Why?

The periodic table is often considered to be the "best friend" of chemists and chemistry students alike. It includes information about atomic masses and element symbols, but it can also be used to make predictions about atomic size, electronegativity, ionization energies, bonding, solubility, and reactivity. In this activity you will look at a few periodic trends that can help you make those predictions. Like most trends, they are not perfect, but useful just the same.

1. Consider the data in Model 1 on the following page.
   a. Each element has three numbers listed under it. Which value represents the atomic radius?

   b. What are the units for the atomic radius?

   c. Write a complete sentence to convey your understanding of atomic radius. *Note:* You many not use the word "radius" in your definition.

2. In general, what is the trend in atomic radius as you go down a group in Model 1? Support your answer, using examples from three groups.

3. Using your knowledge of Coulombic attraction and the structure of the atom, explain the trend in atomic radius that you identified in Question 2. *Hint:* You should discuss either a change in distance between the nucleus and outer shell of electrons or a change in the number of protons in the nucleus.

4. In general, what is the trend in atomic radius as you go across a period (left to right) in Model 1? Support your answer, using examples from two periods.

5. Using your knowledge of Coulombic attraction and the structure of the atom, explain the trend in atomic radius that you identified in Question 4.

Model 1 – Main Group Elements

1 H							2 He
37							31
1312							2372
2.1							N/A
3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne
152	112	83	77	71	66	71	70
520	900	801	1086	1402	1314	1681	2081
1.0	1.5	2.0	2.5	3.0	3.5	4.0	N/A
11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
186	160	143	117	115	104	99	98
496	738	578	786	1011	1000	1251	1521
0.9	1.2	1.5	1.8	2.1	2.5	3.0	N/A
19 K	20 Ca	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
227	197	122	123	125	117	114	112
404	550	558	709	834	869	1008	1170
0.8	1.0	1.7	1.8	1.9	2.1	2.5	N/A

Atomic Number
Element Symbol
Electron Shell Diagram
Atomic Radius (pm)
1st Ionization Energy (kJ/mol)
Electronegativity

Note: The transition elements and f-block elements have been removed from the periodic table here to ease the analysis of the trends.

6. Locate the numbers in Model 1 that represent the ionization energy. The **ionization energy** is the amount of energy needed to remove an electron from an atom.

   a. Using your knowledge of Coulombic attraction, explain why ionization—removing an electron from an atom—takes energy.

   b. Which takes more energy, removing an electron from an atom where the nucleus has a tight hold on its electrons, or a weak hold on its electrons? Explain.

7. In general, what is the trend in ionization energy as you go down a group? Support your answer using examples from three groups.

8. Using your knowledge of Coulombic attraction and the structure of the atom, explain the trend in ionization energy that you identified in Question 7.

9. In general, what is the trend in ionization energy as you go across a period? Support your answer using examples from two periods.

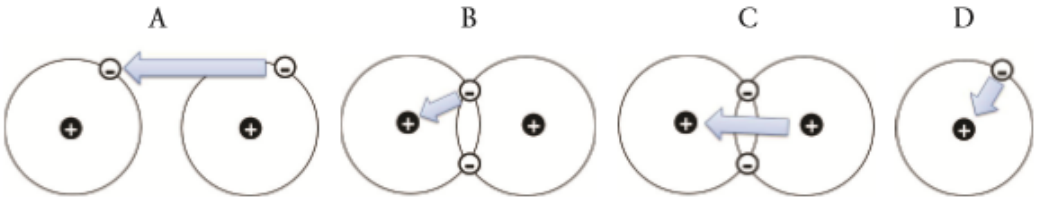
10. Using your knowledge of Coulombic attraction and the structure of the atom, explain the trend in ionization energy that you identified in Question 9.

11. Atoms with loosely held electrons are usually classified as metals. They will exhibit high conductivity, ductility, and malleability because of their atomic structure. Would you expect metals to have high ionization energies or low ionization energies? Explain your answer in one to two complete sentences.

Read This!

Electronegativity is a measure of the ability of an atom's nucleus to attract electrons from a different atom within a covalent bond. A higher electronegativity value correlates to a stronger pull on the electrons in a bond. This value is only theoretical. It cannot be directly measured in the lab.

12. Using the definition stated in the *Read This!* box above, select the best visual representation for electronegativity. Explain your reasoning.



13. Locate the electronegativity values in Model 1.

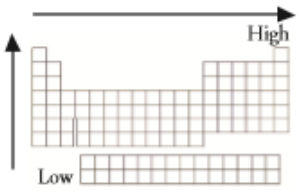
    a. What is the trend in electronegativity going down a group in Model 1?

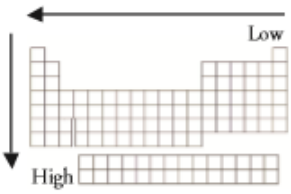
    b. Explain the existence of the trend described in part *a* in terms of atomic structure and Coulombic attraction.

    c. What is the trend in electronegativity going across a period in Model 1?

    d. Explain the existence of the trend described in part *c* in terms of atomic structure and Coulombic attraction.

14. The two diagrams below can summarize each of the three trends discussed in this activity. Write "atomic radius," "ionization energy," and "electronegativity" under the appropriate diagram.





Appendix D

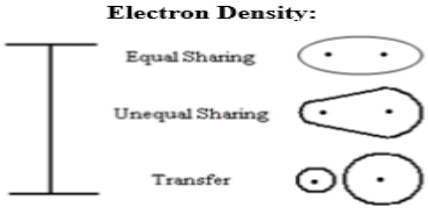
WHAT IS A COVALENT BOND POGIL

What is a covalent bond? How do they form?

Information 1- Bond Types

- When a metal and a non-metal bond, the result is often an ionic bond. However, predicting bond type (or character) is not always that simple. Chemists rely on experimental evidence.
- Chemical bond character is determined by calculating the electronegativity difference between the atoms involved in bonding. The following rough continuum is used:

Electronegativity Difference (Pauling Scale)	Bond Character
< .4	Nonpolar covalent
Between .4 and 1.5	Polar covalent
Between 1.5 and 2	Covalent / ionic
> 2	Ionic

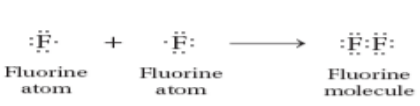


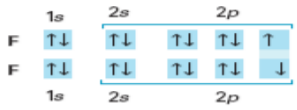
Critical Analysis Questions

1. Determine the bond character of the chemical bonds present in each of the following compounds:
   a. NaCl
   b. N_2
   c. H_2O
   d. $MgCl_2$
2. In terms of electron density, what is the difference between an ionic and covalent bond?

Information 2- Covalent Bonds

- Substances containing covalent bonds are called **molecular compounds**.
- **Molecule**- a neutral group of atoms joined by covalent bonds.
- Atoms within molecules obtain stability by sharing one or more pairs of electrons.





Critical Analysis Question

1. How many pairs of electrons are shared in a diatomic fluorine molecule? Label them in the picture above.

2. How many unshared pairs are in a diatomic fluorine molecule?

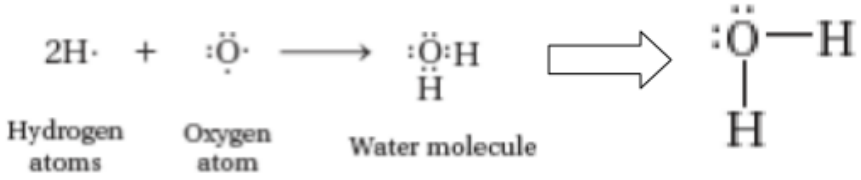
3. Explain why the fluorine molecule is more stable than the individual atoms.

4. Hydrogen and nitrogen combine to form a molecular compound. Use electron dot structures to write an equation showing how the individual atoms combine to form a more stable compound. Include the orbital notation of each atom in the molecule.

5. How many shared pairs are in the molecule? How many unshared pairs are present?

Information 3- Structural Formulas

- **Structural formula**- show the arrangement of atoms in a molecular compound.
- Shared pairs are called **single covalent bonds** and are shown with a dash.
- Unshared pairs are called **lone pairs** and are left as dots.



A water molecule contains 2 single covalent bonds and 2 lone pairs.

Critical Analysis Question

1. Write the structural formula of methane, CH_4. Indicate the number of single covalent bonds and lone pairs.

Appendix E

LEWIS STRUCTURES POGIL PART A

ChemActivity **2**

Part A: Lewis Structures

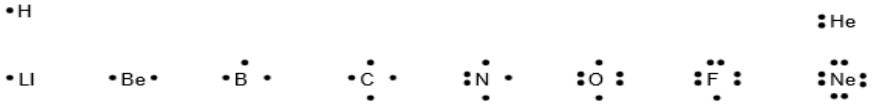
(How do I draw a legitimate Lewis structure?)

Dot and line-bond representations which follow certain rules will be called "legitimate" Lewis structures.

Model 1: G. N. Lewis' Method for Predicting Molecular Properties

In the early part of this century, a chemist named Gilbert N. Lewis devised a system for diagramming atoms and molecules. The system is still used today because predictions made from these simple diagrams often match experimentally determined ion charges, bond angles, molecular shapes, bond orders and other chemical properties.

Lewis proposed the following representations for the first ten elements with their valence electrons.



Of these 12 elements, only He and Ne are found in nature as single neutral atoms (as shown). The other elements are found as ions or as parts of molecules.

Lewis proposed that any atom, ion or molecule that can be represented by a "legitimate" Lewis structure should exist in nature or be possible to make in the laboratory.

A "legitimate" Lewis structure is a dot or line bond representation in which:

1. *The sum of the electrons around a hydrogen is two (a bonding pair).*
2. *The sum of the electrons (in bonding pairs and lone pairs) around a **carbon, nitrogen, oxygen or fluorine atom** is eight–an **octet**.* (**The "octet rule."**)

For example:

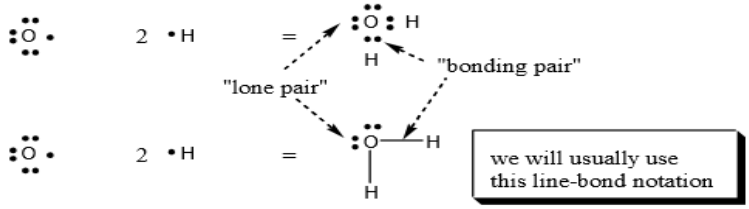
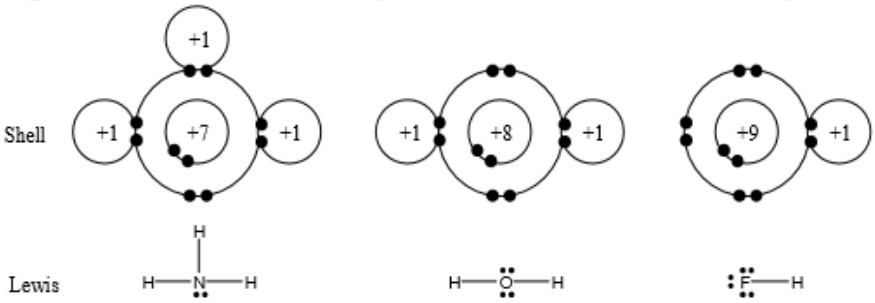


Figure 1: Shell and Lewis Representations of Selected Compounds

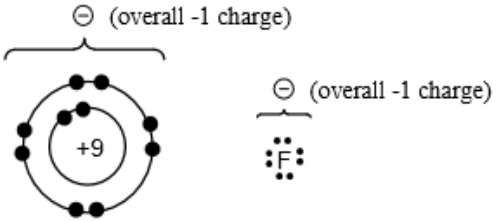


Critical Thinking Questions

1. The valence shell of an atom in a legitimate Lewis structure (e.g. N, O, F or H, *above*) has what in common with the valence shells of He, Ne and all elements in the last column of the periodic table?

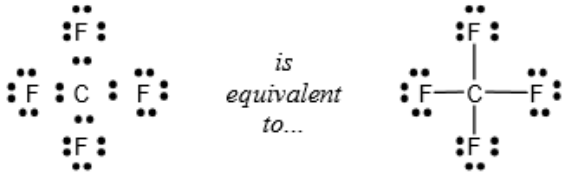
They all have a completely filled outer shell (valence shell).

2. Draw a shell representation and Lewis structure for the ion of fluorine that you predict is most likely to be stable. Explain your reasoning.



F with an extra electron has a filled valence shell.

3. Draw a Lewis structure of a neutral molecule that is a naturally occurring combination of fluorine atoms and one carbon atom.



4. What is the shape of the molecule in CTQ 3?

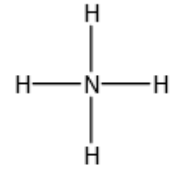
tetrahedral

5. Make a checklist that can be used to determine if a Lewis structure for a molecule is legitimate.

   i. Make sure the total number of valence electrons is correct
   ii. Make sure there are 8 electrons around each C,N,O or F.
   iii. Make sure there are 2 electrons around each H.

6. a) How many valence electrons does one nitrogen atom have? ***5***
   b) How many valence electrons does one hydrogen atom have? ***1***
   c) Hypothetically, how many valence electrons would a (neutral) NH_4 molecule have if it could exist? ***9***
   d) How many valence electrons does one NH_4^+ ion have? ***8***
   e) Draw the Lewis structure for NH_4^+

⊕ (overall +1 charge)

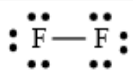
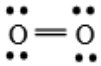
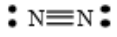


7. Describe how to calculate the total number of valence electrons in an ion (+ or -)?

Count the number of valence electrons you would expect for a neutral molecule and then add one if the ion has a – charge, or subtract one if the ion has a + charge.

Model 2: Multiple Bonds

Table 2a: Bond Information for Second Row Diatomic Molecules

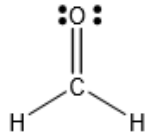
Formula	Lewis Structure	Bond Order	Type of Bond	Number of Bonding Domains
F_2		1	single bond	1
O_2		2	double bond	1
N_2		3	triple bond	1

Critical Thinking Questions

8. Does the Lewis structure of O_2 satisfy the checklist you made in CTQ 5? ***yes***

9. How many electrons are involved in a triple bond? ***6***

10. Consider the molecule H_2CO.
    a) Draw the Lewis structure.



    b) How many bonding domains are there around carbon, the central atom? ***3***
    c) What is the shape of this molecule? ***Trigonal planar***
    d) Are your answers above consistent with a HCO bond angle very close to 120°? ***Yes***

Appendix F

POLAR BEAR AND PENGUINS POGIL

Student Worksheet

Polar Bears and Penguins

Name: _____

Period: ____ Date: _____

Purpose: In this lesson you will be exploring polarity and bonding between atoms in greater detail. A comic book will provide new information about these topics and will introduce you to the concept of electronegativity, which helps us to understand partial charges.

Use the comic book called "The Bare Essentials of Polarity" to answer the following questions.

1. How does the comic book define a "polar molecule?"

2. Define electronegativity as you understand it, after reading the first two pages of the comic book.

3. Interpret the picture at the bottom of page 1. Explain how the iceberg, penguins, and polar bears represent trends in electronegativity.

4. What is the artist trying to represent when there are two polar bears arm wrestling together, or two penguins arm wrestling together?

5. What three types of bonds are represented on page 3 of the comic book? What happens to the bonding electrons in each type of bond?

6. Explain why there are four scoops of ice cream in the illustration of O_2 on page 3.

7. What do the six scoops of ice cream represent in the illustration of N_2 on page 4?

8. Describe what you think is happening to the penguin in the CO_2 molecule in the picture on page 4.

9. Name three things that the picture of CO_2 on page 4 illustrates about the molecule.

10. Describe what you think is happening to the penguins in the illustration of H_2O on page 4.

11. Explain what you think the crossed arrow represents in the comic book.

12. What are the two definitions of "dipole" given in the comic book?

Making Sense

What does electronegativity have to do with polarity?

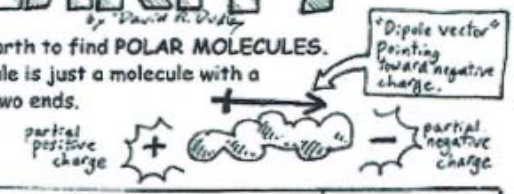
If you finish early. . .

Using polar bears and penguins, create an illustration showing a hydrogen sulfide molecule, H_2S. (Hint: You may wish to start with a Lewis dot structure.)

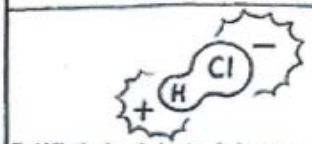
The BARE ESSENTIALS of POLARITY

by David R. Dudley

You don't have to go to the ends of the earth to find **POLAR MOLECULES.** They're all over the place. A polar molecule is just a molecule with a difference in electrical charge between two ends.

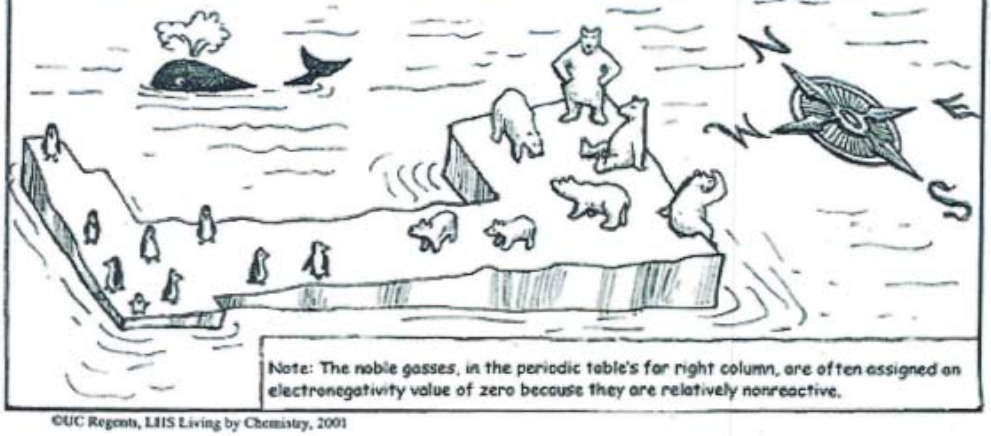


The electrical imbalance of **POLARITY** is caused by differences in **ELECTRONEGATIVITY** between atoms. Electronegativity is the ability of an atom/nucleus to attract bonding electrons toward itself.



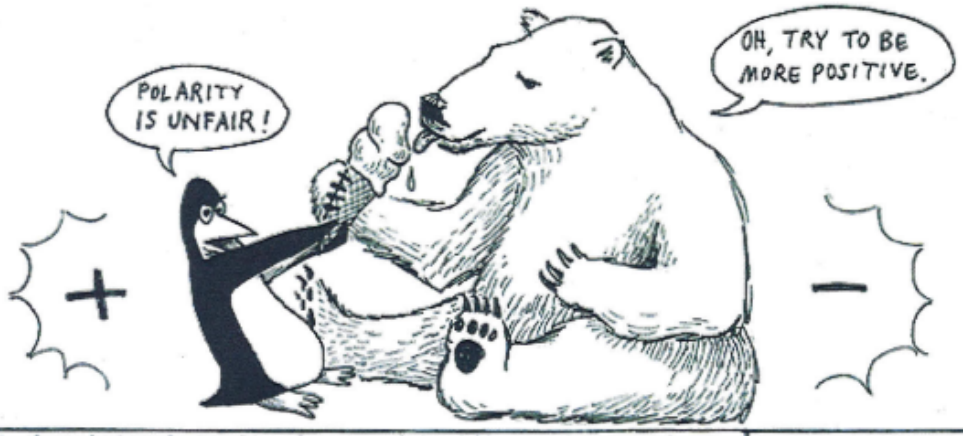
In HCl, the bonded pair of electrons spends more time near the chlorine's nucleus because chlorine is more electronegative than hydrogen.

The periodic table shows a general trend in the electronegativity of the elements. Electronegativity tends to rise as you move "northeast" on the periodic table, and fall as you move "southwest."



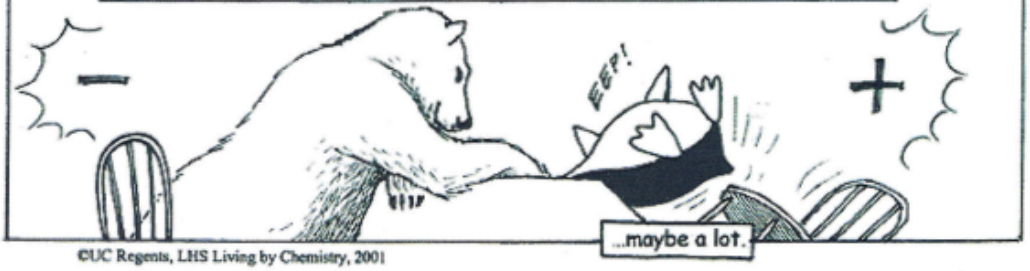
Note: The noble gasses, in the periodic table's far right column, are often assigned an electronegativity value of zero because they are relatively nonreactive.

When two atoms with unequal electronegativity values bond, they do not share the bonding electrons evenly. The bonding electrons spend more time around the more electronegative atom, creating a PARTIAL NEGATIVE CHARGE on that atom. The other atom then has a PARTIAL POSITIVE CHARGE, and the bond is polar.



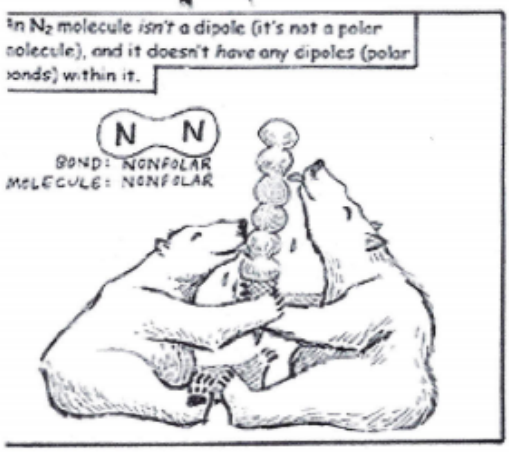
So the polarity of a bond is a function of the difference between the electronegativity values of two bonding atoms. Bonded atoms with equal electron-attracting strength will have nonpolar bonds.

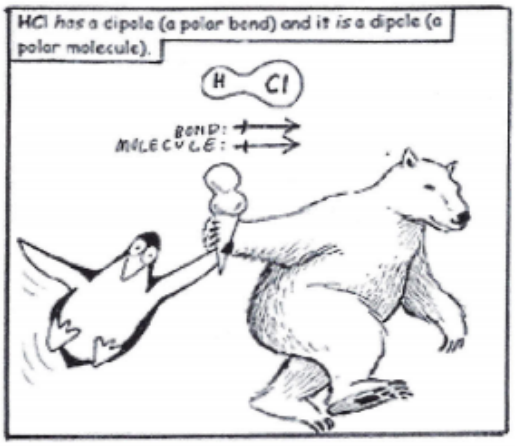
However, if the electronegativity of two bonded atoms is unequal, then their bond will be polarized—maybe a little...

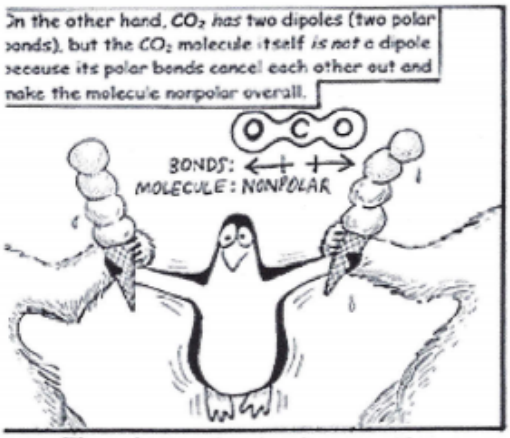


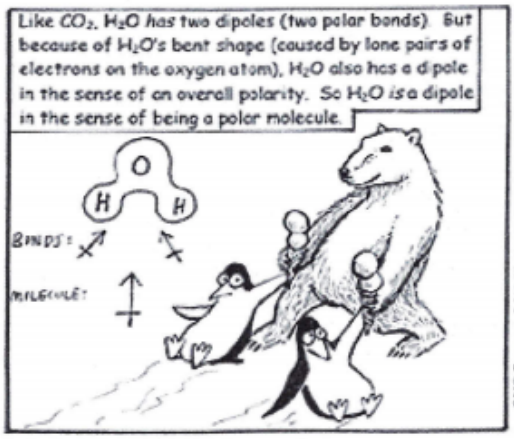
Polar bonds between atoms constitute **DIPOLES**. Actually, the word "dipole" can refer to several different things that are relevant here: (1) the polarity of an individual polar bond between atoms, (2) the net polarity of a polar molecule that may have several polar covalent bonds within it, and (3) the polar molecule itself.

Confusing? Let's look at some examples:









The polarity of molecules can affect many of their other properties, such as their solubility, their boiling and melting points, and their odor.

Appendix G

PERFORMANCE TASK

Experiment

Molecular Geometry and Polarity[1]

THE OHIO STATE UNIVERSITY

Objectives

At the end of this activity you should be able to:

- Write Lewis structures for molecules.
- Classify bonds as nonpolar covalent, polar covalent, or ionic based on electronegativity differences.
- Recognize exceptions to the octet rule; draw accurate representations.
- Describe 3-dimensional shapes of simple molecules based on VSEPR theory.
- Predict polarity based on geometry and individual dipole moments.

Introduction

The substances in our world exhibit remarkably different properties. At room temperature some substances are solids, others liquids, and others gases. Some participate in sudden chemical reactions, whereas others are quite inert and unreactive. Perhaps most remarkably, this wonderful diversity occurs even though the substances are comprised of a limited number of elements. Indeed, only a very small number of different elements are present in almost any pure substance we encounter in the environment or the laboratory. How can this wide diversity of properties be explained?

A key to understanding the wide range of physical and chemical properties of substances is recognizing that atoms *combine* with other atoms to form molecules or compounds and that the *shape or geometry* of a collection of atoms strongly affects the properties of that substance. One reason this occurs is because the distribution of charge in a molecule affects many properties of the substance. For example, if the negative change is concentrated in one region of a molecule its' properties will be widely different than if the charge is distributed evenly throughout the entire molecule.

In this investigation you will examine a theory that chemists use to explain different aspects of chemical bonding: *Valence-shell electron-pair repulsion* (VSEPR) theory. Attention will be given to how molecules are arranged in different shapes and how chemists can predict the geometry of a given molecule. It will then be shown how a molecule's shape, along with electronegativity differences for

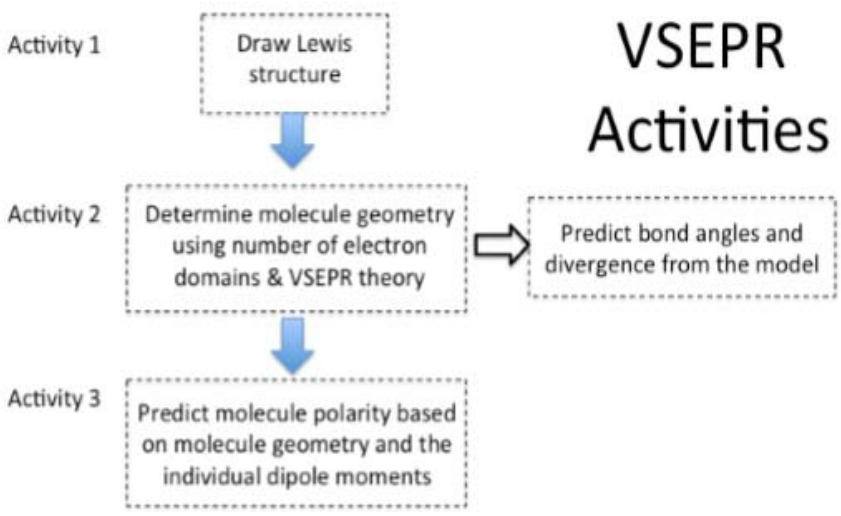
[1] Prepared by Dr. Ted M. Clark and Dr. Patrick Woodward, the Ohio State University, Department of Chemistry and Biochemistry. If you have questions, comments or suggestions, please contact Dr. Clark: clark.789@osu.edu.

its' atoms, determine the molecule's polarity. As suggested above, the best way to understand and predict the physical and chemical properties of substances in our world is by understanding their structure at the molecular level.

Discussion of Activities

In this investigation you will complete activities that ask you to examine molecular geometry and molecular polarity. These activities are based on computer simulations and ball-and-stick models. All of these activities can be discussed with classmates and/or completed in small groups. Your Teaching Assistant will check on your progress.

The VSEPR model can be used to predict the geometry of molecules and polyatomic ions. *Molecular geometry* describes the positions of the nuclei in relation to each other. Included in the description are the *bond angles*, the angles made by the lines joining the nuclei of bonded atoms. In order to predict geometry using the VSEPR model, we need to know the number of electron pairs in the valence shell of the central atom. That can easily be determined by drawing a Lewis structure.



Activity 1: Drawing Lewis Structures

Guidelines for Drawing Lewis Structures

1	Determine the total number of valence electrons; for polyatomic ions remember to adjust for charge.	
2	Arrange atoms in a skeleton structure and connect them with single bonds.	>>> If you are working with a molecule or ion that has three or more atoms, the least electronegative atom is most likely to be the central atom (remembering that hydrogen can only form one bond and therefore is never a likely candidate to be the central atom).
3	Complete octets of the terminal atoms (remember H atoms can only accommodate 2 electrons).	
4	If not all of the valence electrons have been used place any extra electrons on the central atom.	>>> Extra electrons placed on the central atom may in some cases bring the number to more than eight. This is called *expansion of the valence shell* and is an exception to the octet rule; this is acceptable for atoms in the **third period and below**.
5	If the central atom does not have an octet, use lone pairs from terminal atoms to form multiple bonds.	>>> Only the second period elements C, N, O and sometimes S (in combination with C or O) form multiple bonds. This leads to another exception to the octet rule, i.e. when an atom like Be is combined with either hydrogen or halogens, as in BeH_2. Since Be does not form multiple bonds, the central atom is electron deficient.

- If more than one acceptable Lewis structure can be drawn by simply choosing a lone pair from a different terminal atom to form a double bond with the central atom, the different structures are called *resonance forms*. The "extra" electron pair is *delocalized*, spread out among the possible bonding sites.

Table 1. Drawing Lewis Structures and Determining Electron & Bonding Domains.

	Sketch of Lewis structure	Does the structure violate the octet rule"?	Number of electron domains (central atom)	Number of bonding domains (central atom)
NH_3				
H_2O				
BF_3				
CO_2				
XeF_6				

One reason Lewis structures are useful is because they help to identify the number of *electron domains*, or regions of high electron density, about a central atom. An electron domain can be a bonding pair, a lone pair, or a double or triple bond. A multiple bond is counted as one domain.

The Lewis structure for HCN is shown at right. Notice that the central carbon atom has two electron domains (a single bond and a triple bond) and also two *bonding domains*. The nitrogen atom also has two electron domains (a lone pair of electrons and a triple bond) but only one bonding domain. The hydrogen atom only has one electron domain (the single bond) and one bonding domain.

Activity 2: VSEPR and Predicting Molecular Geometry

Once we have the Lewis structure, we have the information needed to predict the geometry. It's important to remember that what we really want to know is the *molecular geometry*—the positions of the nuclei in relation to each other. The molecular geometry is dependent on the electron domain geometry; that is why the initial step is drawing the appropriate Lewis structure! As noted above, the simple concept behind valence shell electron pair repulsion theory (VSEPR) is the idea that electron pairs in the valence shell of an atom will repel each other and arrange themselves as far apart as possible. This arrangement of electron pairs will determine the geometry of the molecule or polyatomic ion.

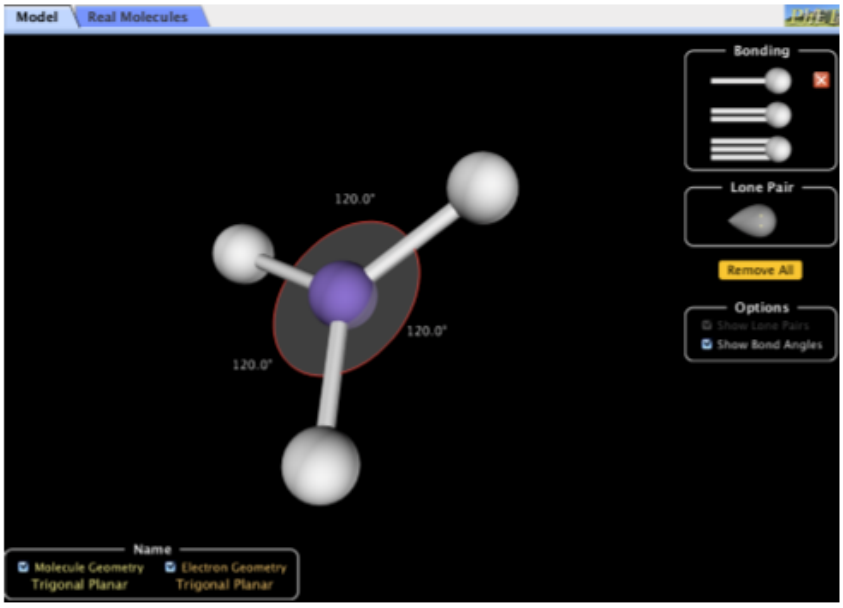


Figure 1. The PhET Computer Simulation "Molecule Shapes".

Your initial task in this activity is to determine the molecule geometry as the number of electron pairs changes. Accomplish this by using **the computer simulation "Molecule Shapes"** (shown at left) and fill in the table.

Notice, in this simulation you can increase the number of electron domains by adding single, double, or triple bonds, or lone pair electrons. In the lower left corner you will find both the molecule geometry and the electron geometry.

Table 2. Model Electron Domain Geometries.

Number of Electron Domains	Electron Domain Geometry	Bond Angles
2	Linear	180°
3		
4		
5		
6		

The molecular geometry is the same as the electron domain geometry **if** all domains contain bonding pairs. What if lone pair electrons are present on the central atom? The molecular geometry will **NOT** be the same as the electron domain geometry. To investigate this, return to the simulation and complete Table 3. If you do not understand the names for the different geometries ask your Teaching Assistant.

Table 3. Electron and Molecular Geometries.

Number of electron domains	Bonding Pairs	Nonbonding Pairs	Electron Domain Geometry	Molecular Geometry
2	2	0		
3	3	0		
3	2	1		
4	4	0		
4	3	1		
4	2	2		
5	5	0		
5	4	1		
5	3	2		
5	2	3		
6	6	0		
6	5	1		
6	4	2		

Question 1. VSEPR standards for "valence-shell electron-pair repulsion". How does electron pair repulsion determine the molecular geometry? Discuss two specific examples from the table. (Hint: In the simulation is it possible to force the electron domains to be close together?)

Question Set 2.

For each shape identify the molecular geometry.

i.

ii.

iii.

Determine the electron-domain geometry on which the molecular geometry is based.

i.

ii.

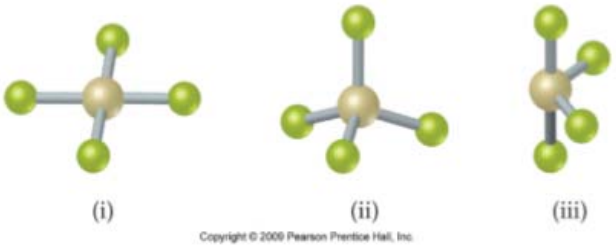
iii.

How many lone-pairs are there on each central atom?

i.

ii.

iii.



Which of the following element(s) could be the central atom in shape (iii)?

Be, C, S, Se, Si, Xe?

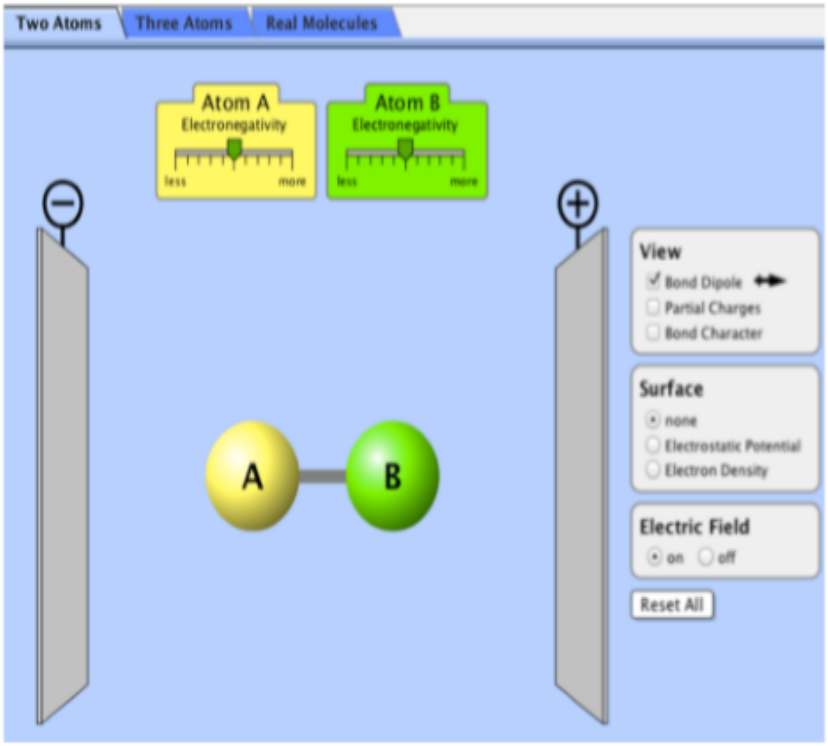
You may have noticed that some electron domains appear larger than others. To investigate how this may affect the resulting molecular geometry, complete Table 4 and predict both the geometry and the bond angles. Then, compare your predictions with the experimental determined bond angles (as shown in the simulation under the tab **"Real Molecules"**).

Table 4. Comparison of Electron Domains.

Molecule	Lewis Structure	Predicted Molecular Geometry	Predicted Bond Angles	Experimentally determined bond angles
NH_3				
H_2O				
SO_2				

Question 3. Which assumption about the space occupied by nonbonding (lone pair) electron pairs is most consistent with the experimental bond angles: do nonbonding pairs occupy more, less, or the same amount of space as bonding pairs?

Activity 3: Molecular Polarity



Investigating Bond Polarity with the molecule AB

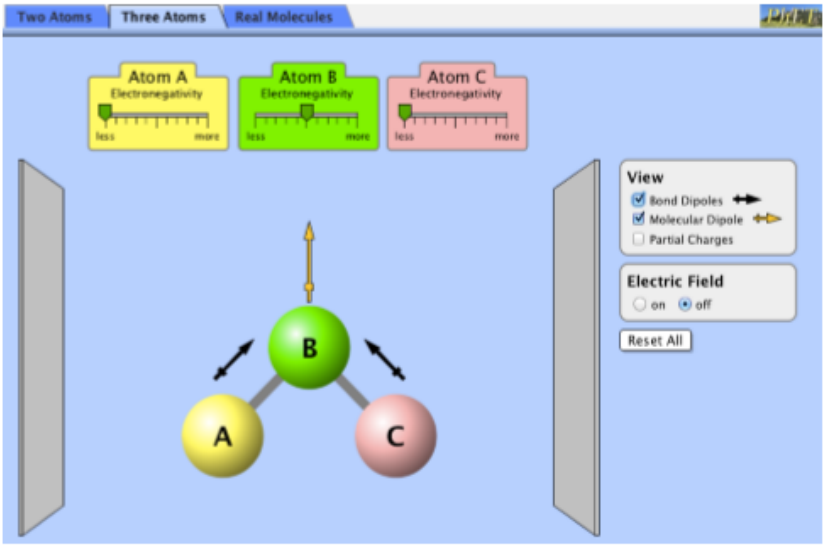
Select the "Two Atoms" tab on the top.

In this simulation you will examine the **bond polarity**, which is a measure of how equally the electrons in a bond are shared between the two atoms of the bond.

There are different ways of representing where the electrons are in a bond. Take a few minutes and try the different "views" in the simulation, i.e. bond dipole, partial charges, and bond character. The electron density or electrostatic potential are other ways of communicating where the electrons are in the molecule.

Note: **Within the simulation you change the relative electronegativity of atoms A and B**.

Investigating Bond Polarity & Molecular Polarity with the Molecule ABC

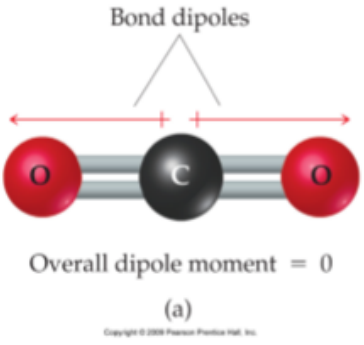


Select the "**Three Atoms**" tab on the top.

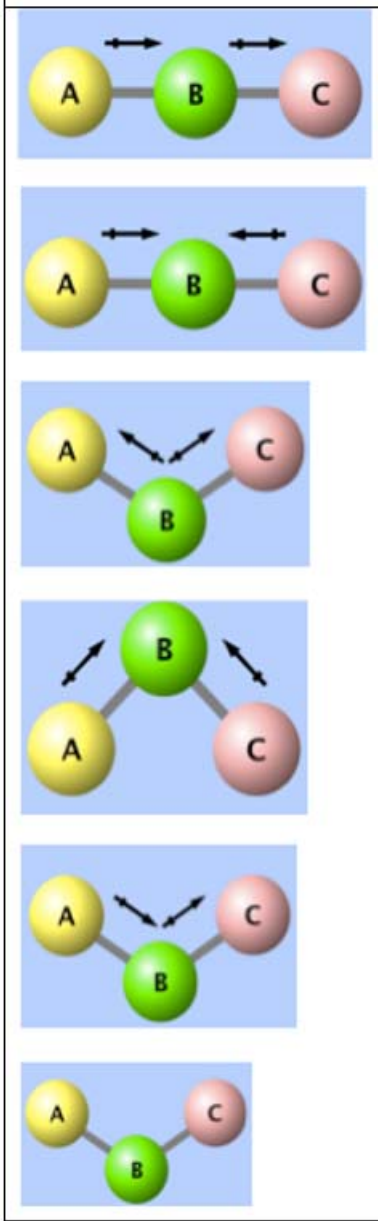
In this portion of the simulation you can manipulate molecule ABC. The relative electronegativity of each atom can again be changed. However, it is now also possible to the change the geometry by clicking and dragging an atom to change the angle ∠ABC. Once again, your can spin the entire molecule.

In the view section a new option has been added, "Molecular Dipole". Molecular polarity describes the charge distribution in the entire molecule, not just a bond. If centers of positive and negative charge do not coincide, the molecule is *polar*. How can you predict if a molecule is polar? The two important variables are 1) the bond dipoles in the molecule, and 2) the molecular geometry.

It is important to note that bond dipoles are vector quantities; that is, they have both a magnitude and a direction. In a polyatomic molecule, like ABC, the magnitude and the direction of the individual bond dipoles must be considered when summing vectors. As an example, consider the molecule CO_2. In this molecule there are two bond dipoles because the electronegativity of carbon and oxygen differ. There is no overall molecular dipole, however, because the bond dipoles "cancel" since they are of equal magnitude and pointed in opposite directions. Carbon dioxide is an example of a *nonpolar molecule* that has polar bonds.



To explore the idea of molecular polarity, complete the following table. Make an initial prediction as to whether each ABC molecule will be polar or non-polar based on the bond dipoles and the geometry; remember, bond dipoles are vector quantities. Then, construct the molecule in the simulation and see how it behaves in the electric field. Were your predictions correct?

Molecule	Which atom is most electro-negative in the molecule?	PREDICTION: Is the molecule going to be polar or non-polar?	TEST your molecule in the simulation. Is it affected by the electric field?
			

Putting it all together…

Being able to predict the polarity of a molecule is extremely important since many properties of molecules depend on whether they are polar or non-polar. As you have seen in this activity, determining a molecule's polarity is a multi-step process:

Draw Lewis Structure

↓

Use VSEPR to determine molecular geometry

↓

Determine bond polarity (based on electronegativity differences)

↓

Determine molecular polarity based on bond dipoles & molecular geometry

For the following molecules complete this step-by-step process.

Molecule	Lewis Structure	Molecular Geometry	Is there a molecular dipole? A molecular dipole indicates it is a polar molecule.
N_2			
H_2O			
BF_3			
HCN			
CH_2F_2			

* Make a prediction, and then check it in the "Real Molecules" section of the simulation.

Appendix H

NGSS THREE DIMENSIONAL LEARNING

www.nextgenscience.org/three-dimensions

The National Research Council's (NRC) *Framework* describes a vision of what it means to be proficient in science; it rests on a view of science as both a body of knowledge and an evidence-based, model and theory building enterprise that continually extends, refines, and revises knowledge. It presents three dimensions that will be combined to form each standard:

Dimension 1: Practices

The practices describe behaviors that scientists engage in as they investigate and build models and theories about the natural world and the key set of engineering practices that engineers use as they design and build models and systems. The NRC uses the term practices instead of a term like "skills" to emphasize that engaging in scientific investigation requires not only skill but also knowledge that is specific to each practice. Part of the NRC's intent is to better explain and extend what is meant by "inquiry" in science and the range of cognitive, social, and physical practices that it requires.

Although engineering design is similar to scientific inquiry, there are significant differences. For example, scientific inquiry involves the formulation of a question that can be answered through investigation, while engineering design involves the formulation of a problem that can be solved through design. Strengthening the engineering aspects of the Next Generation Science Standards will clarify for students the relevance of science, technology, engineering and mathematics (the four STEM fields) to everyday life.

Dimension 2: Crosscutting Concepts

Crosscutting concepts have application across all domains of science. As such, they are a way of linking the different domains of science. They include: Patterns, similarity, and diversity; Cause and effect; Scale, proportion and quantity; Systems and system models; Energy and matter; Structure and function; Stability and change. The Framework emphasizes that these concepts need to be made explicit for students because they provide an organizational schema for interrelating knowledge from various science fields into a coherent and scientifically-based view of the world.

Dimension 3: Disciplinary Core Ideas

Disciplinary core ideas have the power to focus K–12 science curriculum, instruction and assessments on the most important aspects of science. To be considered core, the ideas should meet at least two of the following criteria and ideally all four:

- Have **broad importance** across multiple sciences or engineering disciplines or be a **key organizing concept** of a single discipline;
- Provide a **key tool** for understanding or investigating more complex ideas and solving problems;
- Relate to the **interests and life experiences of students** or be connected to **societal or personal concerns** that require scientific or technological knowledge;
- Be **teachable** and **learnable** over multiple grades at increasing levels of depth and sophistication.

Disciplinary ideas are grouped in four domains: the physical sciences; the life sciences; the earth and space sciences; and engineering, technology and applications of science.

Read more about the three dimensions in the NRC *Framework* online here.

1/2

Dimension 1: Pract

1. The National Academies, Board on Science Education, Designing a Conceptual Framework for New Science Education Standards, Frequently Asked Questions, pg. 1.

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Dimension 2: Cross-cutti

The NRC cross-cutting concepts have application across all domains of science. As such they are a way of linking the different domains of science. They include: Patterns, similarity, and diversity; Cause and effect; Scale, proportion and quantity; Systems and system models; Energy and matter; Form and function; Stability and change. The Framework also emphasizes that these concepts need to be made explicit for students because they provide an organizational schema for interrelating knowledge from various science fields into a coherent and scientifically-based view of the wor

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Appendix I

TEACHER QUESTIONNAIRE

Teaching Molecular Geometry

1. What models, animations, or resources do you typically use to teach the topic of molecular geometry?

2. What do your student typically find most challenging when learning this topic?

3. What instructional tools have you used that you found most effective in addressing these learning difficulties? Please describe why?

4. What instructional tools/approaches have you used that you found to be least effective in addressing leaning challenges? Please describe why?

Appendix J

UNIVERSITY OF DEALAWARE IRB EXEMPTION

RESEARCH OFFICE

210 Hullihen Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE:	December 16, 2014
TO:	Nader Makarious, EdD
FROM:	University of Delaware IRB
STUDY TITLE:	[693464-1] Designing an Educative Curriculum Unit for Teaching Molecular Geometry in High School Chemistry
SUBMISSION TYPE:	New Project
ACTION:	DETERMINATION OF EXEMPT STATUS
DECISION DATE:	December 16, 2014
REVIEW CATEGORY:	Exemption category # *(2)*

Thank you for your submission of New Project materials for this research study. The University of Delaware IRB has determined this project is EXEMPT FROM IRB REVIEW according to federal regulations.

We will put a copy of this correspondence on file in our office. Please remember to notify us if you make any substantial changes to the project.

If you have any questions, please contact Nicole Farnese-McFarlane at (302) 831-1119 or nicolefm@udel.edu. Please include your study title and reference number in all correspondence with this office.