MODEL-BASED INQUIRY IN THE HIGH SCHOOL CHEMISTRY CLASSROOM:

HOW DOES MODEL-BASED INQUIRY AFFECT LEARNING RETENTION?

by

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A professional paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Science Education

MONTANA STATE UNIVERSITY
Bozeman, Montana

July 2023

DEDICATION

To my students, whose consistent growth and optimism encourage me to become a better teacher and learner every day.

To my husband, Thomas, for everything.

ACKNOWLEDGEMENTS

This work would not have been possible without the vital help and ongoing feedback from my graduate advisor, Walt Woolbaugh. Thank you, Walt, for your kindness and consistent encouragement.

Many thanks also to those who lent an ear or an opinion as I formed ideas for this research and finalized my thoughts in writing: Samuel Cohen, for offering knowledgeable feedback and guidance in the early stages; Kelsey Mitchell, for helping make sure my treatment plan made sense from a statistical and scientific standpoint; David Porter, for continuously encouraging my action research in the classroom.

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ABSTRACT

Model-based inquiry is a style of pedagogy that involves the creation and analysis of physical, conceptual, and mathematical models as a means of teaching and learning science. This study aimed to ascertain the capacity of model-based inquiry (MBI) to impact learning retention in students of a 9th and 10th-grade chemistry course. Over the course of two introductory chemistry units, students used MBI-styled activities and unit storylines to uncover essential ideas. The fundamental concepts of each unit were assessed using a pre-test and post-test (Post I), with an additional post-test (Post II) administered several weeks after the culmination of that unit. Students were also prompted for their confidence level on these assessments. To analyze the interplay between MBI, attitudes about science, and comprehension, students were surveyed using the Colorado Learning Attitudes about Science Survey before and after the research period. Additionally, a sample of students was interviewed about their knowledge and experience using scientific models. Analysis of the quantitative and qualitative data from this study has revealed that a guided approach to MBI has some positive effect on learning retention. This study's use of MBI was found to have a moderate impact on student attitudes about learning chemistry, and a limited impact on student understanding of scientific modeling.

CHAPTER ONE

INTRODUCTION AND BACKGROUND

Context of the Study

In my experience in teaching, I have observed students' widespread pattern of losing mastery of science skills and concepts after completing a unit and moving on to new material. This is particularly concerning for me as I have identified these gaps and weaknesses when new lessons have necessitated mastery of prior learning; students who "memory dump" most frequently often struggle when that forgotten content is imperative to building new understandings.

I observed this pattern during much of my teaching career, but in the past few years, I have been more sensitive to examples of "lost" content in my students' learning processes. I have wondered about the effect of virtual or distanced learning over the COVID-19 pandemic, which runs closely in appearance to "memory dumping," and considered focusing my research on this recent phenomenon in education. However, there have been other issues that are nearly inextricable from COVID-19: changes in our school population over the last few years (students transferring in and out), an inconsistent scope and sequence in our school, and ongoing change to the school assessment and grading system. The issue of learning loss after the culmination of a unit has recently been apparent to me among students in my science and math classes. The math course I teach is a two-year program, so there is plenty of opportunity for students to let a concept or unit sit untouched without review for a long time. In particular, I was surprised that 11th and 12th-grade math students struggled so noticeably to apply their prior learning about functions to later units—whether weeks or months later. This concept is central to the International Baccalaureate course and therefore repeated constantly, so I found it troubling that students repeatedly dumped such concepts from their memory in favor of new learning, such as geometry and trigonometry. Although my primary observation of this phenomenon took place in my math students, the experience brought to light for me this issue that I had always observed and considered to be normal. In the observational phase of determining my question for action research, I began to consider learning loss to be an interesting area for attention and improvement in my teaching and learning in science.

I conducted group interviews with two classes of students to uncover their impressions of learning experiences that led to lasting understanding. Many students recalled experiences when they recreated scientific models using physical materials or pictorial diagrams. They joked that although those experiences seemed arduous and painstaking at the time, there was some benefit as they were still able to recall their learning from those projects. Some students reflected that they struggled to remember all of the details of their learning, but that they could still visualize the models they created in science classes and even made an attempt to explain the concepts embedded in those models. To me, this seemed to be in line with my experiences of successful teaching and learning; when I have given students opportunities to make and evaluate scientific models, the construction, discussion, and evaluation of these models have seemed to have a positive effect on comprehension. With the opportunity to collect and analyze data formally through action research, I decided to focus on the use of model-based inquiry as a tool to promote the long-term retention of science content. Model-based inquiry is a method of teaching and learning which involves exposing students to some phenomenon and tasking them with the creation or revision of a scientific model. By continual revision and reflection on these models, students construct a thorough and, hopefully, lasting understanding of the scientific concepts at play.

The academic setting in which this research was conducted was Mountain Academy of Teton Science Schools, an independent school with two campuses. In total, the school serves 170 students from kindergarten through 12th grade. A large majority (roughly 93%) of these students are white, most speak English as their first language, and come from families with moderate to high levels of affluence compared to the local population. Of the student body, 36% are reported to receive financial aid of some form.

Focus Statement/Question

My focus question was, How can model-based inquiry impact learning retention in a high school chemistry class?

My sub-questions include the following:

1. How do students' attitudes about chemistry relate to their learning?
2. How does MBI impact student understanding of the purpose and use of scientific models?

CHAPTER TWO

CONCEPTUAL FRAMEWORK

To ground my action research in justified methods, I read about foundational theories in education that might explain the issues in learning retention that I have observed. My survey of educational research also revealed potential solutions, treatment methods, and data collection strategies to support my action research design.

Foundational Learning Theory

The theory of constructivism is now the basis of widely adopted educational philosophy. Bodner describes the more recent (at the time of publication) trend toward constructivism in education and summarizes this new theory as, “Knowledge is constructed in the mind of the learner” (Bodner, 1986, p. 874). Bodner (1986) identified Piaget as an epistemologist rather than a developmental psychologist, as Piaget’s Theory of Intellectual Development is more pertinent to identifying how one *develops understanding* than necessarily how one *develops in personhood*. As such, Piagetian theory can justifiably be applied to learning theory in education.

Piaget’s Theory of Intellectual Development describes constructivism as a sequence of events surrounding cognitive sets called “schemes” of understanding. In this sequence leading toward knowledge acquisition, one experiences a trigger, an action or reaction, and the consequence of that action (Bodner, 1986). Through this process, a scheme of understanding is built and reinforced by multiple experiences. These schemas, once built, are the structures by which learners then make meaning of new experiences. Bodner (1986) identifies multiple studies in which student misconceptions are identified as persistent, in apparent support for the constructivist theory. Such students, according to Piagetian theory, approach and accommodate new information by assimilating experiences to their pre-existing schema, regardless of whether the schema accurately aligns with reality. Therefore, the only way to eradicate an erroneous belief is to deconstruct the faulty schema and construct an improved one that adequately represents reality (Kuhn, 1970 as cited in Bodner, 1986). This introduction of a discrepant event is thought to push the limbic system into a higher level of awareness, similar to a “fight or flight” response (Esler, 1982), which focuses the student on a new experience that might reconstruct schemata.

Bodner’s (1986) discussion of Piagetian theory extends further into implications for the science, and specifically chemistry, classroom. Bodner argues that the constructivist approach to teaching shifts the role of the teacher from one of direct instructor to a facilitator guiding student learning by discovery. Also included in Bodner’s model of a constructivist classroom is one in which students and teachers have a two-way dialogue throughout the learning process, and wherein disequilibrium is frequently used to define a problem before students can build the schema required to describe the inner workings of the observed phenomenon (Bodner, 1986).

Colburn (2000) reiterates the idea that students are not blank slates when they approach new ideas in the classroom, but rather they are already in possession of myriad schemas by which they make meaning of the world. Therefore, to teach new ideas means to frequently identify misconceptions and rebuild student understanding in turn. Colburn touts the following teaching methods as in line with constructivist theory: open-ended activities designed to identify and challenge misconceptions, collaborative learning, questions and wait time, demonstrations that offer a visible discrepant event, lectures and textbooks (in proper timing and implementation), and assessment (Colburn, 2000). Colburn's recommendations for teaching with a constructivist mindset generally involve providing more room for students to ask questions and think critically when faced with discrepant events, and allowing students to design their own scientific experiments toward the goal of making meaning from scientific phenomena.

Experiential learning in science education has long been viewed as an effective application of constructivist theory in the classroom. Esler (1982) expounds on the direct relation between physiological brain structure and methods of learning by encoding new experiences, and concludes the following:

> Nerve cells are altered and memory clusters are established only through stimulation. Furthermore, for purposes of recall, the greater the number of the specialized regions of the brain in which one or more networks are established, the greater the chance of the event being recalled. This would appear to support the position of some educators who advocate multiple sensory approaches to instruction that are provided by "hands-on" laboratory activities (p. 800).

Active learning, as discussed by Aykan and Dursan (2022), centers on the involvement of students in experiential learning through a variety of age-appropriate methods including "role-playing, … poetry writing, conceptual caricature, etc." (Aykan & Dursan, 2022, p. 43). Through their study, these authors tested the effect of active learning about "Lighting and Sound Technologies from Past to Present" (p. 43) on learning retention within a group of fourth-grade students and found that, "…active learning techniques improved students' academic performance and learning retention in the science course" (p. 46).

Model-Based Inquiry

Model-based inquiry is centered on the theory of knowledge acquisition, as described by Mark Windschitl, Jessica Thompson, and Melissa Braaten (2007). In this article, Windschitl et al. (2007) defined the scientific method (TSM) to be a process that seeks to answer a specific question with the end goal being a model or working theory, whereas Model-Based Inquiry (MBI) has a goal of defining phenomena using a model and seeking to refine and improve that model using critical thought and experimentation. TSM has long dominated the tone and design of science curricula in American schools, but MBI turns this method on its head. Windschitl et al. argue that TSM limits students' ability to fully understand the nature of science by designating experimentation to only serve as a process for data collection and analysis in a vacuum from other scientific thoughts and concepts. MBI instead allows students to realize that much of real-world science is not limited to the strict scientific method of making and testing predictions concerning a rigidly-defined hypothesis. Rather, much field study regards variables that cannot be easily directly observed or tested. MBI expands student thought about the nature of science by introducing simple visual, physical, or conceptual models that can be tested in place of the actual matter of study (Windschitl et al., 2007).

The authors also identify that TSM does not provide an opportunity for students to build the underlying conceptions on which a hypothesis must be based. (Concerning the previous discussion of constructivism in this literature review, this may perhaps encourage students to assimilate new ideas into an ill-fitting schema, thereby producing tightly-held misconceptions!) The MBI approach more fully allows students to build models of understanding that can be revised and adapted according to the discovery of new information, much in alignment with ways of knowing employed outside of the traditional classroom (Windschitl et al., 2007).

Rinehart et al. dive more deeply into the best practices associated with an MBI curriculum, as a result of the authors' project titled "Promoting Reasoning and Conceptual

Change in Science (PRACCIS)" through the National Science Foundation. This project was implemented for two periods of 5-6 months in addition to a shorter implementation, and through these phases, a set of design challenges was identified when developing an MBI unit. These design challenges are as follows: (1) choosing phenomena, (2) developing models, (3) developing evidence, and (4) generating productive disciplinary engagement (Rinehart et al., 2016). When it comes to (1) choosing phenomena, Rinehart et al (2016) described the need for phenomena to drive the MBI; for a phenomenon to authentically inspire MBI, it should be accessible to students but not easily explained at the first attempt, thereby facilitating the use of a model to drive inquiry and learning. Students should then be presented with a model that was designed or chosen by the facilitator (Design Challenge 2). This model should be developmentally appropriate to the students and therefore intuitively understood at that level. To allow students the opportunity to examine and analyze evidence, the authors recommend that evidence be provided in some way (Design Challenge 3) as appropriate to the level of the learner. This evidence should be balanced in terms of complexity and quality, as well as representative of resources of evidence that are realistic to scientific settings outside of the classroom. Finally, the authors recommend that once evidence has been analyzed, students should be driven to discuss and apply their revised model (Design Challenge 4) to real-world issues or other authentic assessments through a process of scaffolding and dialogue regarding epistemology (Rinehart, et al, 2016).

While Model-Based Inquiry has been thoroughly described and defined through research, only a handful of studies have made an effort to link Model-Based Inquiry to lasting retention of learning. Dauer and Long (2015) focused their study on the retrieval of learning two years after participants were enrolled in an undergraduate biology course that facilitated MBI. Long-term content retention was assessed through interviews which prompted students to recreate mental models built during their study of genetics, evolution, and ecology. The core motivation of this study was the investigation of cognitive structures facilitated by participants, but the authors reflect on the key role of model-based inquiry in the process of developing understanding as opposed to memorization of facts. Ultimately, these authors found some evidence of student success in recreating models to explain biological phenomena during the interview process, but it should be noted that they also found evidence of misappropriated terminology, incorrect relationships between biological concepts, and some student difficulty with the model-construction process in the interview task (Dauer & Long, 2015).

Campbell et al. (2011) used MBI as a potential tool to address issues in student learning both in the short and long term, as well as to study the effectiveness of this tool based on teacher familiarity with the subject matter. This research was performed on secondary physics classes; the treatment group learned through a MBI-driven curriculum while the control group learned by traditional lecture and demonstration (TLD) as defined by the researchers. They assessed student competency at three stages using a pre-test, post-test, and delayed test (one month after the post-test). Data analysis showed that both the MBI and TLD groups made measurable increases in competency, but the TLD group's gains were higher (Campbell et al., 2011). Interestingly, the delayed-test results showed only slight variation between the two groups, but both groups showed a drop in competency in comparison with the post-test data. The researchers reflected that there may have been inconsistencies or areas for improvement in the teaching methods.

Both Dauer and Long's (2015) and Campbell et al.'s (2011) studies of Model-Based Inquiry addressed some issues in the teaching method's application and assessment, though each of these papers reiterated the value of MBI for connecting underlying concepts in science and allowing students to build an in-depth understanding of scientific principles driving phenomena. Though other publications describe and outline the foundational principles of MBI, I struggled to find many other instances of research focused on the impact of MBI on long-term learning retention. I was inspired to test the effectiveness of MBI in my chemistry course with the hope that the constructivist roots of this style of science pedagogy would be an effective solution to learning loss.

Considerations for Treatment Design

Jenkins and Howard (2018) discuss a study in which a high school chemistry course was taught using Modeling Instruction (somewhat of a variation of MBI as discussed in the previous section) over the course of a unit. Researchers developed two assessment questions which were administered as a pre-and post-test to determine growth over the unit, in addition to a third assessment of these on the semester exam. The nine weeks of this treatment involved MBI activities relating to the two objectives defined for the unit. These objectives were to (1) "Relate Kinetic Energy, Particle Motion, and Thermal Expansion" and (2) "Explain the Relationship between Temperature and Particle Motion," each through cycles of modeling using physical or pictorial representations and group discussions to improve these models (Jenkins & Howard, 2018). In their paper, Jenkins and Howard (2018) describe their use of statistical analysis to summarize and discuss the results of their study. They categorized student responses to assessment questions as "proficient, apprentice, or novice" so that they could quantify the improvement in student comprehension over time. They found that mastery improved in both assessment objectives, though not in equal proportion between the two questions; they concluded that this was due to the nature of each question, the second requiring a greater degree of higher-level thinking than the first (Jenkins & Howard, 2018). This study is useful in guiding my own AR design; I think the timeframe of the Jenkins & Howard (2018) study is appropriate to determine how effective the treatment was in terms of developing mastery. I adopted the same use of assessments before, immediately after, and several weeks after each treatment unit in my action research. I also facilitated the use of categorizations of student competency on these assessments, as is discussed in the following chapter.

Samia Khan (2007) studied the proceedings of an undergraduate introductory chemistry course in great detail. Khan sought to determine how teacher-designed inquiry activities impacted student engagement and the development and critique of mental models of chemical concepts. Khan collected a variety of data to describe the learning process at play; these data included student surveys, classroom observation notes, rubrics used to quantify classroom observations, and transcripts from student problem-solving sessions. Khan found that there was a pattern in the teaching/learning process of "Generating, Evaluating, and Modifying hypotheses, (GEM)" through student-student and student-teacher interactions (Khan, 2007). This process was repeatedly used to refine and correct student mental models. Khan includes multiple examples and evaluations of student dialogue and descriptions of methods and phrasing used by the teacher to elicit the GEM process.

Khan's (2007) study was performed from the perspective of a researcher observing a class to find patterns and meaning from methods of teaching and learning. My action research project was more directed toward finding if there is a discernable effect on learning retention due to the treatment. However, Khan's methodology was helpful to me in addition to providing further foundational support for MBI. Khan surveyed students regarding their attitudes toward learning and chemistry using a Likert scale at the end of the course. I used a similar method of data collection regarding student attitudes about chemistry, but I collected this data as a pre-and post-unit measurement because I was also interested in learning how student perceptions change due to the treatment unit.

In their discussion of the importance of training on models and model-based inquiry for teachers, Dass et al. (2015) emphasize that "chemistry teachers should be able to design experiences where students are given opportunities to elucidate underlying relationships by constructing and evaluating models" (p. 1306). In my application of MBI in chemistry, I determined that a more guided structure to inquiry would best allow me to design a course that afforded my students these opportunities, considering the experience and academic needs of my sample group. Dass et al. (2015) discuss the importance of teacher proficiency in MBI and the common inhibitors of successful implementation. Among these, they cite the students' lack of readiness to adapt to new methods of learning by inquiry. I observed this in my own implementation of MBI, and reflect on the possible role played in my action research in the last chapter of this paper.

Justification for Data Collection Methods

Toward the goal of incorporating my sub-questions into the methodology, I took the opportunity to find some research basis for these ideas. I was also interested in collecting data about how students' perceptions of science and models may impact their learning and content retention. A tool developed by educators at the University of Colorado, Boulder, in connection with the Physics Education Technology (PhET) Project and Physics Education Research Group (PERG) there, the Colorado Learning Attitudes about Science Survey (CLASS), was developed for the group's research about physics education but was adapted to reflect student learning attitudes about the subject of chemistry in particular. This research paper describes how student attitudes are closely tied to academic success, but that this relationship had not been previously studied in great depth in the subject of chemistry (Barbera et al., 2008). The CLASS instrument relates specifically to student attitudes about "(1) learning chemistry, (2) the content of chemistry knowledge, (3) the structure of chemistry knowledge, and (4) the connection of chemistry to the real world" (Barbera et al., 2008, p. 1435). The CLASS was revised and validated through repeated testing of undergraduate students in chemistry and other science courses, as well as through interviews to identify problematic or confusing phrasing that distracted from the purpose of the assessment questions.

The CLASS for Chemistry was developed to identify trends and changes in student attitudes as a result of chemistry teaching. Barbera et al. (2008) note in their paper on the reliability and validity of this tool that student attitudes about chemistry should theoretically shift toward "more expert-like" as a result of learning. However, through the analysis of a large dataset collected during that study, it was determined that student attitudes shifted toward "more novice-like," arguably indicating that the teaching methods used in that course could have been improved. The use of this tool to evaluate the effectiveness of pedagogy inspired me to apply it to my action research not only to assess changes in student attitudes as a result of MBI but also to provide insight as to the validity of my application of MBI.

As I was also interested in the effect that MBI might have on student understanding and perceptions of models, I looked for research to justify the approaches in my treatment and data collection. Schwarz and White (2005) directly address the challenge of changing student perceptions and awareness of models through hands-on experience. They found that students often struggled to explain the purpose of scientific modeling even during and after a modeling-intensive science curriculum. They defined student understanding of models to be summarized by four key categories: “nature, process, evaluation, and utility” (p. 181). I used the authors’ outline of these categories and their suggested framework for assessing perceptions of models (Schwarz & White, 2005, p. 182) in my interviews with students.

CHAPTER THREE

METHODOLOGY

The goals of my research were to determine if MBI could be effectively implemented in a secondary introductory chemistry course to improve learning retention, to assess the relationship between MBI and student attitudes about science, and to assess the extent to which MBI informed student understanding of scientific models. Model-based inquiry, as previously discussed, would theoretically address issues in learning retention due to its application of constructivist learning theory. In each of the two units I selected to implement my treatment, I used guided applications of model-based inquiry to engage students in their learning and to push them to think critically about scientific phenomena, hopefully, to construct lasting understanding.

Demographics of the Sample

The sample group consisted of 15 students split between two sections of a chemistry course for grades nine and ten in a mixed-grade cohort. Within this group there are six ninth-grade students and nine tenth-grade students, 7% are non-White and speak a language other than English at home, 7% of students are home-bound and therefore participate in learning through adapted assessments virtually, 2/3 of students identify as strictly female, 1/3 identify as strictly male, and none identify as non-binary.

The two sections of students that comprised the sample group varied somewhat in prior learning about chemistry, but most students had not thoroughly learned about atoms or properties of matter before the start of this course. In the two learning units before the treatment application, students learned through a mixture of self-directed inquiry-style activities, as well as through direct instruction about physical and chemical properties of matter, measurement, and conversions between units. During that time, I observed that most students in this sample group were unfamiliar with and often uncomfortable with ambiguity and autonomy in the science classroom; most students required direct instruction to practice measuring using lab tools or perform simple calculations or find sources for research during an interdisciplinary project. I observed growth in this area throughout the year, but this observation was part of the reason I chose to design my treatment around guided inquiry versus open inquiry. Although students did not generate their own scientific models for these treatment units, they did participate in the recreation of historically generated models through a guided process of discovery and revision, and they practiced different modes of modeling phenomena. Therefore, the MBI theme of this action research was maintained even without full, open inquiry.

Throughout my treatment period and data collection, I observed cheating and plagiarism at a higher level than I feel I have observed in previous years. I considered this when analyzing data, sometimes excluding data that seemed inauthentic and limiting the sample group to a subgroup for that tool.

Because of the already small sample size split between two sections, it would be difficult or impossible to identify valid statistical differences between a treatment and a comparison group. Therefore, the sample group of 15 students all experienced the treatment plan for this action research project.

All requirements have been met within the IRB process and this capstone research was approved for IRB exemption (Appendix A) for documentation of exemption.

Treatment

To collect sufficient data to conclude the effectiveness of MBI in improving learning retention, I applied the treatment to two different learning units: one focused on atomic structure and one focused on the periodic table.

Atomic Structure Unit

Overview of Unit. My goal in designing this unit was to use a guided approach to Model-Based Inquiry in which students investigated atomic structure by experiencing the historical timeline of atomic theory. As they learned about each stage in this development of atomic models, students engaged in inquiry-based activities designed to prompt thinking about the properties and subatomic particles discovered by each scientist significant to atomic theory. Along the way, each atomic model was revised to incorporate these historical discoveries.

Learning Activities. Students learned about the earliest models of the atom through direct instruction and grounded this learning through thought experiments, much like the thinkers of that time. I prompted them to think about what matter would remain if a rock was cut in half repeatedly, which brought them to Democritus's concept of *atomos*, or *indivisible*. They learned about Aristotle and Lavoisier's contributions similarly. From there, I introduced them to John Dalton's billiard ball model of the atom. I guided them to consider what experiments would need to be done to prove that the atom was more complex than a solid sphere; to uncover the role and existence of charge in the atom, they experimented with clear tape and found attractive and repulsive charges. The discovery of charge altered their model of the atom to Thomson's Plum Pudding Model, an understanding of the atom as a mass of positive charge with evenly distributed lone negative charges which would need to be revised through a simulation of

Rutherford's gold foil experiment. Students rolled marbles underneath pieces of cardboard which hid internal structures (Appendix B). Based on the patterns of marble deflection, students had to figure out the hidden shape beneath the cardboard, analogous to Rutherford's experiment on gold foil. Throughout this experience, I prompted students to analyze and evaluate the simulation as a model of Rutherford's experiment. To shift from Rutherford's to Bohr's model of the atom, students observed and drew conclusions about a flame test performed on several different chlorides. To finish the unit, they used dried beans to stand in for isotopes and experimentally determined how to calculate average atomic mass. The unit ended here, with Bohr's structural model of the atom and the recognition of varying isotopes of each element. I decided to hold Schrodinger's model of the atom for the following unit, as it relates closely to the structure of the periodic table.

On the Atomic Structure Pre-test, Post I test, and Post II test, students were prompted to describe the process by which electrons are energized and emit visible light and to describe how Bohr's model explains this phenomenon. This key idea hinges on Bohr's model of the atom and was therefore a significant illustration featured in the teaching of this unit.

Timeline. This unit spanned roughly six to seven weeks of instruction from November 2022 through December 2022. The class met three times per week for 65 minutes each class.

Periodic Table Unit

In my design of this unit, I decided to focus student attention on the role of the periodic table as a model of elements using periodicity. To do this, students required some direct instruction to understand the properties of elements and the subatomic phenomena that cause changes in electronegativity, 1st ionization energy, atomic radius, and electron configuration. The anchor of this unit, rather than a phenomenon, was the periodic table as a model.

Learning Activities. Students began their inquiry into the organization of the periodic table by first arranging large puzzle pieces, each representing a different element on the periodic table with coded information in the form of a shape and color and some numerical values (Appendix C). This encoded information stood in for electronegativity, 1st ionization energy, atomic radius, and electron configuration, though students did not yet know this. Ultimately, they were able to figure out that the puzzle made up the periodic table.

During the unit, students learned about the properties of element families, the classification of metals, nonmetals, and metalloids, states of matter, valence electrons, and electron configurations by a combination of direct instruction and lab-based learning. They also developed an understanding of periodic trends through three activities in physical and mathematical modeling, simultaneously reflecting on the applications and limitations of scientific models.

One of the concepts that bridged the two MBI units of learning was the conceptual change that occurred between Niels Bohr's model of the atom and Erwin Schrodinger's model of the atom. Students learned about the difference between these models and applied their learning by drawing and analyzing Bohr diagrams and by writing and analyzing electron configurations according to Schrodinger's atomic theory. Students practiced these skills in class activities, discussed the difference between these models, practiced explaining the differences between these models in writing, and were assessed on this content on the Periodic Table Post I and Post II tests.

To culminate the unit, students reconstructed the periodic table puzzle with a fresh understanding of the elements. Mendeleev's model of the elements emphasized the importance of periodicity as a unifying organizational tool in the periodic table, which could be used descriptively and predictively. Their understanding of Mendeleev's model of the elements as represented in the periodic table was assessed through their completion of claim-evidence-reasoning (CER) statements. Students individually constructed three CER statements to identify the information on the puzzle pieces (electronegativity, first ionization energy, and atomic radius) with the support of evidence gleaned from the modeling activities in this unit.

Timeline. This unit spanned roughly six weeks from January 2023 through February 2023. Classes met three times per week for 65 minutes per class.

Data Collection and Analysis Strategies

During these MBI trials, I collected data as laid out in the matrix included below. The most important data collection method concerning my main research question was the tracking of student comprehension before the unit, immediately after the unit, and three to four weeks following the unit. During treatments, I collected qualitative data from student discussions and qualitative and quantitative data from formative assessments.

Table 1. Data collection matrix.

	Focus Questions		
Data Collection Instruments	How can MBI impact learning retention in a high school chemistry class?	How do students' attitudes about chemistry relate to their learning?	How does MBI impact student understanding of the purpose and use of scientific models?
Atomic Structure Unit: Pre, Post I, Post II	X	X	X
Periodic Table Unit: Pre, Post I, Post II	X	X	X
Student Interviews			X
CLASS Assessments (Pre and Post)		X	
Formative Assessments & Activities	X		X

Unit Assessments

Before each unit, I administered a pre-test (Pre) that focused on the main content and concepts within the unit. This assessment was not formally recorded as a grade for students. After implementing the MBI treatment unit, I administered a post-test that mirrored the same key content and concepts as the unit pre-test. This test (Post I) was graded as usual for the course, through the three core competencies defined in the school's assessment program, described later in this chapter. The final post-test (Post II) was implemented several weeks after the culmination of each respective treatment unit to assess retention of prior learning once new learning had begun. To help ensure validity in these measurement tools, I identified key content and concepts before each unit so that no main goals of the unit would be missed in the pre-test data. I also referred to curricular resources (textbooks) and teaching guides (mainly through the American

Association of Chemistry Teachers) to ensure that my goals for each unit were reasonably aligned and that assessments were fair and valid. Reliability can be ensured in these assessments through comparison between pre-and first post-test data with student performance on activities within the unit, discussion transcripts, and formative assessments; the larger accumulation of data supports the results of this data collection instrument.

Student responses from these assessments were graded and categorized in two ways: once by core competency in line with the school grading system, and once by major topics within the unit. This two-dimensional analysis allowed the data to more fully represent student learning and retention over time by specifying the type of learning changes taking place. The core competencies, referred to in this study as (1) Knowledge & Understanding (K&U), (2) Application (App), and (3) Analysis and Evaluation (A&E), are more formally described by their respective learning outcome statements:

1. I can demonstrate knowledge and understanding of scientific facts, concepts, and terminology.
2. I can apply scientific facts, concepts, terminology, methodologies, and techniques.
3. I can formulate, analyze, and evaluate scientific explanations, hypotheses, methodologies, and data.

Competency-based assessment, the system for grading in my school, involves scoring student work as Not Meeting, Approaching, Meeting, or Exceeding expectations using the above learning outcomes. On a typical assignment, these designations are described in great detail in a rubric for students to follow. To quantify this data, these designations were ascribed numerical values as follows: Not Meeting = 1, Approaching = 2, Meeting = 3, and Exceeding = 4.

The core concepts in each unit were identified during unit planning. In the first unit, Atomic Structure, the main concepts were (1) protons, (2) neutrons, (3) electrons, and (4) models of the atom. The second unit, The Periodic Table, incorporated core concepts grouped as (1) properties and element families, (2) periodic table trends, and (3) electron configuration.

Each item on the unit assessments was scored for correctness on a scale from 1-5 to be comparable with student responses about their confidence in their answer to each assessment item. Students were prompted to indicate their confidence by selecting a number of stars from 1-5, as seen in Figure 1.

Figure 1. Confidence ranking tool.

To quantify student learning between Pre and Post I, as well as possible learning loss between Post I and Post II, the normalized gain was calculated for both styles of assessment groupings (core competencies and core concepts). To calculate the normalized gain, the change in class averages over the desired period of the treatment unit was divided by the possible increase, as directed by Hake (1998). Normalized gains less than 0.3 were considered to be indicative of a limited learning increase, gains between 0.3 and 0.6 were considered to be moderate and gains above 0.6 were designated as considerable (Hake, 1998). A similar structure was used to interpret learning loss between Post I and Post II; if the normalized gain was represented as a negative, the statistic indicated some learning loss, the extent to which mirrors the classifications of magnitudes in learning gains as described above.

Formative Assessments

During both treatment units, students often completed short formative assessments in the form of short quiz-style warm-ups, exit tickets, homework assignments, and open-ended questions on activities such as the modeling activities from the Periodic Table Unit. These check-ins on student learning helped me to assess how much learning was taking place during each unit and consequently guided my teaching to review key concepts or continue through the unit as planned. I collected many of these formative assessments to provide qualitative data that could be used to uncover themes in student learning during the treatments.

Colorado Learning Attitudes about Science Survey

This data collection instrument was developed by members of the Physics Education Research Group (PER) at the University of Colorado Boulder (Appendix D). The extensive research and revision of this survey through the PER Group bolster the reliability and validity of this data collection instrument. The survey features a Likert scale response to fifty questions designed to assess student attitudes about learning in chemistry. This instrument deals specifically with my first research sub-question: How do students' attitudes about chemistry relate to their learning? Because my class size is very small, I administered this survey to all 15 of my ninth and tenth-grade chemistry students during the first treatment unit and after the culmination of the final treatment unit, but some students chose not to respond, resulting in a final subset of 12 students for this data collection instrument.

The PERG also designed an Excel spreadsheet that provides easy data analysis in line with the tool's design and validation. The process used by this spreadsheet begins with the conversion of student data on a one through five Likert scale to instead reflect if the student was undecided (0), in agreement (+1), or disagreement (-1) in response to the prompt. In this step, the tool eliminates some of the depth provided by the extreme ends of the Likert scale (responses of "strongly agree" and "strongly disagree") but also eliminates some error that may occur through the variety of student interpretations and perceptions of terminology like "somewhat," and "strongly;" rather, a student's choice of affirmative or negative alone can be used to draw conclusions about student attitude changes overall. These recalibrated scores are then processed and compared to "expert data" as defined by the CLASS analytical tool. The "expert" response to each survey question was determined through the administration of the CLASS to "over 50 chemistry faculty from several universities" (Barbera et al., 2008). The majority of these expert scores (89.2%) were in agreement and therefore validated the use of a comparative expert score for each question; survey questions that had repeated validation were included in the final draft of the CLASS for Chemistry. Student responses are then categorized as "favorable," "unfavorable," or "neutral" in relation to the expert response. This designation does not always align with "agreement" or "disagreement" as the questions do not consistently align one or the other with the expert opinion.

The CLASS design categorizes the fifty questions based on correlations between student responses during the instrument's development. These categories are as follows: Personal Interest, Real World Connection, Problem Solving General, Problem Solving Confidence, Problem Solving Sophistication, Sense-making and Effort, Conceptual Connections, Conceptual Learning, and Atomic-Molecular Perspective of Chemistry (Barbera et al., 2008). The PERG-developed spreadsheet is programmed to complete the scoring transformations and statistical analysis as described and to automatically represent pre-and post-test data graphically using both raw favorable/unfavorable percentages and normalized changes between pre-and post-test data.

Student Interviews Regarding Understanding Scientific Models

This next data collection instrument was used during one-on-one interviews with ninth and tenth-grade chemistry students about their understanding and perception of scientific models (Appendix E). This instrument supports my second research sub-question regarding the impact of student understanding of scientific models on student learning. I implemented this data collection method using a stratified sampling method: once students had some exposure to the concept of scientific modeling within the course, I sorted students into groupings based on test performance and randomly selected students from each of these groupings for interviews. I wanted to use this sampling method so that I could draw larger conclusions about the role of the cognitive approach of discussing models while using MBI in a chemistry class, and how these two factors may affect learning and learning retention. In total, six students were interviewed, of which three were ninth-graders and three were tenth-graders. Though coincidental, this even split between grade levels contributed to a stronger representation of the full sample group when analyzing themes in the data.

To help ensure the validity and reliability of this data collection instrument, I sought feedback from peers regarding the survey questions and probes I would use to solicit student feedback. To analyze the qualitative data collected using this instrument, I recorded audio from student interviews and made transcripts from which I pulled key phrases and important patterns in content and perceptions from students.

CHAPTER FOUR

DATA ANALYSIS

Results

Model-Based Inquiry and Learning Retention

The primary focus question of my research was "How can MBI impact learning retention in a high school chemistry class?" Analysis of quantitative and qualitative data across both treatment units suggests that Model-Based Inquiry is an effective teaching tool with a reasonable capacity to limit learning loss.

Quantified Learning Gains. The following tables represent the normalized gains from the sample group of 15 students over both intervals: Pre to Post I and Post I to Post II.

Table 2. Normalized learning gains: Atomic structure unit, (*N*=15).

	Core Competency			Core Concept			
	Knowledge & Understanding	Application	Analysis & Evaluation	Protons	Neutrons	Electrons	Models of the Atom
Pre to Post I	0.4	0.1	0.1	0.7	0.6	0.7	0.6
Post I to Post II	-0.2	0.5	0.3	0	0.2	0.2	-0.8

During the first interval of learning within the Atomic Structure unit, the analyses summarized in Table 2 indicate that students made only limited increases in their ability to apply their knowledge (normalized gain of 0.1) and analyze and evaluate scientific concepts (normalized gain of 0.1). As a group, students made moderate improvements in their ability to demonstrate their knowledge and understanding (normalized gain of 0.4), as well as in their learning about neutrons and models of the atom (normalized gain of 0.6 in each concept). The group demonstrated considerable increases in learning around protons and electrons (normalized gain of 0.7 in each concept). Likely, the students' notable lack of prior learning around this topic made them particularly open to constructing new understanding since misconceptions were not so tightly held. As such, measurable learning gains would be expected to be high.

In the second interval of this treatment unit, the data reveals an interesting change in learning by category. The sample group demonstrated moderate gains in their ability to apply their learning (normalized gain of 0.5) and analyze and evaluate scientific concepts (normalized gain of 0.3). However, their ability to demonstrate knowledge and understanding within this unit showed a limited decrease (normalized gain of -0.2). The demonstration of learning gains in two core competencies and learning loss in one may have been caused by continued practice in application and analysis as necessary for the subsequent unit. Practicing these skills may have allowed students to continue their learning outside of the atomic structure unit, though the immediate content knowledge about the atomic structure was set aside in favor of new content learning.

The second interval of normalized gains can also be analyzed through the lens of core concepts. Students demonstrated no change in their learning regarding protons (normalized gain of 0) and only limited gains in their learning regarding neutrons and electrons (normalized gain of 0.2 in both concepts). These smaller gains may once again be attributed to the inherent review of neutrons and electrons as necessary within the subsequent unit about the periodic table.

However, the data speaks to a considerable learning loss regarding models of the atom. This core concept experienced a normalized learning loss of 0.8.

Table 3. Normalized learning gains: Periodic table unit, (*N*=15).

	Core Competency			Core Concept		
	Knowledge & Understanding	Application	Analysis & Evaluation	Properties	Periodic Table Trends	Electron Configuration
Pre to Post I	0.4	0.5	0.4	0.7	0.5	0.7
Post I to Post II	0.1	0.4	-0.1	0.2	-0.3	-0.6

Table 3 displays the normalized learning gains within the two intervals of the periodic table treatment unit, from Pre-test to Post I, and between Post I and Post II. The statistics within the first interval of initial learning speak to moderate to considerable learning gains as a result of the MBI unit. The sample group demonstrated a learning gain of 0.4 in both core competencies of demonstration of knowledge and understanding and analysis and evaluation and a normalized gain of 0.5 in their ability to apply their learning. When student assessment results were grouped by core concepts, students demonstrated moderate learning gains in their learning about periodic table trends (normalized gain of 0.5), and considerable gains in their learning about properties of the periodic table and electron configurations (normalized gain of 0.7 in each concept).

Post II data from the periodic table unit revealed that learning loss was limited in most competencies and content areas, but considerable in the area of electron configurations. On these questions, it was noticeable that students were unable to apply their learning to write electron configurations or articulate their understanding through questions relating the structure of the periodic table to the structure of the atom. Many students were unable to even recall the notation used to write electron configurations.

The following histograms (Figures 2-5) expand our insight into the data summarized by the normalized gain calculations.

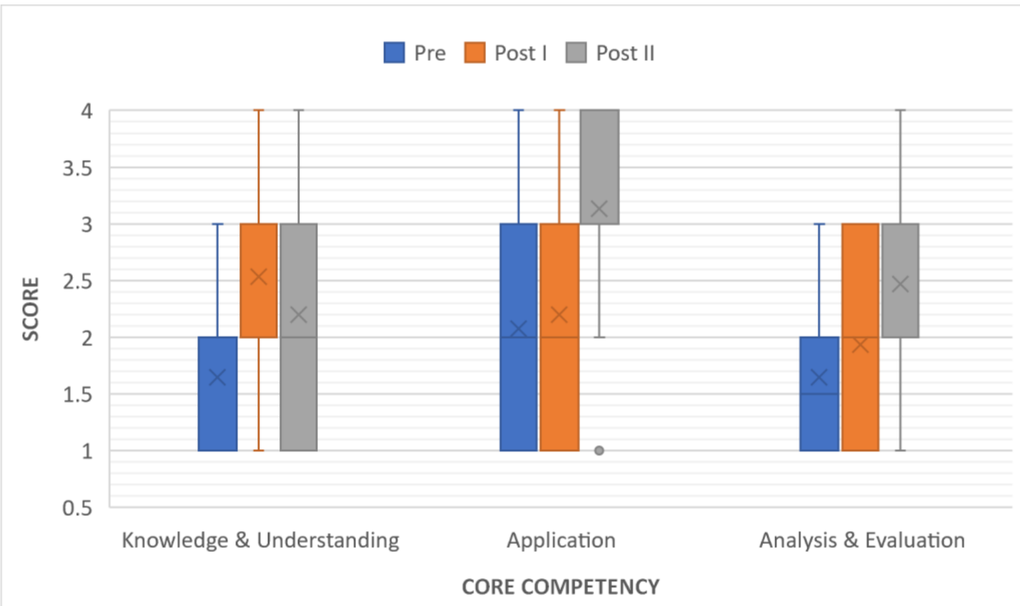


Figure 2. Atomic structure unit: Assessment results grouped by competency, (*N*=15).

Student learning as demonstrated by assessments before, after, and several weeks following the atomic structure unit has been grouped by core competency in Figure 2. Regarding the core skill of demonstrating knowledge and understanding, the data speaks to an initially strong improvement in the first interval of learning between the pre-test and unit test. However, while the Post II data indicate a minor decrease in average score in this competency, the increased interquartile range (IQR) of this dataset suggests that student learning retention or loss was not consistent among the group of 15 students. The range of the highest quartile of scorers on Post II in this category, however, did not change in range, indicating that learning loss was more noticeable than learning retention or gain. The skill of application, however, included a considerable class increase in competency between Post I and Post II. While student performance in this competency was fairly consistent between Pre and Post I, a much tighter interquartile range and higher minimum on Post II point to consensus in student competency in the ability to apply learning. The core skill of analysis and evaluation showed steady but only moderate improvement over the course of the three assessments. It can be considered a reasonable success that the Post II distribution has a smaller IQR, indicating more consistent performance in this competency across the sample group.

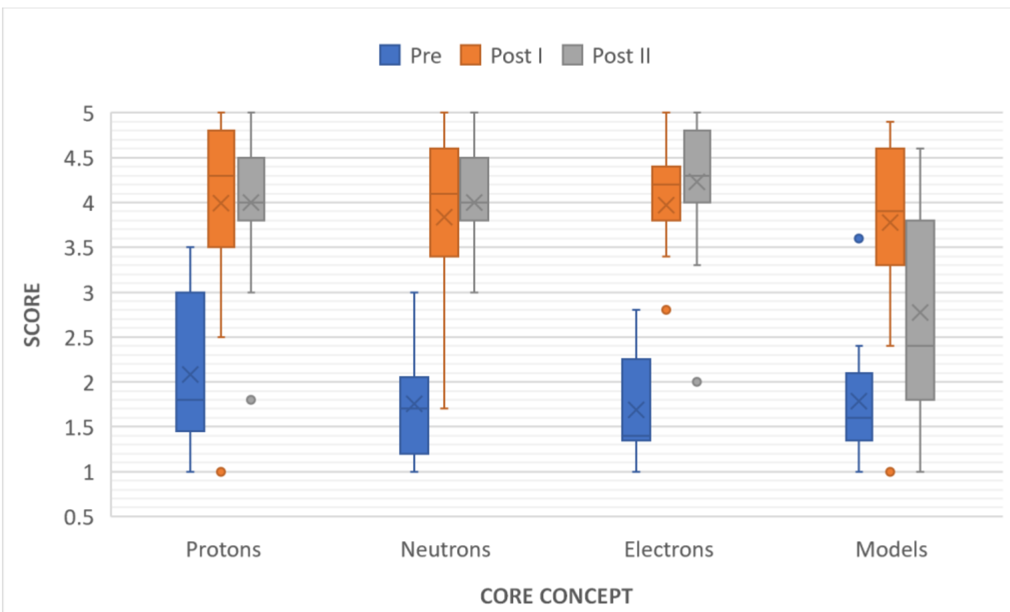


Figure 3. Atomic structure unit: Assessment results grouped by concept, (*N*=15).

The data from unit assessments about atomic structure are grouped by core concept in Figure 3. In all four core concepts, Pre data are considerably lower than the subsequent datasets, indicating learning gains as a result of the unit teaching. In the core concepts of protons, neutrons, and electrons, the change between Post I and Post II data shows a tightening of IQR and a slight increase in average score. These two changes indicate an overall improvement in learning over the entire sample group, as supported by the normalized learning gains reported in Table 2. The learning loss regarding Models of the Atom indicated by the normalized gain calculation in Table 2 is also supported by the increased spread of the data for this concept in the Post II dataset and a considerable decrease in each quartile and the average of the dataset.

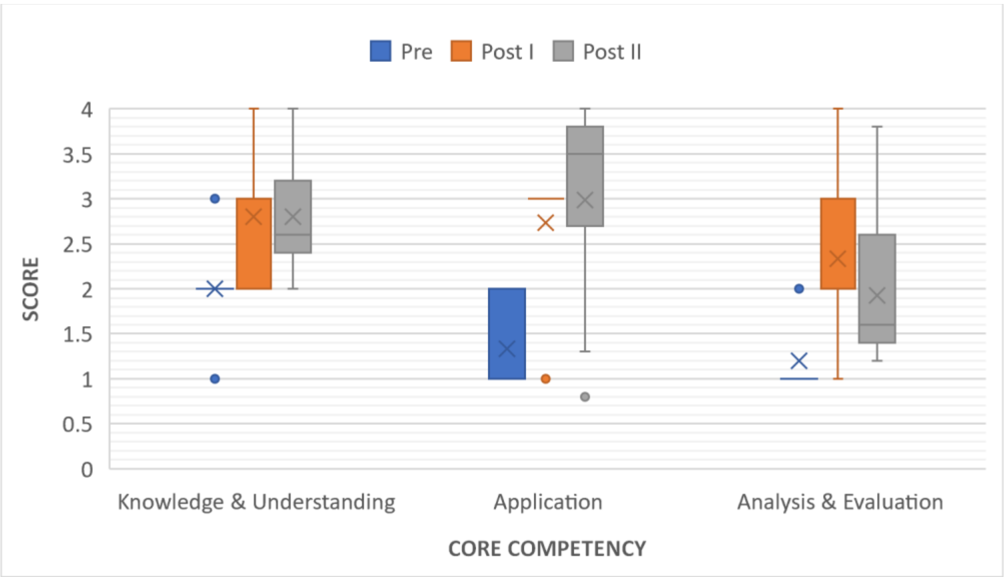


Figure 4. Periodic table unit: Assessment results grouped by competency, (*N*=15).

During the first interval within this treatment unit regarding the periodic table, students demonstrated growth across all three core competencies. Notably, the pre-test data in the Knowledge & Understanding, and Analysis & Evaluation competencies each has an interquartile range of zero. In these two competencies, I observed that students did not have a fully formed understanding of the new content, but they were able to use some prior learning and skills practice to earn at least an Approaching (marked numerically as a 2) on these questions. Similarly, students nearly all earned a Meeting (marked numerically as a 3) on the Application section of the unit test.

The interval of time between Post I and Post II was revealed to include little to no change in knowledge and understanding among the sample of students, as indicated by a near-consistent median score in this area and a smaller IQR to indicate similarity between students on this competency. While the median score in the skill of application rose slightly, the spread of data increased, indicating inconsistent results in this area. Most notably, students struggled to articulate their learning through analysis and evaluation on the post-test.

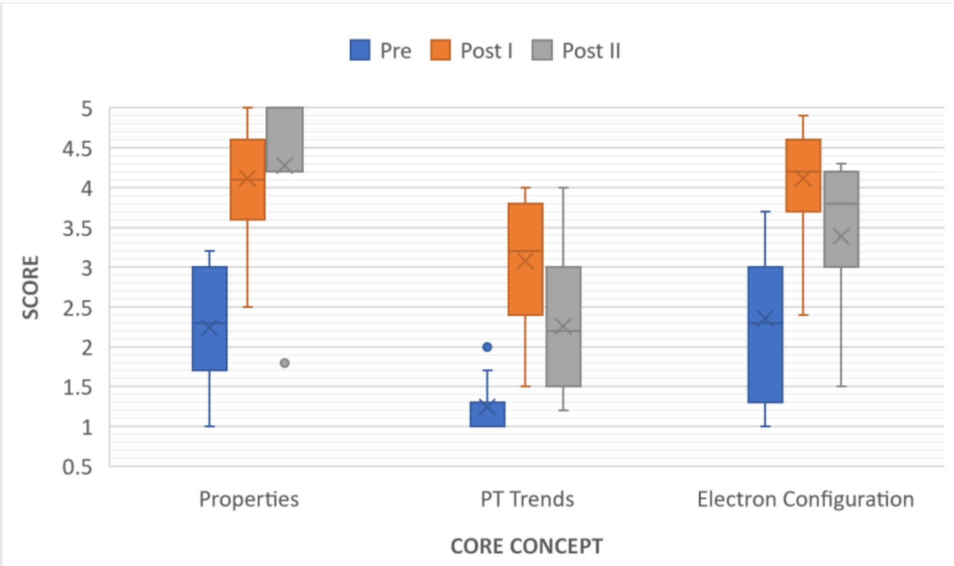


Figure 5. Periodic table unit: Assessment results grouped by concept, (*N*=15).

When assessment data regarding the periodic table treatment unit was grouped by core concept, considerable learning was indicated across all three concepts. Notably, the IQR between the pre-test and unit test decreased while the mean score increased in the Properties and Electron Configuration concepts. While the IQR increased for the concept of Periodic Table Trends, the pre-test data indicated that nearly all students had no prior knowledge about this topic, so the learning gains can still be considered to be a relevant indicator.

Student learning loss can be seen in Figure 4 during the interval between Post I and Post II about the periodic table. While the median score for the concept of properties barely changed, the IQR for that set of data remained small, indicating little loss in that concept. However, trends and electron configuration in the periodic table both held remarkably lower scores in Post II, as indicated by lower median scores.

Evidence of Learning Through Corrected Misconceptions. The Atomic Structure unit pre-test revealed some misconceptions embedded in students' prior understanding of atoms. Most students reported that they had either never learned about the structure of atoms or that they had most recently learned these concepts in 5th or 6th grade. Most student responses were wrong; some students stated they simply did not know the answer, some gave a partially correct answer with some key information omitted, and some students demonstrated some seemingly common misconceptions when compared with their classmates.

Multiple students gave responses that indicated learned misconceptions about the nature of the atom. It seems that some students have confused atomic structure with cell structure, indicating the presence of mitochondria and a (cellular) nucleus. In this same category, it was apparent that some students confused the internal structure of an atom with the external function and behavior of an atom, describing an atom as containing bonds between parts (Figure 6). At least three students repeatedly used the term "molecules" to describe the constituent parts of an atom. In all of these examples, the general theme emerges wherein students interpret the internal structure of an atom as including parts much too large to be contained within an atom. Most of these misconceptions likely stemmed from a lack of prior learning about atoms or from learning loss, as most students indicated that they have either never learned about atoms before or had most recently learned about atoms in the fifth or sixth grade. For this group, this lack of learning or loss of learning may be attributed to changes in curriculum or learning as a result of the covid-19 pandemic. However, this group of students comes from a variety of educational settings within the last few years, so the cause of these misconceptions remains inconclusive.

Some students were aware of the existence of protons, neutrons, and electrons, but failed to place these components in the appropriate locations within an atom. These students were likely to identify protons or neutrons on orbiting paths around an atom, rather than located within a nucleus.

Multiple students made claims about incident energy on an atom which implied they believe that any radiation striking an atom would cause it to “expand” or “change” in some way other than being energized. One student, possibly thinking of nuclear reactions, stated that when an atom absorbs energy, “It starts to create things,” and another stated that the atom would “expand[s] and get[s] bigger, then get[s] destroyed.” Some students communicated further miscommunications about energy; one explained that isotopes are within an atom (see Size and Structure) and that these provide energy to the atom.

While many students were able to report that protons are positively charged and electrons are negatively charged, six of the fourteen incorrectly described electrons as able to have a positive or negative charge. Two of these additionally explained an incorrect idea about incident energy on an atom—that this energy would change the charge on particles, such as protons, neutrons, and electrons. This group of students fundamentally misunderstood that charge (or lack thereof) is an inherent characteristic of protons, neutrons, and electrons, and cannot be altered on a single particle.

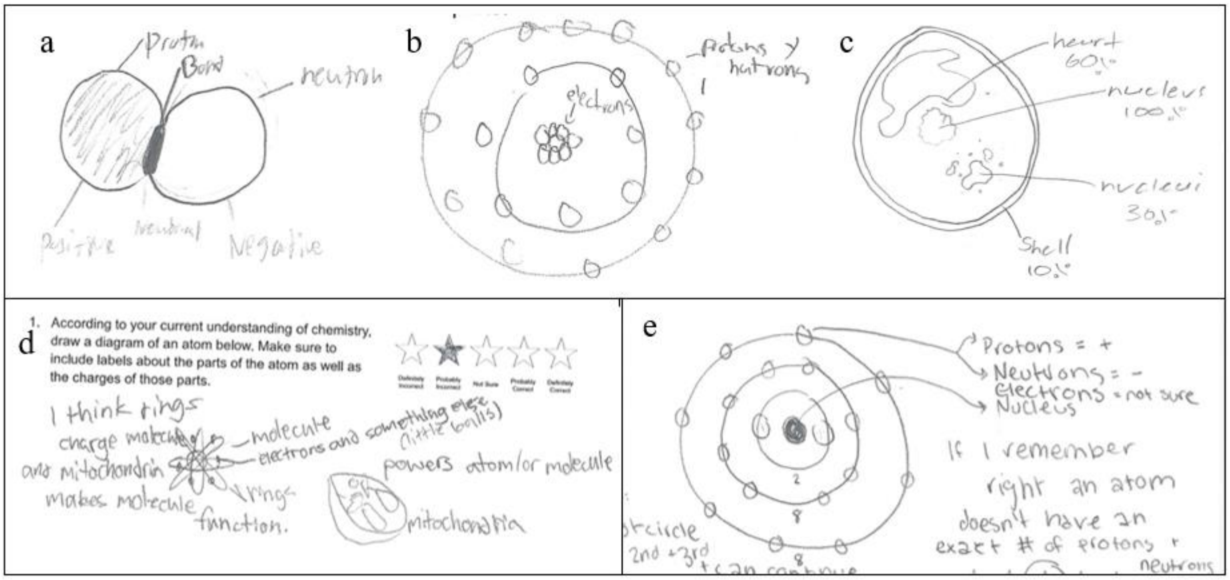


Figure 6. Student representations of the atom (Pre-Test).

These themes in misconceptions regarding atomic structure are valuable observations on the unit pre-test because by the time the unit test was administered, none of these misconceptions were retained. As seen in Figure 7, by the end of the unit, students were able to identify which subatomic particles belonged inside or outside the nucleus, correctly identify charges, and use these properties to describe energy changes in the atom. Additionally, it is important to note that these misconceptions did not recur during the interval after Post I, as indicated by Post II data. Although students had difficulty recalling information about the difference between atomic models throughout atomic theory's development, all students showed evidence of measurable learning by correcting prior misconceptions.

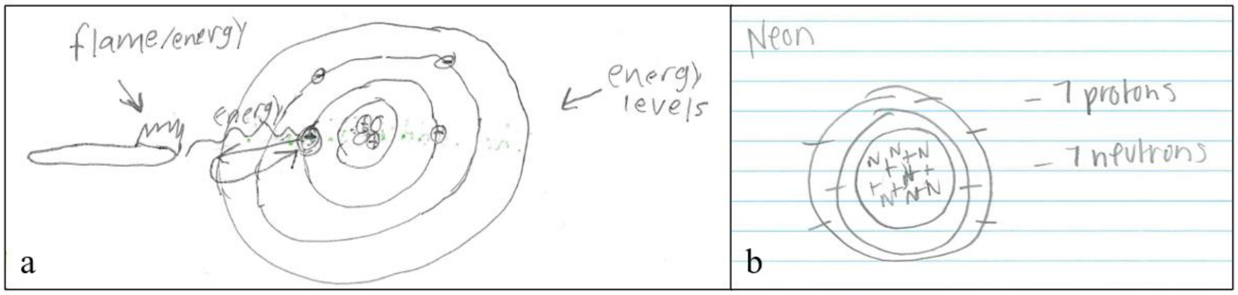


Figure 7. Student representations of the atom (Post I).

<u>Content Retention: Models of the Atom.</u> Post-Test II revealed some interesting patterns in student understanding and errors. Multiple students demonstrated some knowledge of models of the atom, even including the names and diagrams of atomic models, but struggled to correctly attribute these to the originator of that theory. It is clear that these students developed a strong understanding of these models, but struggled to correctly memorize the name of the associated scientist. While this is regrettable, it is validating that students gained a conceptual understanding of atomic theory enough to reproduce these diagrams and explanations without significant review before Post II.

An overwhelming theme in Post II for the Atomic Structure unit was students' difficulty explaining the justification or experimentation that supported each atomic model they learned about. Most students left this section of the assessment blank, but some made guesses about the justifications of each model. For example, one student used the phrase, "evenly distributed positive and negative charge" in their justification of the Plum Pudding Model (while this is not a justification, it is a fairly accurate description of the model), and "unevenly distributed" as justification for all of the other models. Another student explained the justification of J. J. Thomson's model also by stating, "He related it to plum pudding with his model having a relatively random amount of protons and electrons," similarly describing the model rather than justifying it with scientific concepts. Another student followed this pattern by responding, "There was positive particles and negative particles mixed in a sphere."

<u>Bohr's Model of Emission Spectra.</u> On the Post II test for the Atomic Structure unit, students were prompted to use Bohr's model to describe how electrons are energized and consequently emit light. In my analysis of the assessments during this unit, it was clear that students who were successful on this question had retained the visualization of the flame via the diagram drawn during this lesson, as the diagram appeared in their responses.

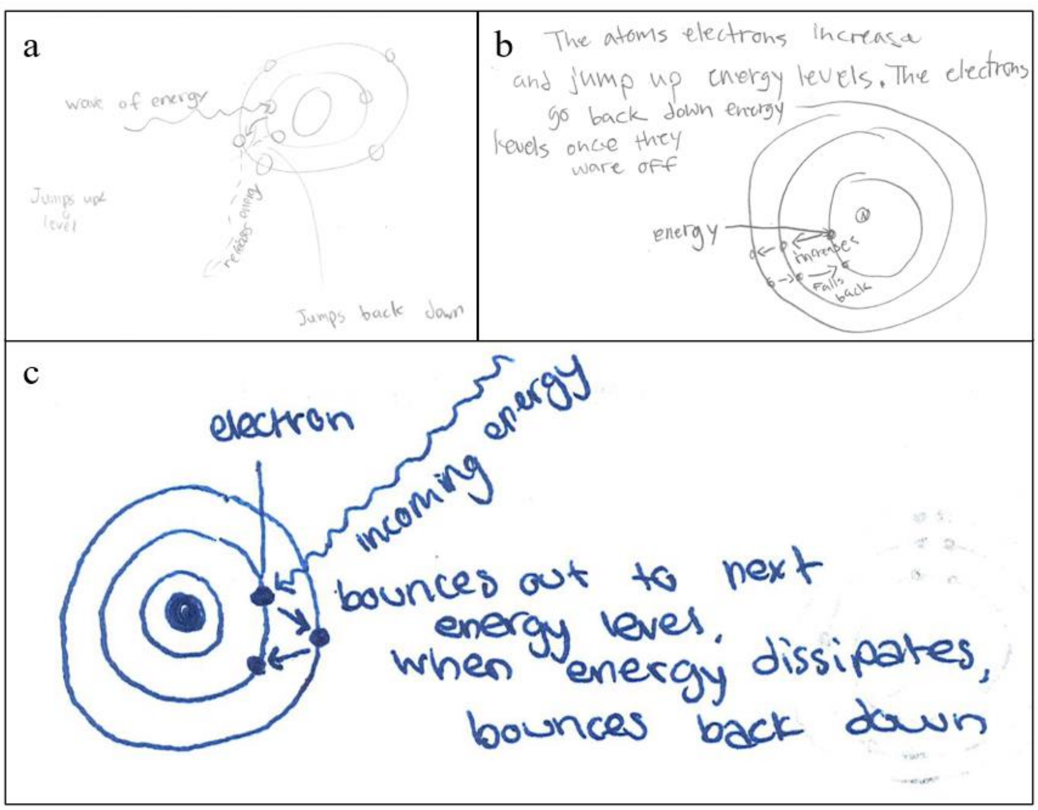


Figure 8. Student diagrams and explanations of Bohr's model (Post II).

While the student responses pictured in Figure 8 also include some imprecise language regarding the movements of energized electrons, the use of these diagrams indicates a key experience in constructing meaning during the flame test demonstration. It was also notable that students who struggled more to retain their understanding between Post I and Post II used some misguided language in their discussion of the movement of energized electrons and did not support their explanations with diagrams. One student explained the phenomenon by saying, "The electrons in an atom 'bounce' around to different energy levels and receive [sic] a great amount of energy." Another student with seemingly similar misconceptions on this topic stated, "When an atom is struck by electricity the electrons gain energy to pull farther from the nucleus. The energy makes the electrons more excited so they start shaking and release more energy through color." Both of these students, along with others, were able to retain some conceptual understanding of this phenomenon in that they knew that the electrons became more energetic and moved somewhere other than their standard position in the atom. However, they were unable to retain their understanding of the step-by-step process by which electrons are struck by radiation, move upward in energy level, and fall back down to their ground state upon the release of this energy in the form of light. It is noted that a deep understanding of Bohr's model of the atom should allow students to put these pieces together, even well after the unit. Therefore, it can be concluded that there was a loss of learning regarding atomic structure and the application of models.

Trends on the Periodic Table. A key component of the MBI design of the Periodic Table unit was the progression of three activities using physical and mathematical models to uncover trends in the periodic table. To assess the effect these activities had on student understanding of periodic table trends, I averaged the scores from the MBI-related portions of these activities, adjusted them to match the 5-point scale used to measure the accuracy of student test responses, and compared these averages to individual student performance on the unit test regarding periodic table trends. Table 4, below, summarizes this data. As shown, most learning scores improved between the learning activities and the unit assessment, indicating that students benefitted from the experience and the written feedback they received on these assignments. Table 4 also indicates the four students (whose score changes are italicized) who decreased in proficiency in this topic between the MBI activities and the test. Three of these students generally do well on tests, so I would suggest that this test score is not the best single representation of their overall understanding, while one of these students frequently requires relearning and repetition.

Table 4. Student scores on MBI activities and Post I assessment items (*N*=15).

Student	Average of MBI Activity Scores	Score on Post I Periodic Table Trends Items	Change in Score
A	2.9	3.6	0.7
B	3.3	3.6	0.3
C	2.5	3.6	1.1
D	1.7	2.8	1.1
E	3.3	4	0.7
F	2.1	3.2	1.1
G	2.5	3.8	1.3
H	2.5	1.8	***-0.7***
I	3.3	2.4	***-0.9***
J	2.9	3.8	0.9
K	3.3	2.8	***-0.5***
L	2.9	3.8	0.9
M	3.8	2.4	***-1.4***
N	1.3	1.5	0.2
O	2.1	3	0.9

The Periodic Table Puzzle (described in the methods section) was a successful tool that provided students practice both in making arguments based on a model and connecting their learning from the aforementioned scientific modeling assignments (scores of which were averaged in Table 4) to the periodic table as a model itself. One student demonstrated mastery of this skill and content with the following CER statement:

> I believe that the circles below the number refer to electronegativity. Electronegativity increases left to right and from the bottom left to top right. It decreases from top to bottom. As the amount of circles increases, I believe it means the electronegativity also increases. The highest amount of electronegativity occurs near the Halogens. Fluorine is a Halogen located on top of the column. The electronegativity for Fluorine is 4. The amount of circles is 3. The element Potassium, which is located 4 rows down and farthest on the left has an electronegativity of 0.8. Potassium has 1 circle. I couldn't connect any other trends with electronegativity so I believe the circles are the electronegativity trend.

This student and many others adeptly applied their learning to writing strong CER statements, as evidenced by a correct interpretation of puzzle symbols, reasonable citation of evidence from the modeling activities, and clear reasoning tying the puzzle information to their claim. However, students with a looser grasp of the concepts in the core topic of periodic trends struggled to connect their evidence from the scientific modeling activities to claims about periodic trends. For example, the following quote was written by a student who only earned "Approaching Expectations" on this task.

> The bigger the shape the bigger the atomic radius. Francium has the largest atomic radius and is the first element in period 7. As the periodic table moves left to right the atomic radiuses start to get smaller along with the shapes. The right side of the periodic table may have higher electronegativities than the left but it is the opposite with the atomic radius.

Notably, this student did not cite the three activities in which periodic trends were examined by scientific modeling. This student received such feedback on this writing before the test, which may explain their successful score on this core concept on the unit test.

Another significant trend that emerged from this assignment is that three of the four students whose proficiency decreased in the core concept of periodic table trends between the modeling activities and the unit test (as seen italicized in Table 4) did not submit this assignment. Therefore, those three were unable to practice explaining and applying their understanding of periodic trends in electronegativity, first ionization energy, and atomic radius, and also missed the opportunity to learn from feedback on their writing. This may have contributed to their poor performance on the unit test items relating to this core concept.

Learning Attitudes

My second research question was "How do students' attitudes about chemistry relate to their learning?" Analysis of my data suggests that learning through Model-Based Inquiry had a marginally positive effect on students' attitudes about science, from the way they view chemistry to how they view their participation and success in science class.

Changes in Student Confidence. The previously discussed unit assessments also provided data regarding student confidence in each assessment question. This data was similarly grouped by core competency as well as by core concept for each unit.

Table 5. Normalized confidence gains: Atomic structure unit (*N*=15).

	Core Competency			Core Concept			
	Knowledge & Understanding	Application	Analysis & Evaluation	Protons	Neutrons	Electrons	Models of the Atom
Pre to Post II	0	0.7	0.5	0.6	0.6	0.8	0.1

Table 5 summarizes the calculated normalized gain in student confidence over the course of the Atomic Structure unit. While students demonstrated moderate to considerable growth in their confidence in application skills and analysis and evaluation skills, it is notable that they did not increase in confidence as a group between the start of the unit and the follow-up post-test. This lack of increase in confidence exists regardless of the learning gained in this competency. Student confidence increased moderately to considerably in the first three core concepts, though the last concept, Models of the Atom, saw only a limited increase in confidence.

Table 6. Normalized confidence gains: Periodic table unit (*N*=15).

	Core Competency			Core Concept		
	Knowledge & Understanding	Application	Analysis & Evaluation	Properties	Periodic Table Trends	Electron Configuration
Pre to Post II	0.4	0.6	0.3	0.7	0.4	0.4

The data displayed in Table 6, above, indicates that student confidence in the learning module about the periodic table increased moderately during the unit and the subsequent period preceding the follow-up assessment. There was limited learning loss between Post I and Post II, as indicated in Table #, so it is likely that student confidence also dipped in this interval as well. In particular, it was observed that student confidence regarding the core concept of elemental properties and similarities in element groups increased considerably over the course of the treatment.

<u>Shifts in Learning Attitudes.</u> Using the CLASS statistical analysis Excel product, I found that student attitudes shifted as a result of learning through MBI-style activities. The pre-test data revealed that students originally held views about chemistry that were statistically far from expert views. The pre-test data was nearly symmetric about a mean of 40-50% with the highest score only achieving 60-70% of agreement with expert views. This tool was designed and

revised in an undergraduate setting, so these pre-test results are not overly surprising. However, these low pre-test results could serve as an indicator of growth if the post-test results indicated a shift in attitudes.

However, the overall shift was not drastic (within 0 to 20%) and the subgroup of my sample that completed both pre-and post-tests were nearly evenly split between shifts in the "expert-like" direction and the "novice-like" direction (Table 10). This amalgamated representation of student shifts in attitudes oversimplifies the data; more can be understood when shifts in attitudes are sorted by category. The full representation of attitude shifts by category can be found in Appendix F, but the most notable shift categories were in the categories "Real World Connection" and "Conceptual Connections."

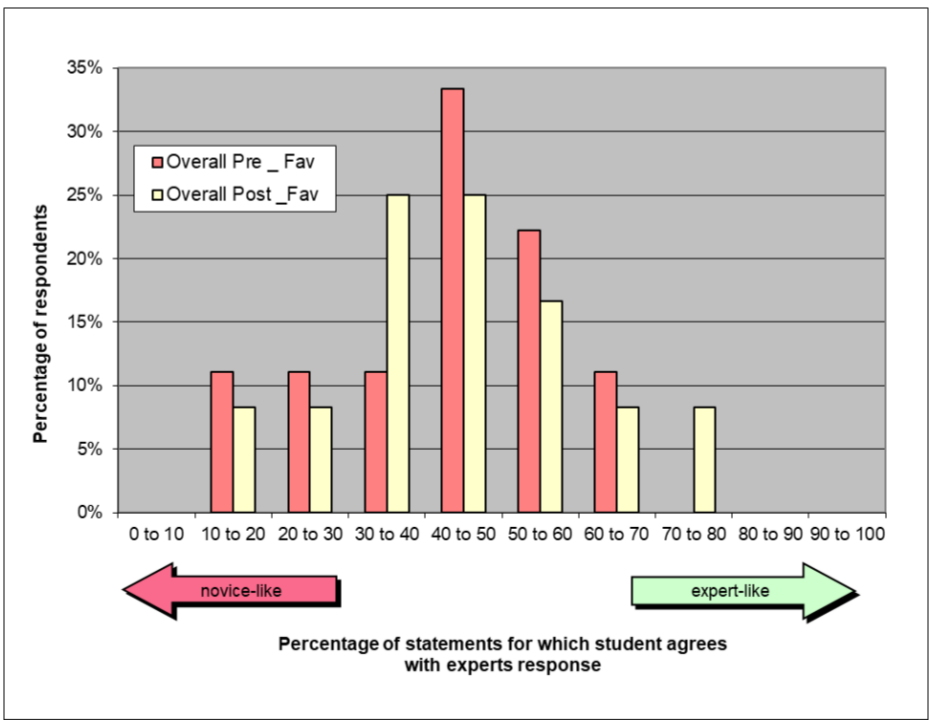


Figure 9. Binning of data by beliefs relative to an expert's (*n*=9).

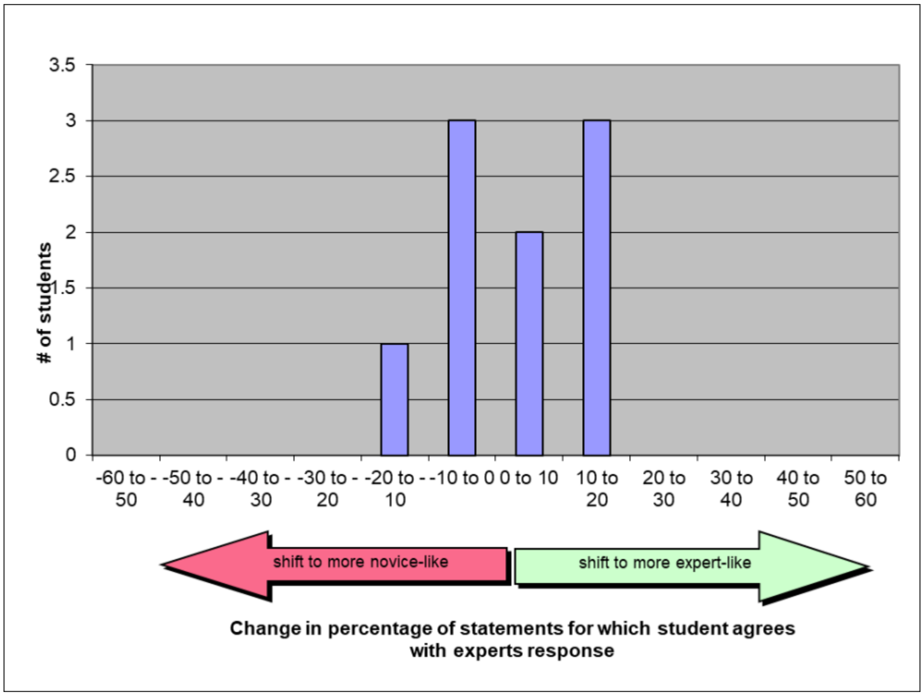


Figure 10. Binning of data by shift in beliefs (*n*=9).

The categories established within CLASS reveal interesting themes in student attitudes. Though there were multiple areas of growth, two categories were marked as a “large shift” by the statistical tool. The tool identified that students demonstrated considerable growth in the area of Real World Connections, wherein students increased their agreement with the expert point of view considerably. There was also considerable growth in the area of Conceptual Connections, wherein students considerably decreased their disagreement with the expert opinion. Some areas were marked as a movement toward the “novice-like” view, but none of these were flagged as large decreases.

Not many students elected to expand on their Likert score answers, but those who did contribute to the themes represented in the quantitative data. One student remarked that “It is so much more beneficial for me to understand the whole concept not just what I NEED to know,” supporting the higher score observed in the area of Sensemaking/Effort for this prompt. Within the category of Personal Interest in Chemistry, one student expanded on their answers by saying "I don't usually need any chemistry knowledge in day to day life." This was emblematic of a lot of the observations I made throughout the treatment units; students were not highly motivated to learn about chemistry and seemed to struggle to see the connections between chemistry and other topics in their lives.

Understanding of Scientific Models

My final research question asked, "How does MBI impact student understanding of the purpose and use of scientific models?" The results of my action research led me to conclude that this application of Model-Based Inquiry was effective for increasing students' exposure to the concept of scientific modeling, but that there was room for improvement when it came to student understanding of the broader benefits and limitations of scientific models.

Using the foundational guidance from Schwarz and White (2005), I chose to analyze student interviews through the lenses of the nature of models, the evaluation of models, the utility of models, and the process of modeling (p. 182).

Nature of Models. On the Post I assessment, students were allowed to attempt more difficult problems to earn "Exceeding expectations" on each outcome. One such problem prompted students to evaluate a periodic table arranged differently from the standard classroom model. They were asked to identify its primary organizational property and discuss a possible purpose of this model. Only some students attempted this problem, but eight gave a short response to explain what they recognized from the familiar periodic table. Once again, students' depth of inquiry concerning this periodic table was limited; few students identified that the table was arranged according to Schrodinger's model of electron configuration. One student attempted to describe the model a bit further, stating "The periodic table is organized by families with color. It increases and goes by number of orbitals and horizontally labels each elements number of valence electrons." Except for this response, all other students merely described that the four orbital types (s, p, d, and f) were separated, with perhaps one or two more details about the spacing and shape of the table.

One student, to discuss the purpose of this model, said, "Most useful purpose is to organize elements into their s, p, d, [and] f blocks." Another said, "The primary purpose of looking at it this way is to see the different levels more clearly by separating them in order to have clear lines between the blocks." Another student commented vaguely on trends in this model: "Its primary purpose is to show a lot of the trends all at the same time." Students struggled to make connections between the classic periodic table and this new arrangement and did not show competence in the skill of thoughtfully evaluating models.

One of the questions Schwarz and White (2005) identified within this category of knowledge around scientific modeling was "Can there be different models for the same object or phenomena?" (p. 182). Students neglected to touch on the patterns and properties represented in the classic representation as they discussed the new model of the periodic table, indicating that they have further learning before understanding that different models can represent the same object or information.

During student interviews, a theme emerged suggesting that students primarily view scientific models to be physical or pictorial rather than mathematical, conceptual, or other. When asked to describe an experience in which they used models, all students described physical models or diagrams. When asked to explain what a model is, one student said, "I could see it as like a 3D or a visual model that has a picture and then little dots and lines connecting to like stuff in that picture like what it is." Multiple others referred to the physical model they built during the Periodic Table treatment unit, in which they constructed a 3D model of electronegativity patterns on the periodic table. It is apparent that the modeling opportunities in these treatment units (the atom, trends in the periodic table), along with prior experience in science learning, strongly influenced students to have a limited perspective of the different forms that models can take.

Evaluation of Models. On the Atomic Structure Post I test, students were asked to analyze a model they used during an inquiry lab to simulate Rutherford's gold foil experiment. This simulation involved striking a hidden shape beneath cardboard by rolling a marble and tracing the paths of the marble to use deductive reasoning to determine the shapes. In their lab, students analyzed this model to compare it with Rutherford's experiment and make meaning of his findings. On their unit test, students were reminded of this simulation and asked again to draw comparisons and contrast the simulation with Rutherford's actual experiment. Students were generally able to identify at least one or two components of the activity and how they simulated Rutherford's experiment but did not go into detail about each component. As I often observed, their language around drawing comparisons and evaluating scientific models fell flat, even after guided practice with these examples. Students seemed to struggle in particular with analyzing the accuracies and inaccuracies of the model. One student simply said, "It was accurate because underneath the cardboard it was mostly empty space. The shapes were inaccurate." But this student did not elaborate, much like most other students. A few students were able to discuss the accuracies and inaccuracies further but tended to answer the question as though it was a prompt for a personal opinion about how enjoyable the activity was, rather than its merit as a simulation.

When asked to discuss the features of the periodic table that qualify it to be considered a scientific model, students generally struggled to evaluate the model thoughtfully. Many provided the simple, straightforward answers that they might've expected to be the "textbook response" without much deeper thinking. One student said, "It is modeling the order of elements that we know exist." Another stated, "It represents scientific data in a clear and concise [sic] table used across the world." These responses echo many others in the sample group, and lend to the generally understood purpose of models among these students, discussed further in the following sub-heading.

However, a few students thought about their learning about the revision of models as they discussed the periodic table. One said, "It can be considered [a scientific model] because it was made to model a lot of information in a specific way that demonstrate [sic] multiple trends at the same time: Lots of previous models has [sic] been improved over many years." Another said, "The periodic table was worked on and edited by dozens of different scientists from different fields. Because of all the information that has been added over time, and because of the diversity in information, it is considered a scientific model." These answers suggest that these students recalled their learning from the treatment unit about atomic structure and interpreted that the revision of models is important to the nature of modeling.

To assess whether there was a quantifiable improvement in students' ability to evaluate models, I pulled data from the three assessments (Pre, Post I, and Post II) in each treatment unit only for the questions which asked students to evaluate or explain models. This data, represented in Figures 11 and 12, indicates that there was some improvement during each of the treatment units; students improved in their ability to describe and evaluate models in each unit of learning. However, average scores in both units were fairly low, indicating much room for improvement in student understanding of models as a scientific tool. Additionally, the second treatment unit (the Periodic Table unit) had lower scores than the first, which argues against any claims that might be made about definitive student improvement in understanding of models.

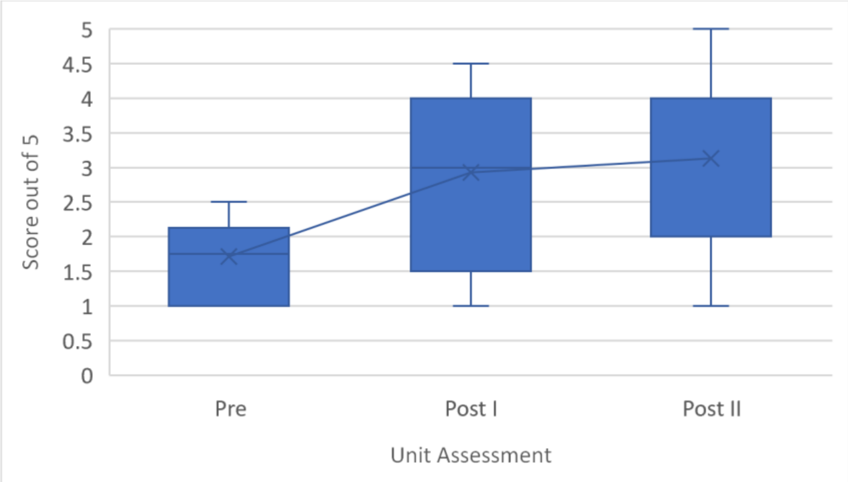


Figure 11. Atomic structure unit: Proficiency scores relating to models (*N*=15).

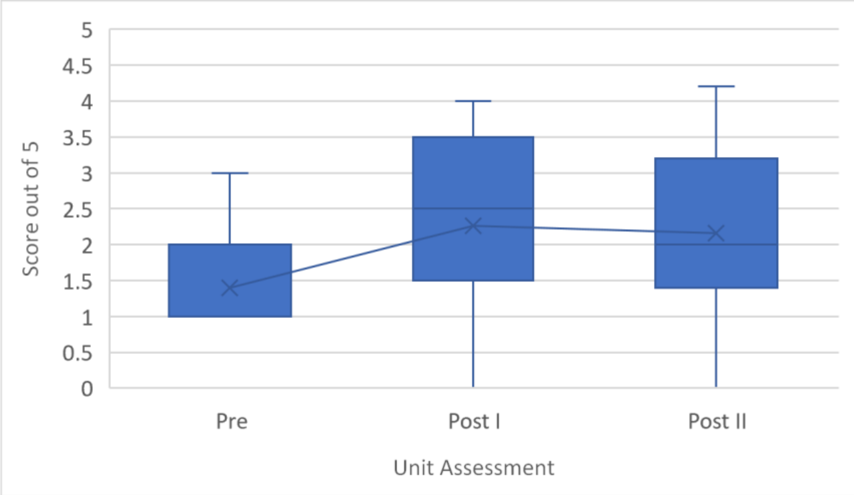


Figure 12. Periodic table unit: Proficiency scores relating to models (*N*=15).

Purpose or Utility of Models. Students generally understand scientific models to be utilized as a learning tool in the classroom. As previously mentioned, students tended to discuss scientific models through the lens of practicality in the classroom to display or organize information. All of the interview participants indicated that students are primary users of models, while only some commented that professional scientists might need models as well.

Students strongly held the belief that the primary purpose of models is to educate or to demonstrate knowledge. When asked to discuss who uses models and how models are used, one student said "[Scientists] would use them to help people understand how to solve equations. They use models that scientists have made … and teachers understand them … and teach them to students." Another student said that models are used by "all people demonstrating knowledge … to share or understand." Another student discussed a time they used a model to explain the purpose of models: "We used a model of the human skeleton to help us visualize where each bone is and their names." A different student, thinking directly of their learning in the first treatment unit, said "[Bohr's Model] showed the evolution of how the structure of the atom had formed and it showed progress," also reiterating the idea that models are used to demonstrate understanding of the time. Another student explained that a model user might be "A scientist or a student—to learn or to visualize. I would say mostly to … have a physical [model] instead of just having it in your head."

I was also interested in the themes that emerged about imperfect models. Most interviewees recognized that imperfect models could serve a purpose, but only a few were able to discuss how such models could be useful. It was clear that earlier misinterpretations of the purpose of models bled into these answers at times. One student, adamant that models are primarily used to identify and display information, said that improperly labeled models could be accepted, but it would be important to know which labels were incorrect. They continued that it would be unhelpful "When a model is just a straight picture and doesn't explain what it is." A few students were particularly insightful on this topic, one stating that:

> I don't think they need to be perfect because I don't think they can physically be perfect, like exactly like what you're gonna talk about. Because it's a model—you can't make an element that big, or like an atom or something. But I think it should be pretty close, and you should know what's not actually there or what is there.

Another student, who has performed well academically in these units, discussed the revision of models at length, saying "[Models are] not definitive because science is still learning. … Facts aren't really facts because they could be disproven. … I feel like scientific models could be disproven." They went on to discuss a particular example: "So the current model of an atom could be disproven. … [Imperfect models could be used] for younger kids to learn things—teaching us the basics of atomic science."

Although some students demonstrated a working understanding of the purpose of scientific models, their revision, and the practicality of imperfect models, there was not overwhelming evidence that this idea was accepted throughout the entire sample group of students.

<u>Nature or Process of Modeling.</u> Student responses in interviews did not reveal an enduring understanding of the nature or process of modeling. Admittedly, the application of MBI for this action research did not focus on the process of modeling as much as the applications referenced in the literature review of this paper.

CHAPTER FIVE

CLAIM, EVIDENCE, AND REASONING

Claims From the Study

Model-Based Inquiry and Learning Retention

In response to my question "How can MBI impact learning retention in a high school chemistry class?" I determined that Model-Based Inquiry is an effective teaching tool with a reasonable capacity to limit learning loss. Key evidence in support of this teaching method was the normalized learning gains that were observed in each unit between the Pre, Post I, and Post II tests, viewed through both competency-based and content-based scoring of student responses. Additionally, the distributions of these scores imply that student comprehension improved during the initial learning period, thus validating the application of MBI in this study, but also that student comprehension did not drop considerably in the time following the treatment unit. The application of MBI in these treatment units was additionally validated by evidence of corrected misconceptions in student responses over the course of data collection; students eradicated misconceptions about atomic structure that they demonstrated on the Pre-test, but admittedly did not achieve perfect comprehension by the end of the unit. The theory of constructivism as described by A. Colburn suggests that the eradication of misconceptions is a signal of effective inquiry (Colburn, 2000).

While there were limitations and flaws to the application of MBI in this study, as discussed in the subsequent section of this chapter, the general evidence of increased proficiency in each unit and the remediation of misconceptions support the use of this application of guided

MBI to encourage learning retention. However, it must be stated that much of the success that students demonstrated on assessment questions can also be attributed to repeated practice explaining scientific phenomena using different forms of communication through different activities and formative assessments in each unit. Similarly, student scores decreased noticeably on skills and concepts that were not practiced or reviewed in the interval between Post I and Post II, such as electron configuration and deeper analysis of Rutherford's model of the atom. Therefore, a strong adaptation to MBI is the addition of these formative assessments to promote learning retention.

Learning Attitudes

In response to my second research question, "How do students' attitudes about chemistry relate to their learning?" I found that Model-Based Inquiry had a marginally positive effect on students' attitudes about science, from the way they view chemistry to how they view their participation and success in science class. In particular, this theme was supported by moderate to significant increases in student confidence over the course of the two treatment units. In my grading of student work, I found that their confidence levels often underestimated the correctness of a given assessment response. While confidence levels were not at a maximum across all students by the end of the treatment units, the normalized gains in this area were remarkable enough to signify growth in this area. The CLASS results also indicated some slight growth in student attitudes when compared with the expert opinion. However, this growth was countered by shifts in the "novice-like" direction in equal magnitude.

I noticed during the treatment units that student participation was inconsistent and I often felt myself repeatedly prompting students to dig deeper and think critically about their observations and inquire about their learning. It was common for students to ask if their answer was correct and to phrase their writing in such a way that mimicked "textbook-style" simple answers, or to barely give a complete written response at all. I think students in these classes still operate under the expectation that there are correct or incorrect answers to their learning, rather than an understanding that learning is an iterative and messy process. Students frequently inquired about their grades and hesitated to take risks, even though structured rubrics accompanied every activity (often designed to encourage risk-taking); I found that students rarely read these rubrics and therefore did not understand the grading expectations. I was puzzled by this hyper-focus on grading alongside a lack of attention to grading rubrics. It would be a worthy focus of future action research. For my research, I believe that this attitude in my students may partially explain the trends in data collected regarding learning attitudes.

Understanding of Scientific Models

In response to my third research question, "How does MBI impact student understanding of the purpose and use of scientific models?" I claim that this application of Model-Based Inquiry was effective for increasing students' exposure to the concept of scientific modeling, but that there was room for improvement when it came to student understanding of the broader benefits and limitations of scientific models.

A strong piece of evidence to support this claim was the relationship between student performance on the MBI activities regarding periodic table trends and student comprehension as demonstrated on that unit's test, and how these themes related to student learning through the Periodic Table Puzzle CER. Those students who did not complete the latter assignment, missing an integral part of the MBI learning design, demonstrated lower achievement on the unit test questions relating to trends represented in the model of the periodic table. This supports the efficacy of MBI learning experiences for improving student understanding of models. Student interviews also revealed merely a developing level of understanding around the nature, use, process, and evaluation of scientific models. Although quantitative data collected from unit Pre, Post I, and Post II assessments indicate a gradual growth in student perceptions of models, the overall picture shows that MBI utilized in the manner of this action research was not a fully capable tool to increase student understanding of scientific modeling.

During the two treatment units of this research, I observed frequently that students tended to resist feedback that asked them to consider how models can be revised or evaluated critically. I felt that students were stuck in traditional patterns of teaching and learning, often looking for the “correct” answer to merely complete the task. When I worked one-on-one with students to scaffold them through the process of evaluating models, I sensed that students grew tired of having to explain their thoughts and ideas in such detail—they seemed to find the prompt tedious and unworthy of their time. The setting of this action research made these results particularly interesting; the school holds foundational values around scientific inquiry that would suggest that students have a stronger grasp of the nature of science from an early age, ideally not being as set in patterns of direct instruction as students in a traditional school. However, the students in this sample group were a fairly even mix of returning students and new students from other schools. If I could expand the timeframe of this research, I would continue to increase the level of autonomy built into the design of MBI to make it a “truer” inquiry, and hopefully, student attitudes and motivations would follow this pattern of long-term growth.

Value of the Study and Consideration for Future Research

Over the duration of this study, I uncovered many areas for improvement in the MBI design of my treatment units due to some limitations. I elected to facilitate the use of the built-in models within the atomic theory and the periodic table rather than selecting larger conceptual models which would be investigated in a student-led manner. This decision was based on the lack of prior knowledge and experience among the students in these classes. Before the start of the MBI units, I observed that my students had significant gaps in understanding and experience around the scientific method, methods of inquiry, and concepts of physical science. Therefore, I decided that a more guided inquiry approach would be appropriate. Nevertheless, the results of this study provide valuable guidance for the implementation of MBI in a high school science setting. In particular, strong MBI teaching should also incorporate exhaustive opportunities for formative assessment to reinforce learning and periods of direct instruction when necessary.

The results of this action research do indicate that a guided approach to MBI can be effective in increasing student learning about science concepts; the quantitative data support this application of MBI. While my treatment plan design was a very structured version of MBI in comparison to the work of Campbell et al. (2011), Rinehart et al. (2016), and Windschitl et al. (2008), the retention data I collected validated this approach. Although I have referred to student growth in this paper as gradual and minimal, I do think that this research was a valuable on-ramp to MBI in my teaching, as I observed small changes in students toward thinking more critically and being open to new ideas throughout this treatment.

Looking ahead, I would like to study how MBI can be implemented in high school science courses beyond these topics of chemistry. I am interested in how MBI applied with a more student-led approach might affect student learning retention in comparison to the results of this study. I would investigate whether understanding of core concepts would be strengthened as directly in a student-led approach as compared to this study's teacher-guided approach. I expect that in such research, I would find that students would become more confident in their learning and begin to show more considerable growth in their understanding of the nature of science, problem-solving abilities in chemistry, and the interconnectedness of scientific learning. I also expect that students would gain more understanding of scientific modeling through the repeated practice of this skill. As mentioned previously, the topic of this action research would lend itself well to a much longer timeframe, in which students could warm up to the process of investigating and reiterating scientific models. Previous literature suggests that more in-depth and student-driven trials of MBI in the science classroom would be more appropriate (Campbell et al., 2011) and that assessing learning retention after a longer period might yield more applicable results to inform pedagogy (Dauer & Long, 2015).

Impact of Action Research on the Author

The process of completing this research was valuable to my growth as a teacher in many ways. First and foremost, designing the treatment methods for this action research was a challenge when it came to accommodating the needs of the various learners in my classes; I was surprised by gaps in my students' prior learning to a greater extent than I had experienced in my previous years of teaching. These gaps may have been caused by learning loss during virtual learning as a result of the Covid-19 pandemic or inconsistent scope and sequence standards in previous years or even due to the population of learners being mixed in age and educational background. At times, I needed to make significant adjustments to my hopes for the application of MBI design in my treatment units. However, the experience of trying out MBI on a much more structured level for my students gave me useful insight into the necessary components of valuable inquiry, even if that inquiry is more guided than student-led. There were also several instances in which I recognized from formative assessment data that students required additional modes of learning and reviewing difficult concepts. I continually practiced flexibility and creativity in responding to student learning issues along the way. As a result of this experience, I feel more capable and excited to implement MBI in future classes at a much more open level of inquiry using anchoring phenomena.

Combing through unit assessment data was also a helpful practice for my reflection on teaching. At times during this action research, I felt that my efforts in designing MBI activities were not making a difference in student learning. Upon examining the normalized learning gains and distributions of student assessment results, I was surprised at the amount of quantitative evidence that indicated that these MBI activities had been successful. This lesson for me was encouraging; I feel motivated to continue to critically analyze both quantitative and qualitative data for trends to better understand my students' progress and needs throughout the teaching and learning process.

Analyzing student responses to the CLASS instrument was also an informative process for me; I was forced to consider how each of my choices in teaching might push or pull students toward a more expert-like or novice-like view. I reflected that my previous pedagogical approach may have involved too much leading or guiding student thinking and that my students will likely benefit when I give them more autonomy in scientific inquiry with appropriate structure. I also think that I can do more to weave a variety of connections and applications into my teaching so that students experience the practicality and interconnectedness of different areas of science. I also think that a more open inquiry approach engages students on a deeper level and might drastically increase their personal interest in science.

REFERENCES CITED

Aykan, A., & Dursun, F. (2022). The Effect of Active Learning Techniques on Academic Performance and Learning Retention in Science Lesson: An Experimental Study. *Online Submission, 2*(1), 42–48.

Barbera, J., Adams, W. K., Weiman, C. E., & Perkins, K. K. (2008). Modifying and validating the Colorado learning attitudes about science survey for use in chemistry. *Journal of Chemical Education, 85*(10), 1435–1439. https://doi.org/10.1021/ed085p1435

Bodner, G. M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education, 63*(10), 873–878.

Campbell, T., Zhang, D., & Neilson, D. (2011). Model Based Inquiry in the High School Physics Classroom: An Exploratory Study of Implementation and Outcomes. *Journal of Science Education and Technology, 20*(3), 258–269.

Colburn, A. (2000). Constructivism: Science education's "grand unifying theory." *Clearing House, 74*(1), 9. https://doi.org/10.1080/00098655.2000.11478630

Dass, K., Head, M. L., & Rushton, G. T. (2015). Building an Understanding of How Model-Based Inquiry Is Implemented in the High School Chemistry Classroom. *Journal of Chemical Education, 92*(8), 1306–1314.

Dauer, J. T., & Long, T. M. (2015). Long-Term Conceptual Retrieval by College Biology Majors Following Model-Based Instruction. *Journal of Research in Science Teaching, 52*(8), 1188–1206.

Esler, W. K. (1982). Physiological Studies of the Brain: Implications for Science Teaching. *Journal of Research in Science Teaching, 19*(9), 795–803.

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics, 66*(1), 64-74.

Jenkins, J. L., & Howard, E. M. (2019). Implementation of Modeling Instruction in a High School Chemistry Unit on Energy and States of Matter. *Science Education International, 30*(2), 97–104.

Khan, S. (2007). Model-Based Inquiries in Chemistry. *Science Education, 91*(6), 877–905.

Rinehart, R. W., Duncan, R. G., Chinn, C. A., & Atkins, T. A. (2016). Critical Design Decisions for Successful Model-Based Inquiry in Science Classrooms. *International Journal of Designs for Learning, 7*(2), 17–40.

Schwarz, C. V., & White, B. Y. (2005). Metamodeling Knowledge: Developing Students' Understanding of Scientific Modeling. *Cognition & Instruction*, *23*(2), 165–205. https://doi-org.proxybz.lib.montana.edu/10.1207/s1532690xci2302_1

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the Scientific Method: Model-Based Inquiry as a New Paradigm of Preference for School Science Investigations. *Science Education*, *92*(5), 941–967.

APPENDICES

APPENDIX A

PROOF OF IRB EXEMPTION

Print Protocol Reports

Printed By: Carson, Christa

5/30/2023 11:30:39 AM

Protocol #	Reference #	Version #	Principal Investigator	Author	Protocol Type	Protocol Status	Title	Submission Date	Approval Date	Renewal Date	Expiration Date	Parent Protocol #
2022-318-EXEMPT	318	1	Carson, Christa	Carson, Christa	Original	Approved	Model-Based Inquiry in the High School Chemistry Classroom: How does MBI affect content retention?	10/31/2022	11/2/2022	11/2/2027	11/2/2027	

APPENDIX B

SAMPLE MBI ACTIVITY – RUTHERFORD GOLD FOIL SIMULATION

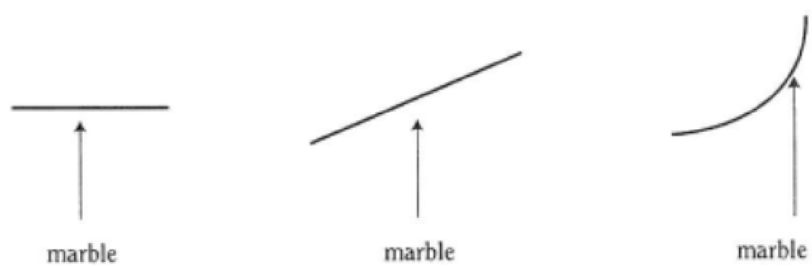
Atomic Target Practice Lab

Adapted from Flinn Scientific ChemFax materials

Pre-Lab Questions:

1. Below, draw a diagram of your "current" understanding of an atom, according to our class's journey through the timeline of atomic theory. Be sure to label components and charges within the atom.

2. Let's practice some basic physics! In the three diagrams below, a path is drawn to indicate how a rolling marble hits a surface. For each surface shape, draw the path of the marble *after* it hits the surface.



Objective:

Around the room you will see four different "atom" models, labeled A, B, C, and D. Your objective today will be to use a marble and your powers of deduction to figure out what is inside of these atoms. *In the pre-lab, you identified how some basic shapes would deflect a marble. Keep that in mind as you move through this lab!*

DO NOT PICK UP YOUR ATOM OR LOOK UNDER THE BOX.

The team that deducts the interior structure of the *most* atoms, *most accurately* will win a Nobel Prize for science! *Picking up an atom or looking under it will disqualify you from this prize!

Procedure:

1. Your group will be assigned an atom to start with. When told to do so, move to that atom's station on the floor.
2. Place your paper on top of the atom.
3. Use your marble to test the atom. Draw rolling path lines on your paper as you investigate.
4. Complete as many test rolls (from as many angles and speeds) as you need to in order to draw in the shape (in the "negative" space) of the hidden object in your atom. **You may NOT pick up the atom yet!!**

5. When you are ready, leave your atom on the floor and physically move over to a new atom and repeat steps 2-4. Please share the atoms fairly with other groups.

Post-Lab Questions:

1. Refer to your group data sheets to record final sketches of each atom here:

A	B
C	D

2. The speed of the marble was an uncontrolled variable in this experiment. How would the outcome of the test have been different if the marble speed had been faster or slower?

3. Compare the overall size of the target with the size of the marble used to probe its structure. How would the outcome of the test have been different if different sized marbles were used? Explain.
4. Read the handout about Rutherford's Gold Foil Experiment. As you read, highlight or underline key information and write short notes in the margins. *Then* continue with the following questions.
5. How did your activity model Rutherford's Gold Foil experiment? Explain what each component in your atomic target practice represented in Rutherford's experiment–be specific!
6. Evaluate the model you experimented with in class. How is this model a good representation of the experiment? How is it inaccurate?

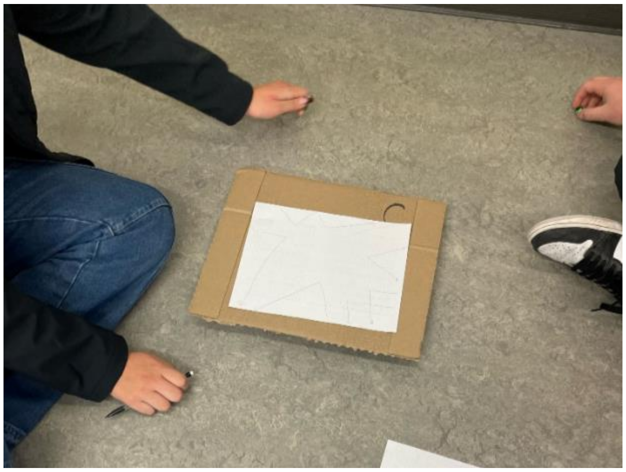
7. Rutherford's experiment can be boiled down to two key discoveries:
    - Atoms have a small, densely packed, positively charged nucleus.
    - Atoms are mostly empty space.

    Now that you know this, evaluate JJ Thomson's Plum Pudding Model. What was accurate about his model? What was inaccurate?

Lab Rubric - Atomic Target Practice Lab

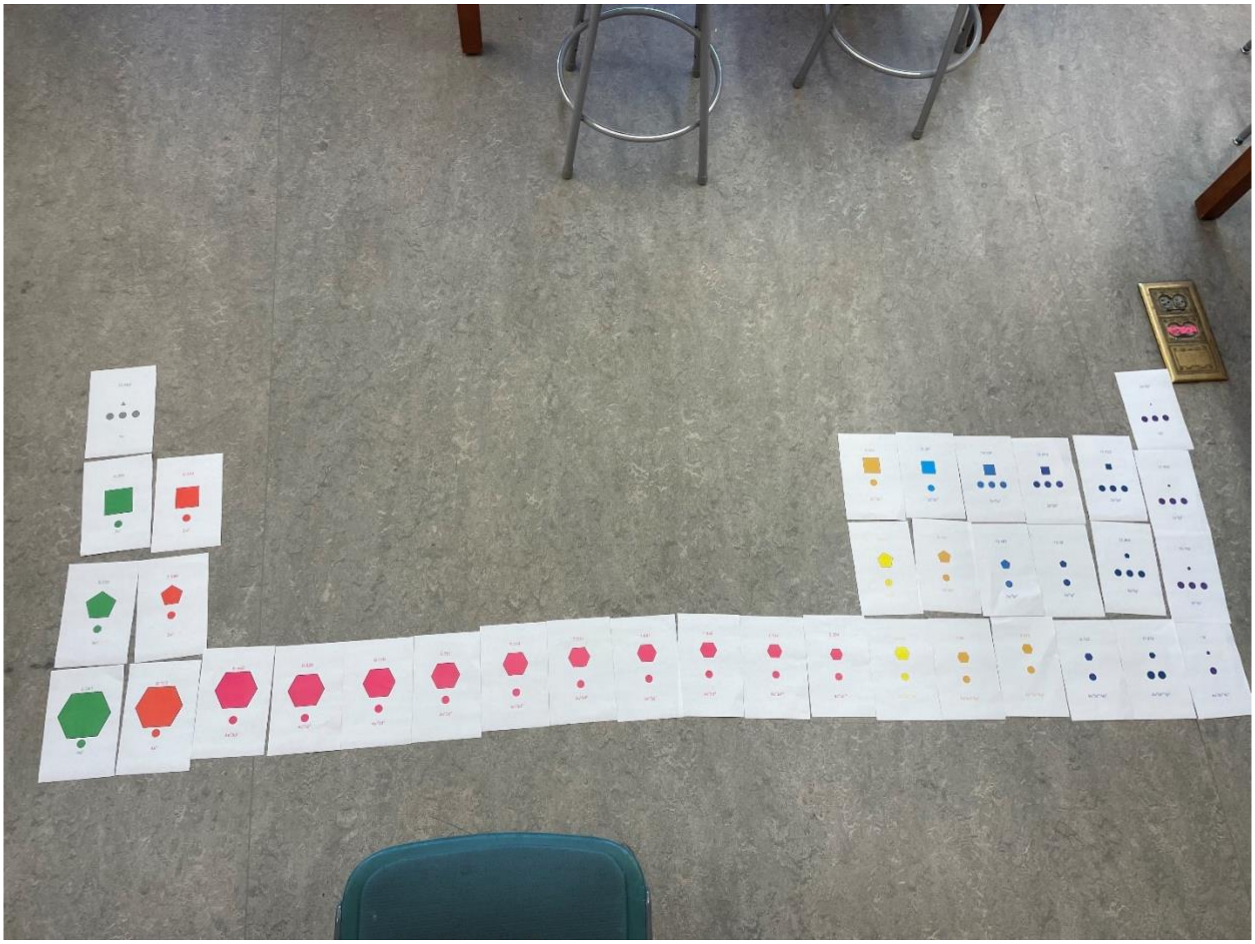
	Not Meeting	**Approaching**	**Meeting**	**Exceeding**
I can formulate, analyze and evaluate scientific explanations, hypotheses, methodologies and data.	My work is incomplete or of such poor quality that it is not legible. OR My written communication is ineffective; it is not clear what I intend to communicate, therefore my analysis and evaluation are not demonstrated.	I may have answered all of the questions in this lab, but my thoroughness was severely lacking. I did not engage critically with the concepts discussed in this lab.	In my written responses, I thoughtfully evaluated the applications and limitations of this simulation as well as the Plum Pudding Model of the atom. I thoroughly analyzed the variables in this lab when prompted.	I met all qualifications in the "Meeting" category. Additionally, I went "above and beyond" to discuss how this simulation relates to the Gold Foil experiment. I suggested additional improvements to this simulation in order for it to be a better model of Rutherford's experiment. This writing is thorough and coherent.
I can plan, prioritize, and manage time effectively to submit a completed assignment on time.	My Lab was submitted more than 2 days late, or not at all.	My Lab was submitted 1-2 days late of the final deadline.	My Lab was submitted on the due date.	My Lab was submitted more than 24 hours in advance of the due date.

Images from Atomic Target Practice Activity – Simulation of Rutherford's Gold Foil Experiment



APPENDIX C

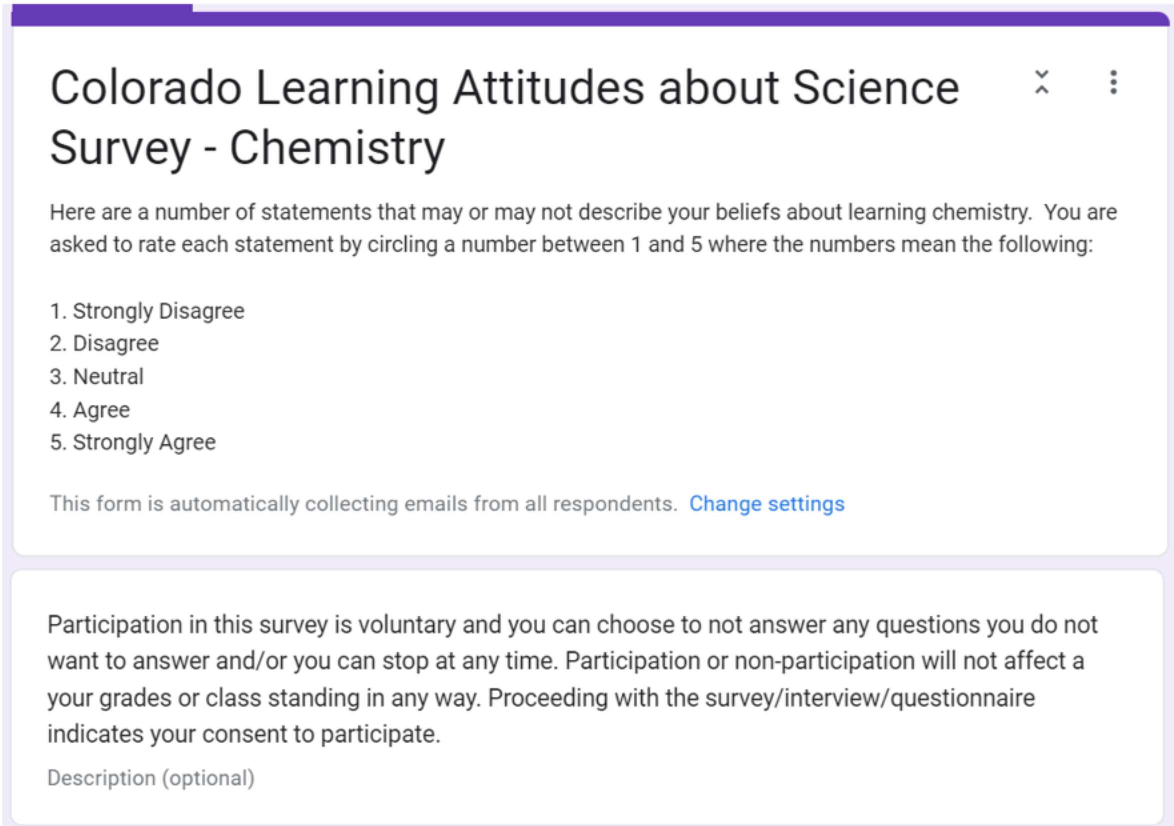
PERIODIC TABLE PUZZLE



APPENDIX D

COLORADO LEARNING ATTITUDES ABOUT SCIENCE SURVEY (CLASS)

Instructions to GoogleForm:



Colorado Learning Attitudes about Science Survey - Chemistry

Here are a number of statements that may or may not describe your beliefs about learning chemistry. You are asked to rate each statement by circling a number between 1 and 5 where the numbers mean the following:

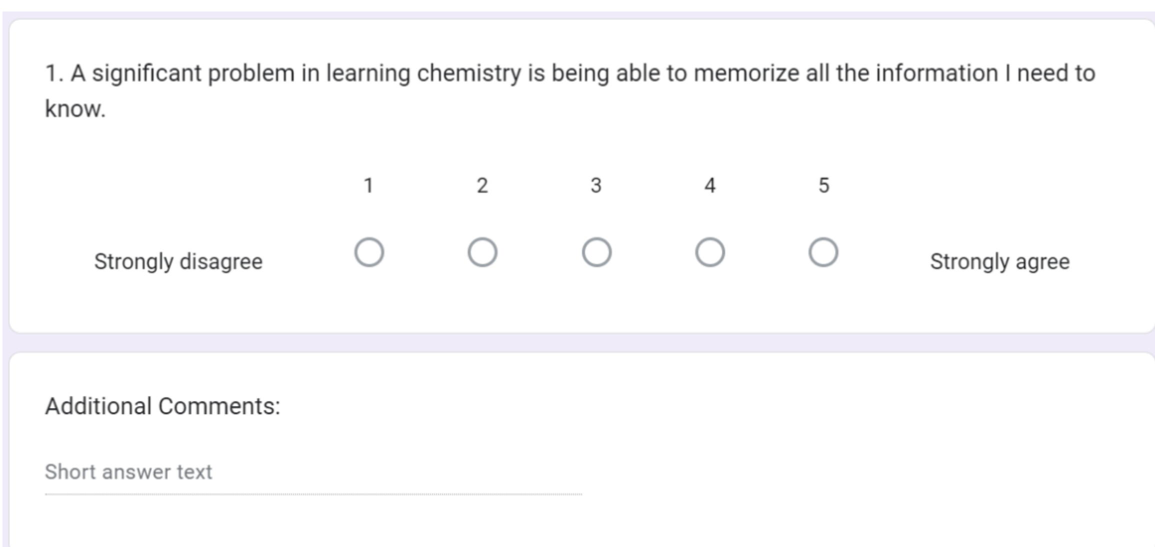
1. Strongly Disagree
2. Disagree
3. Neutral
4. Agree
5. Strongly Agree

This form is automatically collecting emails from all respondents. Change settings

Participation in this survey is voluntary and you can choose to not answer any questions you do not want to answer and/or you can stop at any time. Participation or non-participation will not affect a your grades or class standing in any way. Proceeding with the survey/interview/questionnaire indicates your consent to participate.

Description (optional)

Sample Question as shown in GoogleForm:



1. A significant problem in learning chemistry is being able to memorize all the information I need to know.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Additional Comments:

Short answer text

Full List of CLASS Prompts: (Barbera, et al., 2008)

1. A significant problem in learning chemistry is being able to memorize all the information I need to know.
2. To understand a chemical reaction, I think about the interactions between atoms and molecules.
3. When I am solving a chemistry problem, I try to decide what would be a reasonable value for the answer.
4. I think about the chemistry I experience in everyday life.
5. It is useful for me to do lots and lots of problems when learning chemistry.
6. After I study a topic in chemistry and feel that I understand it, I have difficulty solving problems on the same topic.
7. Knowledge in chemistry consists of many disconnected topics.
8. As chemists learn more, most chemistry ideas we use today are likely to be proven wrong.
9. When I solve a chemistry problem, I locate an equation that uses the variables given in the problem and plug in the values.
10. I find that reading the text in detail is a good way for me to learn chemistry.
11. I think about how the atoms are arranged in a molecule to help my understanding of its behavior in chemical reactions.
12. If I have not memorized the chemical behavior needed to answer a question on an exam, there’s nothing much I can do (legally!) to figure out the behavior.
13. I am not satisfied until I understand why something works the way it does.
14. I cannot learn chemistry if the teacher does not explain things well in class.
15. I do not expect equations to help my understanding of the ideas in chemistry; they are just for doing calculations.
16. I study chemistry to learn knowledge that will be useful in my life outside of school.
17. I can usually make sense of how two chemicals react with one another.
18. If I get stuck on a chemistry problem on my first try, I usually try to figure out a different way that works
19. Nearly everyone is capable of understanding chemistry if they work at it.
20. Understanding chemistry basically means being able to recall something you've read or been shown.
21. Why chemicals react the way they do does not usually make sense to me; I just memorize what happens.
22. To understand chemistry I discuss it with friends and other students.
23. I do not spend more than five minutes stuck on a chemistry problem before giving up or seeking help from someone else.
24. If I don't remember a particular equation needed to solve a problem on an exam, there's nothing much I can do (legally!) to come up with it.

25. If I want to apply a method used for solving one chemistry problem to another problem, the problems must involve very similar situations.
26. In doing a chemistry problem, if my calculation gives a result very different from what I'd expect, I'd trust the calculation rather than going back through the problem.
27. In chemistry, it is important for me to make sense out of formulas before I can use them correctly.
28. I enjoy solving chemistry problems.
29. When I see a chemical formula, I try to picture how the atoms are arranged and connected.
30. In chemistry, mathematical formulas express meaningful relationships among measurable quantities.
31. We use this statement to discard the survey of people who are not reading the questions. Please select agree (not strongly agree) for this question.
32. It is important for the government to approve new scientific ideas before they can be widely accepted.
33. The arrangement of the atoms in a molecule determines its behavior in chemical reactions.
34. Learning chemistry changes my ideas about how the world works.
35. To learn chemistry, I only need to memorize how to solve sample problems.
36. Reasoning skills used to understand chemistry can be helpful to me in my everyday life.
37. In learning chemistry, I usually memorize reactions rather than make sense of the underlying physical concepts.
38. Spending a lot of time understanding where mathematical formulas come from is a waste of time.
39. I find carefully analyzing only a few problems in detail is a good way for me to learn chemistry.
40. I can usually figure out a way to solve chemistry problems.
41. The subject of chemistry has little relation to what I experience in the real world.
42. There are times I solve a chemistry problem more than one way to help my understanding.
43. To understand chemistry, I sometimes think about my personal experiences and relate them to the topic being analyzed.
44. Thinking about a molecule's three-dimensional structure is important for learning chemistry.
45. It is possible to explain chemistry ideas without mathematical formulas.
46. When I solve a chemistry problem, I explicitly think about which chemistry ideas apply to the problem.
47. If I get stuck on a chemistry problem, there is no chance I'll figure it out on my own.
48. Spending a lot of time understanding why chemicals behave and react the way they do is a waste of time.

49. When studying chemistry, I relate the important information to what I already know rather than just memorizing it the way it is presented.
50. When I'm solving chemistry problems, I often don't really understand what I am doing.

APPENDIX E

STUDENT INTERVIEW PROMPTS

Participation in this interview is voluntary and you can choose to not answer any questions you do not want to answer and/or you can stop at any time. Participation or non-participation will not affect your grades or class standing in any way. Proceeding with the survey/interview/questionnaire indicates your consent to participate.

Student Interview Questions –

Prior Understanding and Perceptions of Scientific Models

1. What is a scientific model?
    a. Probe: What could a scientific model look or sound like?
2. Describe a time you used a model in science class.
    a. Probe: What science concept was it related to? How did that model help you learn about the science concept?
3. Who uses scientific models?
    a. Probe: What do they use them for?
4. Do you personally think that scientific models are useful for learning about science concepts?
    a. Probe: What positive or negative experiences do you think of when you say that?
5. Do scientific models need to be perfect to be useful?
    a. Probe: Why or why not?
    b. Probe: Describe how an imperfect model could still serve a purpose.

APPENDIX F

COLORADO LEARNING ATTITUDES ABOUT SCIENCE SURVEY -- DATA

ALL STUDENTS									
PRE			POST			SHIFT			
Agree	Neutral	Disagree	Agree	Neutral	Disagree	Agree	Disagree	Net Shift	Statement
PERSONAL INTEREST: DO STUDENTS FEEL A PERSONAL INTEREST IN /CONNECTION TO CHEMISTRY (Q's: 4,13,16,28,34,36)									
17%	17%	67%	8%	31%	62%	-9%	-5%		4. I think about the chemistry I experience in everyday life.
58%	17%	25%	64%	29%	7%	6%	-18%	EXPERT	13. I am not satisfied until I understand why something works the way it does.
8%	58%	33%	33%	25%	42%	25%	8%	EXPERT	16. I study chemistry to learn knowledge that will be useful in my life outside of school.
42%	25%	33%	25%	25%	50%	-17%	17%	NOVICE	28. I enjoy solving chemistry problems.
42%	33%	25%	64%	21%	14%	23%	-11%	EXPERT	34. Learning chemistry changes my ideas about how the world works.
58%	33%	8%	54%	23%	23%	-4%	15%	NOVICE	36. Reasoning skills used to understand chemistry can be helpful to me in my everyday life.
REAL WORLD CONNECTION: SEEING THE CONNECTION BETWEEN CHEMISTRY AND REAL LIFE (Q's: 34,36,41,43)									
42%	33%	25%	64%	21%	14%	23%	-11%	EXPERT	34. Learning chemistry changes my ideas about how the world works.
58%	33%	8%	54%	23%	23%	-4%	15%	NOVICE	36. Reasoning skills used to understand chemistry can be helpful to me in my everyday life.
36%	36%	27%	23%	8%	69%	-13%	42%	EXPERT	41. The subject of chemistry has little relation to what I experience in the real world.
17%	42%	42%	38%	8%	54%	22%	12%	EXPERT	43. To understand chemistry, I sometimes think about my personal experiences and relate them to the topic being analyzed.
PROBLEM SOLVING GENERAL: (Q's: 15,18,19,21,28,30,40,47,49,50)									
33%	8%	58%	23%	31%	46%	-10%	-12%		15. I do not expect equations to help my understanding of the ideas in chemistry; they are just for doing calculations.
50%	33%	17%	54%	38%	8%	4%	-9%	EXPERT	18. If I get stuck on a chemistry problem on my first try, I usually try to figure out a different way that works.
75%	17%	8%	85%	15%	0%	10%	-8%	EXPERT	19. Nearly everyone is capable of understanding chemistry if they work at it.
27%	36%	36%	25%	33%	42%	-2%	5%		21. Why chemicals react the way they do does not usually make sense to me; I just memorize what happens.
42%	25%	33%	25%	25%	50%	-17%	17%	NOVICE	28. I enjoy solving chemistry problems.
50%	42%	8%	38%	54%	8%	-12%	-1%	NOVICE	30. In chemistry, mathematical formulas express meaningful relationships among measurable quantities.
58%	42%	0%	69%	23%	8%	11%	8%		40. I can usually figure out a way to solve chemistry problems.
9%	55%	36%	23%	38%	38%	14%	2%	NOVICE	47. If I get stuck on a chemistry problem, there is no chance I'll figure it out on my own.
40%	40%	20%	67%	17%	17%	27%	-3%	EXPERT	49. When studying chemistry, I relate the important information to what I already know rather than just memorizing it the way it is presented.
27%	9%	64%	23%	31%	46%	-4%	-17%	NOVICE	50. When I'm solving chemistry problems, I often don't really understand what I am doing.
PROBLEM SOLVING CONFIDENCE: (Q's: 18,19,40,47)									
50%	33%	17%	54%	38%	8%	4%	-9%	EXPERT	18. If I get stuck on a chemistry problem on my first try, I usually try to figure out a different way that works.
75%	17%	8%	85%	15%	0%	10%	-8%	EXPERT	19. Nearly everyone is capable of understanding chemistry if they work at it.
58%	42%	0%	69%	23%	8%	11%	8%		40. I can usually figure out a way to solve chemistry problems.
9%	55%	36%	23%	38%	38%	14%	2%	NOVICE	47. If I get stuck on a chemistry problem, there is no chance I'll figure it out on my own.

PROBLEM SOLVING SOPHISTOCATION: (Q's: 6,24,25,28,40,47,50)									
27%	36%	36%	29%	29%	43%	1%	6%		6. After I study a topic in chemistry and feel that I understand it, I have difficulty solving problems on the same topic.
36%	36%	27%	25%	58%	17%	-11%	-11%		24. If I don't remember a particular equation needed to solve a problem on an exam, there's nothing much I can do (legally!) to come up with it.
45%	36%	18%	58%	17%	25%	13%	7%		25. If I want to apply a method used for solving one chemistry problem to another problem, the problems must involve very similar situations.
42%	25%	33%	25%	25%	50%	-17%	17%	NOVICE	28. I enjoy solving chemistry problems.
58%	42%	0%	69%	23%	8%	11%	8%		40. I can usually figure out a way to solve chemistry problems.
9%	55%	36%	23%	38%	38%	14%	2%	NOVICE	47. If I get stuck on a chemistry problem, there is no chance I'll figure it out on my own.
27%	9%	64%	23%	31%	46%	-4%	-17%	NOVICE	50. When I'm solving chemistry problems, I often don't really understand what I am doing.
SENSEMAKING/EFFORT: FOR ME (THE STUDENT) EXERTING THE EFFORT NEEDED TOWARDS SENSE-MAKING IS WORTHWHILE (Q's: 13,21,26,27,38,42,46,48,49)									
58%	17%	25%	64%	29%	7%	6%	-18%	EXPERT	13. I am not satisfied until I understand why something works the way it does.
27%	36%	36%	25%	33%	42%	-2%	5%		21. Why chemicals react the way they do does not usually make sense to me; I just memorize what happens.
17%	17%	67%	15%	31%	54%	-1%	-13%	NOVICE	26. In doing a chemistry problem, if my calculation gives a result very different from what I'd expect, I'd trust the calculation rather than going back through the problem.
73%	9%	18%	62%	23%	15%	-11%	-3%		27. In chemistry, it is important for me to make sense out of formulas before I can use them correctly.
50%	8%	42%	0%	29%	71%	-50%	30%	EXPERT	38. Spending a lot of time understanding where mathematical formulas come from is a waste of time.
17%	17%	67%	15%	23%	62%	-1%	-5%		42. There are times I solve a chemistry problem more than one way to help my understanding.
80%	10%	10%	77%	15%	8%	-3%	-2%		46. When I solve a chemistry problem, I explicitly think about which chemistry ideas apply to the problem.
0%	36%	64%	8%	38%	54%	8%	-10%	NOVICE	48. Spending a lot of time understanding why chemicals behave and react the way they do is a waste of time.
40%	40%	20%	67%	17%	17%	27%	-3%	EXPERT	49. When studying chemistry, I relate the important information to what I already know rather than just memorizing it the way it is presented.
CONCEPTUAL CONNECTIONS: UNDERSTANDING THAT CHEMISTRY IS COHERENT AND IS ABOUT MAKING-SENSE, DRAWING CONNECTIONS, AND REASONING NOT MEMORIZING. MAKING SENSE OF MATH (Q's: 6,7,15,24,37,38,50)									
27%	36%	36%	29%	29%	43%	1%	6%		6. After I study a topic in chemistry and feel that I understand it, I have difficulty solving problems on the same topic.
8%	42%	50%	8%	31%	62%	-1%	12%	EXPERT	7. Knowledge in chemistry consists of many disconnected topics.
33%	8%	58%	23%	31%	46%	-10%	-12%		15. I do not expect equations to help my understanding of the ideas in chemistry; they are just for doing calculations.
36%	36%	27%	25%	58%	17%	-11%	-11%		24. If I don't remember a particular equation needed to solve a problem on an exam, there's nothing much I can do (legally!) to come up with it.
18%	36%	45%	17%	33%	50%	-2%	5%		37. In learning chemistry, I usually memorize reactions rather than make sense of the underlying physical concepts.
50%	8%	42%	0%	29%	71%	-50%	30%	EXPERT	38. Spending a lot of time understanding where mathematical formulas come from is a waste of time.
27%	9%	64%	23%	31%	46%	-4%	-17%	NOVICE	50. When I'm solving chemistry problems, I often don't really understand what I am doing.
CONCEPTUAL LEARNING: UNDERSTANDING AND APPLYING A CONCEPTUAL APPROACH AND REASONING IN PROBLEM SOLVING, NOT MEMORIZING OR FOLLOWING PROBLEM SOLVING RECIPES (Q's: 1,6,7,12,24,25,47)									
33%	33%	33%	71%	14%	14%	38%	-19%	NOVICE	1. A significant problem in learning chemistry is being able to memorize all the information I need to know.
27%	36%	36%	29%	29%	43%	1%	6%		6. After I study a topic in chemistry and feel that I understand it, I have difficulty solving problems on the same topic.
8%	42%	50%	8%	31%	62%	-1%	12%	EXPERT	7. Knowledge in chemistry consists of many disconnected topics.
36%	45%	18%	46%	15%	38%	10%	20%	EXPERT	12. If I have not memorized the chemical behavior needed to answer a question on an exam, there's nothing much I can do (legally!) to figure out the behavior.
36%	36%	27%	25%	58%	17%	-11%	-11%		24. If I don't remember a particular equation needed to solve a problem on an exam, there's nothing much I can do (legally!) to come up with it.
45%	36%	18%	58%	17%	25%	13%	7%		25. If I want to apply a method used for solving one chemistry problem to another problem, the problems must involve very similar situations.
9%	55%	36%	23%	38%	38%	14%	2%	NOVICE	47. If I get stuck on a chemistry problem, there is no chance I'll figure it out on my own.

ATOMIC-MOLECULAR PERSPECTIVE OF CHEMISTRY (Q's: 2, 11,17,29,33,44)									
36%	18%	45%	**46%**	38%	15%	**10%**	-30%	**EXPERT**	2. To understand a chemical reaction, I think about the interactions between atoms and molecules.
25%	33%	42%	**46%**	23%	31%	**21%**	-11%	**EXPERT**	11. I think about how the atoms are arranged in a molecule to help my understanding of its behavior in chemical reactions.
75%	17%	8%	**57%**	29%	14%	**-18%**	6%	**NOVICE**	17. I can usually make sense of how two chemicals react with one another.
8%	50%	42%	**7%**	43%	50%	**-1%**	8%	**NOVICE**	29. When I see a chemical formula, I try to picture how the atoms are arranged and connected.
36%	64%	0%	**50%**	42%	8%	**14%**	8%		33. The arrangement of the atoms in a molecule determines its behavior in chemical reactions.
27%	64%	9%	**31%**	54%	15%	**3%**	6%		44. Thinking about a molecule's three-dimensional structure is important for learning chemistry.
REMAINING STATEMENTS FOR WHICH THERE IS A CONSISTENT EXPERT PERSPECTIVE (Q's: 3,9,14,20,22,23,32,35,45)									
67%	25%	8%	**83%**	17%	0%	**17%**	-8%	**EXPERT**	3. When I am solving a chemistry problem, I try to decide what would be a reasonable value for the answer.
50%	33%	**17%**	23%	31%	**46%**	-27%	**29%**	**EXPERT**	9. When I solve a chemistry problem, I locate an equation that uses the variables given in the problem and plug in the values.
100%	0%	**0%**	100%	0%	**0%**	0%	**0%**		14. I cannot learn chemistry if the teacher does not explain things well in class.
25%	33%	**42%**	25%	42%	**33%**	0%	**-8%**		20. Understanding chemistry basically means being able to recall something you've read or been shown.
33%	8%	58%	**36%**	36%	29%	**2%**	-30%	**EXPERT**	22. To understand chemistry I discuss it with friends and other students.
17%	17%	**67%**	15%	62%	**23%**	-1%	**-44%**	**NOVICE**	23. I do not spend more than five minutes stuck on a chemistry problem before giving up or seeking help from someone else.
36%	27%	**36%**	31%	31%	**38%**	-6%	**2%**		32. It is important for the government to approve new scientific ideas before they can be widely accepted.
25%	33%	**42%**	8%	33%	**58%**	-17%	**17%**	**EXPERT**	35. To learn chemistry, I only need to memorize how to solve sample problems.
42%	42%	17%	**50%**	29%	21%	**8%**	5%		45. It is possible to explain chemistry ideas without mathematical formulas.