STUDENTS' DEVELOPMENT AND USE OF MODELS TO EXPLAIN ELECTROSTATIC INTERACTIONS

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ABSTRACT

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The National Research Council (2012) recently published *A Framework for K-12 Science Education* that describes a vision for science classrooms where students engage in three dimensions—scientific and engineering practices, crosscutting concepts, and disciplinary core ideas—to explain phenomena or observations they can make about the universe around them. This vision of science instruction is a significant shift from current classroom instruction. This dissertation provides detailed examples of how students developed and used models to build causal explanations of phenomena. I co-taught classes that focused on having students develop and revise models of electric fields and atomic structure using a curriculum that was designed to align with the three-dimensional vision of learning. I developed case studies of eleven students from these classes. I analyzed the students' responses and interviewed the students throughout the school year. By comparing and contrasting the analysis across the analysis of students' interviews, I identified four themes: 1) students could apply their ideas to explain novel and abstract phenomena; 2) students struggled to connect changes in their atomic models to evidence, but ended up with dynamic models of atomic structure that they could apply to explain phenomena; 3) students developed models of atomic structure that they applied to explain phenomena, but they did not use models of electric fields in this way; and 4) too much focus on details interfered with students' ability to apply their models to explain new phenomena. This dissertation highlights the importance of focusing on phenomena in

classrooms that aim at aligning with three-dimensional learning. Students struggled to focus on specific content and apply their ideas to explain phenomena at the same time. In order to apply ideas to new context, students had to shift their focus from recalling ideas to applying the ideas they do have. A focus on phenomena allowed students to show their understanding through applying their ideas to new context. During this transition, students struggled, and in particular, had a hard time using evidence from experiments to justify the changes they made to their models of atomic structure. While the changes students made looked unproductive at times, by the end of the semester, students had developed models of atomic structure that incorporated relationships among charged components that they could apply to explain complex phenomena. Asking students to explore and evaluate their own ideas supported their development of models that they could apply to explain new context they experience in their future.

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Chapter 1: Overview

Vision for Education

What would happen if we mixed all these together? This was a common question students would ask while working on chemical reaction labs in my science classes. Students wanted to deviate from the instructions they were given and test their own mixtures. They were not doing this to cause trouble, they were simply curious and wanted to explore additional possibilities. Children are curious and explore the world around them. John Medina, (2008) a developmental molecular biologist specializing in the brain, highlights this point in his book, *Brain Rules*, which summarizes key theories about how the brain functions and implications for work and school. He ends the book with what he described as the most important rule: Humans are “powerful and natural explorers” (p. 261). He illustrates the natural curiosity and systematic exploration seen in infants, young children, and some exemplary adults. For example, he described how long it took his son, a toddler, to move a few steps along the sidewalk because he had to stop and examine every crack, weed, and bug along the way. His son was fascinated by everything he encountered and even found excitement in something as simple as a blade of grass growing in the crack between two slabs of concrete. Exploration is something humans naturally do and enjoy. Through centuries of exploration and systematic study, humans have developed a wealth of information about the world around us, our own past, and a range of complex questions. As Carl Sagan said, “We are a way for the cosmos to know itself” (1980).

Dewey (1916) argued that part of the necessity of a formal education system for all students is to continue the society. To continue to develop as a society, students need exposure to some of the foundational ideas that have been developed through systematic human exploration. However, the wealth of information that has been collected and developed makes it impossible to study all of it. Instead, the goal is to give students both a background in core ideas and also to refine the skills and tools that will allow students to solve new problems and add to our understanding of the universe when they leave the school system.

> A belief in transfer lies at the heart of our educational system. Most educators want learning activities to have positive effects that extend beyond the exact conditions of initial learning. They are hopeful that students will show evidence of transfer in a variety of situations; for example, from one problem to another within a course; from one course to another; from one school year to the next; and from their years in school to their years in the workplace. (Bransford & Schwartz, 1999, p. 1)

We don't need students who can recall all of the developments from human exploration; we need students who can use that exploration to explain phenomena and solve new problems, because as society grows, we are constantly facing new problems. For example, students do not need to know how to engineer a car—that has already been done. However, with rising carbon dioxide levels impacting global climate, car engineers need to solve new problems like how to make the car more fuel-efficient or how to design a car that runs on renewable and cleaner energy sources.

Unfortunately, schools are not always places where students' natural curiosity is encouraged. Medina (2008) points out that the natural curiosity and drive to explore is often replaced through school with a focus on doing what is necessary to get a desired grade. In many classrooms, students are focused on memorizing facts and formulas that will appear on an assessment. What would it look like if instead, schools supported students' natural curiosity and exploration?

Ultimately, I am interested in studying learning environments that foster students' natural curiosity and encourage students to participate in exploration about their world through science rather than replace curiosity and exploration with a focus on grades. In this dissertation study, I am analyzing how students' ideas and scientific practices developed in classrooms that used a curriculum, called the Interactions Curriculum, that is designed to include students as active participants in the practices of science. Students ask questions, gather and analyze evidence, and develop their own explanations and models of phenomena. This curriculum is being developed to align with new science education standards that aim at defining the practices students should be participating in as well as the ideas they should develop. I am interested in how students develop their understanding of phenomena and the practices of science throughout the curriculum and how students apply those ideas to explain new scenarios, answer new questions, and solve new problems.

School Science Standards

In this section, I provide an overview of previous science standards. In the next section, I review the recent work to define new standards. I provide this overview because this dissertation studies student ideas in a classroom that used a curriculum that was developed based on the new standards and shares the theories of learning that were used to develop those new standards. Therefore, these standards provide an important context for this study.

Previous Science Standards

History and policy

Previous national guidelines for science standards and curricula called for having students participate in scientific "inquiry." These documents argued that students should learn the process of science as well as general problem-solving and thinking skills (American Association for the Advancement of Science [AAAS], 1993; National Research Council [NRC], 1996, 2007; Pellegrino & Hilton, 2012). For example, students should be asking questions, conducting investigations, gathering evidence, forming explanations, and solving problems. These documents often refer to using scientific "inquiry" to study science and develop "scientific literacy" (AAAS, 1993; NRC, 2007). Unfortunately, evaluations of these earlier standards documents found that they were unorganized and lacked the coherence to support students in developing complete and useable understanding of topics (Schmidt, Wang, & McKnight, 2005).

Classroom practice

In these policy documents, terms like "inquiry" and "scientific literacy" were used differently by different stakeholders (Champagne & Lovitts, 1989; DeBoer, 2000). Due to confusion about these vague terms, teachers often implemented them differently, meaning that classroom practices often did not reflect the guidelines set by national organizations (Colburn, 2000). In many classrooms, science education focused on learning discrete facts rather than on a larger understanding of what science is and how it is developed (NRC, 2012). Science teachers often followed textbooks. However, when Keisdou and Roseman (2002) reviewed nine of the most common middle school textbooks, they found that, in general, key ideas were often buried in details; ideas did not build across units; students were not given a purpose for completing a unit or the purpose was uninteresting or disconnected from the topics of the unit; and students were not engaged in enough phenomena to ground the ideas they were learning.

Outcomes of science education

Given these classroom practices, on average, students in the United States are not competitive with students from other industrialized countries on international assessments of science learning (NRC, 2007; Schmidt, et al., 2005). Additionally, student achievement in science varies greatly depending on factors such as socioeconomic status, school, race, and home language. Even students who seem to do well in lecture- and text-based classes may not be learning as well as we hope. Based on interviews with two students in a physics lecture class, Hammer (1989) found that, despite performing well on course assessments and earning high marks in the course, both students struggled to understand physics and had a hard time connecting what they learned to real-world examples. Though people involved in the standards movements have argued that students should develop a deeper understanding of science so that they can apply those ideas to make decisions and solve new problems, the curriculum materials and approaches used in most classrooms are not meeting these goals.

Defining New Expectations for Science Education

In this section, I provide a brief overview of some of the conceptual foundations for defining new science standards. This context is important as these same conceptual foundations underlie the development of the curriculum used in this study. I summarize how proficiency in science and understanding of how students learn science were both used to inform a framework for defining new standards. I then provide an overview of the framework and the structure of the resulting science standards.

Proficiency in science

Experts' knowledge is organized around conceptual ideas that allow them to notice meaningful patterns, identify important aspects of problems, efficiently recall related aspects of their knowledge, and apply that knowledge to form explanations and solve new problems (NRC, 1999). It is helpful to assess expert knowledge not because the goal is to turn all students into experts but because "the study of expertise shows what the results of successful learning look like" (p. 31). Thus, analyzing what experts do is helpful for defining what science proficient students should be able to do. Based on this, *Taking Science to School* (NRC, 2007) stated:

> Students who are proficient in science:
> 1. know, use, and interpret scientific explanations of the natural world;
> 2. generate and evaluate scientific evidence and explanations;
> 3. understand the nature and development of scientific knowledge; and
> 4. participate productively in scientific practices and discourse. (p. 36)

These strands of science proficiency are intertwined. Research has shown that students need to learn these aspects together, in order to build understanding that they can apply. Separating the different aspects of science leads students to view science as a list of facts (NRC, 2007, 2012). Thus, science education should help students understand both the processes of science as well as the body of knowledge that is developed through those processes. Developing a deep understanding of the processes of science as well as the body of science knowledge leads to "knowledge-in-use" (de Jong & Ferguson-Hessler, 1996). Knowledge-in-use describes knowledge that students are able to use and apply to explain phenomena and solve a range of problems.

How students learn science

Focusing only on the outcome of successful education ignores the processes that need to occur in the classroom as well as the ideas that learners bring into the classroom. Early science education reform efforts fell into this trap: Curricula writers focused on expert knowledge without also using understandings of how people learn (NRC, 2007).

The brain develops throughout life by developing new connections between neurons (Medina, 2008). New experiences lead to the development of new neural connections by attaching new ideas to prior ideas that have already been developed. While the brain is developing new neural connections, neural connections that are not used get removed, and neural connections that are repeated regularly become more efficient and resistant to changes (Medina, 2008). The connection between new and existing ideas is an important consideration for designing learning environments and curricula. As a learner encounters new experiences, the brain develops neural connections to link these new experiences to existing concepts. Therefore, it is important that curricula and instruction plan for how ideas build from one topic or unit to the next. This need to build on previous topics has led to an emphasis on coherence. "Calls for coherent curriculum argue for sensible connections and coordination between the topics that students study in each subject within a grade and as they advance through the grades" (Newmann, Smith, Allensworth, & Bryk, 2001, p. 298).

Prior knowledge

Because the brain develops new ideas by attaching them to existing ideas, it is important to pay attention to ideas that students have developed before entering a classroom. Research in science education has highlighted the range of ideas students bring into science classrooms before learning particular topics (e.g., Driver, Guesne & Tiberghien, 1985; Driver, Rushworth, Squires, & Wood-Robinson, 1994). In general, these "misconceptions" are seen as stable ideas that are well-established and often maintained during instruction or returned to after instruction. In fact, studies indicate that even after significant science instruction, earlier naïve ideas are still present, just suppressed by newer knowledge (Shtulman & Valcarcel, 2012). There is debate about how to treat these naïve ideas. While it could seem logical that they would be problematic and should therefore be corrected, some argue that rather than trying to correct, remove, or replace student "misconceptions," these naïve ideas, which are based in students' experiences with the world, could be seen as resources for learning rather than as problems (e.g. Hammer, 1996; NRC, 2007, 2012; Smith, diSessa, & Roschelle, 1993). Since new ideas are attached to previous ideas, it is important that people have a chance to reflect on their current ideas before learning new ideas related to that topic (NRC, 1999).

Sociocultural perspectives on learning

Sociocultural perspectives on learning highlight that the development of connections across ideas does not happen individually. Vygotsky (1980) proposed that students use discussions with others as a way to rehearse ideas that later become internalized. Students practice and clarify their ideas as they state them out loud to others. They also receive feedback from their peers and the teacher, which they can use to evaluate and develop their ideas. Students can also use the ideas they hear others sharing to reflect on and clarify their own ideas. Ideally, students also develop a consensus as a class.

Lave and Wenger (1991) argued that students learn as they become integrated into a community of practice. A community of practice develops and evolves as members of that community learn from each other. Students start at the periphery of the community and become accepted as members through guidance and interactions with experts. However, this view of a classroom community places students, at least initially, as outsiders. Instead, Calabrese Barton and Tan (2010) argued for classrooms where students develop their own community. They argued that, "learning is less about practicing the routines of knowledgeable others than it is about recreating those practices in socially and culturally situated ways that confer on one more (or less) agency with which to participate across communities" (pp. 190-191). I believe a classroom could be seen as a community of practice, where the students are the central members and come to an agreement on ideas and practices as they work with and learn from each other. By gathering evidence and using that evidence to evaluate their ideas, students should form a consensus with each other about phenomena in the world around them. Since this is the same process scientists use, the classroom community grows to incorporate scientific practices.

Framework for K-12 Science Education and Next Generation Science Standards

In an attempt to support students in becoming proficient in science and build on research about how students learn science, the NRC (2012) published *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (Framework)*. The *Framework* articulates disciplinary core ideas, described as foundational ideas that are both useful for describing a range of phenomena and can develop in sophistication over time. For example, students could work on the disciplinary core idea of *Motion and stability: Forces and interactions* by observing moving objects starting in early elementary school then study these same ideas to describe the motion of more objects across different school years and eventually incorporate using mathematical equations to describe motion in high school. Rather than learning a list of disconnected ideas from year to year, students would study the same core ideas year after year, building an integrated understanding of how that core idea relates to a range of phenomena. The *Framework* identifies three to four core ideas for each of the scientific disciplines of physical sciences, life sciences, and earth sciences. These disciplines focus on different systems and phenomena, but use the same overlapping concepts and practices.

In order to help students understand the connections across scientific disciplines, the *Framework* also describes crosscutting concepts and scientific and engineering practices. Crosscutting concepts are ideas and foci that scientists use across different disciplines that help provide different perspectives to apply when examining phenomena. For example, it may be useful to think about changes in energy when studying growth of living things, chemical reactions, and weather. Alternatively, you could study these same problems by looking for patterns. Thus, energy and patterns are both crosscutting concepts. The scientific and engineering practices are also used across different science disciplines. The practices describe how scientists develop core ideas and engineers apply these ideas to develop solutions.

The *Framework* describes a vision for three-dimensional learning, in which core ideas, crosscutting concepts, and scientific and engineering practices are integrated together throughout instruction, to define expectations for what students will be able to do at the end of instruction, and to develop assessment tasks. Students should also be using the three dimensions throughout classroom instruction in order to develop their understanding of science and to explain observations in the world around them.

The goal of preparing students to continue to learn throughout their lives means science classes need to run differently. The *Framework* lays out a vision for what this looks like. Students should be integrating disciplinary core ideas, crosscutting concepts, and scientific and engineering practices in order to explain phenomena and solve problems. This approach to teaching science represents a significant change for science teachers. In current science classes, students are not engaged in scientific and engineering practices. Many textbooks and curricula include a separate unit that provides a review of general lab procedures and then a series of chapters that focus on content. When practices, like *Developing and using models*, are addressed, students are generally not engaged in the practice themselves. For example, students may be presented with models. In contrast, the vision laid out in the *Framework* (NRC, 2012) is that students should be doing the practices, not just hearing about them. Students should be the ones doing things like analyzing data, supporting claims with evidence, and developing models. It is not enough to read about what others did or how it should be done. Integrating disciplinary core ideas, crosscutting concepts, and scientific and engineering practices to explain phenomena means that students are active participants in the scientific and learning processes.

It is important to study classrooms, curricula, and the development of students' ideas in classrooms that are aligned with the vision of science education laid out in the *Framework* (NRC, 2012). The drastic change described in the *Framework* ideally will result in students who have an understanding of science that will support solving new problems. Given that this is such a drastic change in what students do in science classes, it is important to assess how their ideas develop in that environment. In this dissertation, I will analyze how students use the ideas and practices they learn to develop models and how students use those models to explain observations and solve new problems.

Dissertation Overview

In this dissertation, I will study how students' ideas developed in a classroom that used a curriculum designed to align with the vision of three-dimensional learning described in the *Framework* (NRC, 2012). I will analyze how students integrate the disciplinary core ideas, crosscutting concepts, and scientific and engineering practices. The *Framework* describes ambitious goals and significant changes for science classrooms. What does this look like and what are the outcomes of this type of instruction? My dissertation is part of a larger design-based research project. Our team developed a high school introductory physical science curriculum designed to align with the *Framework* (NRC, 2012) and NGSS (NGSS Lead States, 2013). In the curriculum, students develop their own models to explain observations of matter and its interactions.

In order to study how students are developing, using, and integrating the three dimensions, I need to select particular elements of each dimension to focus on. In this dissertation, I will focus on the disciplinary core idea of matter and its interactions, the crosscutting concept of cause and effect, and the scientific practice of developing and using models. This dissertation will explore how students develop and use models of electric fields and atomic structure in order to provide causal accounts of various electrostatic phenomena.

I co-taught four sections of 9th grade physical science classes using the curriculum, which was designed to align to three-dimensional learning, include scaffolds to support students in scientific practices including the practice of developing and using models. I randomly selected

11 students from these classes and developed case studies of these students, based on interview responses and models they developed throughout the curriculum. I focused on classes I co-taught to assess how students' ideas developed when the curriculum was implemented with fidelity to the vision of three-dimensional learning laid out in the *Framework* (NRC, 2012).

Chapter 2: Foundational Concepts and Literature Review

Foundational Concepts for Study

This chapter begins with the research questions for this dissertation. I then review the research focus for looking at the topics I am focusing on and the theoretical foundation that align with and inform this study and the dimensions of the *Framework* I am focusing on. I then describe the curriculum that was used including a review of the curriculum development, learning environment, and scaffolding included in the curriculum.

Research Questions

1. How do students' models of electric fields and atomic structure change over time through instruction based on a scaffolded curriculum designed to align with three-dimensional learning?
    a. Are the models students develop retained after instruction?
2. How do students use their evolving models from curriculum designed to align with three-dimensional learning to explain electrostatic phenomena?
3. How do students apply their evolving models of atomic structure to novel phenomena?

Research Focus

Matter and its Interactions

I am focusing on electrostatic phenomena in order to evaluate students' models of atomic structures and electric fields. These core ideas are powerful ideas for explaining a range of phenomena. One of the disciplinary core ideas identified in the *Framework* (NRC, 2012) is matter and its interactions. The driving question for this idea is, "How can one explain the structure, properties, and interactions of matter?" (NRC, 2012, p. 106). This question covers a huge range of observations and can develop from simple observable characteristics to deeper unobservable causes. For example, you could examine the difference between a plastic spoon and a metal spoon (Rogat, et al., 2011). You could compare the function and characteristics of these spoons. Test them in different situations to note how they interact with magnets or the sound they make when banged on the counter. You could also observe what happens to the spoons when placed in different solutions—they may appear to dissolve or rust. Through more and more systematic experiments you could eventually describe the different observations using the unobservable structure of the different materials. Over years of speculation and research, science has developed the atomic theory of matter—the idea that all materials are made of tiny, invisible particles called atoms. The interactions among atoms and the changes of energy associated with those interactions accounts for a wide range of observations—ranging from the everyday, such as water boiling in a pot and what happens when you throw salt in when making pasta, to scientific procedures like collecting magnetic resonance spectra of materials. This ability to explain a wide variety of phenomena is what makes an atomic model that includes the relationships between charged sub-atomic particles so powerful (Stevens, Delgado, & Krajcik, 2010). In fact, Feynman (1989) famously said,

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic *fact*, or whatever you wish to call it) that *all things are made of atoms — little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.* In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied. (p. 1-2)

Atoms are made of smaller electrically charged sub-atomic particles. The interactions between the positively charged particles and the negatively charged particles within atoms cause the attractions and repulsions between the atoms. When the attractive and repulsive forces are balanced, potential energy is minimized and the atoms are in a stable arrangement. Changing the atoms from the stable arrangements requires energy to be transferred from the surroundings and when atoms form a stable arrangement, energy is transferred out to the surroundings.

While the idea of atoms is extremely powerful for explaining a range of phenomena, in traditional classrooms, students do not develop an atomic model that they can use to explain observations and solve problems. Instead students are shown images to represent atomic structure. Moreover, most curricula do not focus on electrostatic interactions among sub-atomic particles (Nahum, Mamlok-Naaman, Hofstein, & Krajcik, 2007). As such, students generally have simple, incomplete models of atomic structure that do not include electric interactions to explain why matter sticks together, and students struggle to connect their models with observations (Griffiths & Preston, 1992; Stevens et al., 2010). Park and Light (2009) found that students tend to continue to use a planetary model of atoms—in which negative electrons are represented orbiting a positive nucleus in set paths—even when this model is no longer useful for explaining phenomena (Park, & Light, 2009). Harrison and Treagust (1996) noted that students tended to select and use more concrete models of atomic structure rather than vague but more scientifically accurate ideas. Based on their interviews, Harrison and Treagus (2000) then followed how students' ideas about atoms developed in a class where the teacher discussed the strength and limitations of key models. They reported that a particularly strong student was able to develop and use multiple atomic models. However, in the interview and data presented, they focus on the students' concept of atomic structure and do not review how this student related his ideas about atomic structure to explain macroscopic phenomena. Further, these studies have analyzed how students interpret and work with canonical models that are presented in textbooks and by the teacher. Thus, there is a need for research that evaluates different approaches to teaching atomic structure beyond presenting and discussing canonical representations to see how to best support students in developing and using more powerful atomic models that include electrostatic relationships.

While an atomic model that includes electrostatic interactions is incredibly useful for explaining and making predictions about a wide range of phenomena, many electrostatic interactions can also be described at the macroscopic scale without invoking an atomic model. Electric fields, gravitational fields, and magnetic fields—collectively force fields—explain how objects and particles interact without contact. Fields can transfer energy through space and interact with particles depending on the properties of the particle. An object or particle with an electric charge interacts with the electric field and, therefore, multiple electrically charged objects also interact with each other through the electric field. While developing the idea of force fields is an important disciplinary idea in the *Framework* (NRC, 2012), it was not a significant topic in earlier national science standards (AAAS, 1993; NRC, 1996). Little research has been done on how high school students interpret representations of fields or develop an understanding of fields. The few articles in this area focus on introducing fields in order to help students understand other topics (e.g., Brunt & Brunt, 2012) or as examples of questions and misunderstandings students have about interactions between matter and energy (e.g., Van

Heuvelen, 1983). In studies of college students, Furió and Guisasola (1998) observed that students tended to rely on other ideas to explain electrostatic interactions rather than using electric fields, even at advanced levels.

Atomic structure and electric fields are models that are powerful and useful for explaining and making predictions about a range of phenomena. However, research shows that given current common instructional practices, students generally are not able to apply these ideas to explain phenomena or make predictions about new phenomena. Students are not able to apply the ideas they learned nor are they able to transfer their ideas to new context.

Preparation for Future Learning

As mentioned in Chapter 1, a general goal of education is that students are able to transfer what they have learned to new problems, new classes, and beyond school. However, we know students struggle to apply models of atomic structure to explain phenomena. Ideally students would be developing models that they can use to explain phenomena they are studying in class and to transfer to new context and new phenomena that they encounter outside of the classroom. Unfortunately, early studies of transfer indicated that it is difficult to find evidence that students apply their learning to new situations (NRC, 1999; Bransford & Schwartz, 1999). Thus, Bransford and Schwartz (1999) proposed "preparation for future learning" as an alternative way to look for evidence of transfer. Studies of preparation for future learning have shown that learners who could approach new problems by applying their background knowledge flexibly were able to develop more meaningful solutions to novel problems (Bransford & Schwartz, 1999; Schwartz & Martin, 2004). Bransford and Schwartz (1999) found that when 5th grade students and college students were asked to develop a solution to an unfamiliar problem, both groups were unable to develop reasonable solutions. This seems to indicate that additional education does not support a student's ability to transfer their knowledge to solve new problems. However, the college students were able to better identify what they needed to know in order to develop a solution and were able to ask questions that, if answered, would have led to better solutions. Neither group knew what to do, but the college students were more prepared to seek out and take in new information that would lead to more complete solutions. Schwartz and Martin (2004) used the idea of preparation for future learning to develop curriculum and learning environments. They found that if 9th grade students in a math class were given time to explore problems and invent their own solutions before instruction from the teacher, the students were better able to understand these new concepts. These 9th grade students performed better than college students who had learned the same information through lectures. Additionally, the 9th grade students retained the information when they completed a delayed post-test a year later. Giving students time to explore their own thinking and their own solutions, even if incorrect, helped prepare students to learn the content when presented later by the teacher.

Three-Dimensional Learning

The idea of preparation for future learning aligns with the *Framework* (NRC, 2012).

> The overarching goal of our framework for K-12 science education is to ensure that by the end of 12th grade, *all* students have some appreciation of the beauty and wonder of science; possess sufficient knowledge of science and engineering to engage in public discussions on related issues; are careful consumers of scientific and technological information related to their everyday lives; are able to continue to learn about science outside school; and have the skills to enter careers of their choice, including (but not limited to) careers in science, engineering, and technology. (p. 1)

In other words, the goal is that students will transfer what they have learned to new context throughout their lives.

The *Framework* builds on research of how students learn and engage in science in classrooms and informal settings (NRC, 1999, 2007). Based on the review of past research, the *Framework* takes the stance that students need to learn both the practices and knowledge of science through science instruction. The *Framework* defines three dimensions—disciplinary core ideas, scientific and engineering practices (practices), and crosscutting concepts—as a means to lay out a vision for science instruction that integrates learning about the body of knowledge of science and how scientists develop and revise those ideas. The *Framework* emphasizes, “in order to facilitate students’ learning, the dimensions must be woven together in standards, curricula, instruction, and assessments” (NRC, 2012, p. 30). The Next Generation Science Standards (NGSS, NGSS Lead States, 2013) have been defined to align with the *Framework* by describing standards in the form of Performance Expectations (PEs) that describe both what students should know and practices how students could demonstrate their understanding. Each PE blends a disciplinary core idea, a scientific and engineering practice, and a crosscutting concept. Thus, on assessments students should be using a combination of disciplinary core ideas, practices, and crosscutting concepts to demonstrate their understanding. Additionally, the *Framework* emphasizes that on assessments and in instruction, the work students are doing should be organized around phenomena. Phenomena are observable and repeatable events. The early work that has been started based on the *Framework* and NGSS has emphasized the role of using anchoring phenomena when writing assessments and lessons (DeBarger, Penuel, & Harris, 2013; Lo, Krist, Reiser, Novak, & Lo, 2014). Thus, in a classroom, students are developing and using the core ideas, practices, and crosscutting concepts to explain a phenomenon they are studying and on assessments, students are applying those same core ideas, practices, and crosscutting concepts to answer questions in the context of a new phenomenon.

The *Framework* and NGSS described the vision and goals of three-dimensional learning, but these are theoretical documents. Curricula need to be designed that aligns with this new vision, and the resulting learning environments need to be analyzed and evaluated. We need to analyze how students integrate the three dimensions, what forms of support students need as they are learning to do this work, and how students respond to three-dimensional assessments. In this dissertation, I am studying how students develop in a classroom using a curriculum that was designed to align with the *Framework* and NGSS.

As discussed earlier, the ideas of atomic structure and electrostatic interactions are elements of the disciplinary core idea of matter and its interactions. However, to evaluate how students' ideas develop during instruction that is designed to align with three-dimensional learning, I also need to identify a practice and a crosscutting concept to focus on and integrate with the elements of the core ideas that I am focusing on.

Scientific and Engineering Practice

It is difficult to discuss students' developing understanding of atomic theory without discussing their development of their models of atoms. Thus while analyzing how the dimensions work together to support deeper student learning, it is logical to focus on the practice of developing and using models (NRC, 2012). In addition to the natural fit between the practice of modeling and the core idea of matter and interactions, there are several other reasons for focusing on the practice of modeling.

Models are simplified representations of a causal account of phenomena that explains observations or help make predictions (Harrison & Treagust, 2000; Lehrer & Schauble, 2006; NGSS Lead States, Appendix F, 2013; Penner, Lehrer, & Schauble, 1998; Schwarz, et al., 2009). Models can include representations, such as diagrams or equations. For example, models of the solar system can often be observed on classroom walls. However, alone, most of these "models" are just representations or diagrams. If these representations are used to explain observations, such as the phase of Venus or path of the planets visible in the night sky, then these representations would be models—a simplified representation of a system including causal relationships that can be used to explain observations or make predictions.

Modeling is a key aspect of what scientists do across scientific disciplines (Giere, 1988). Models provide a framework for the abstract idea of scientific inquiry (Lehrer, Schauble, & Lucas, 2008; Passmore, Stewart, & Cartier, 2009; Windschitl, Thompson & Braaten, 2008). In fact, Passmore, Stewart, and Cartier (2009) proposed a practices framework that is organized around modeling as a central component of scientific inquiry in classrooms. Models are developed and revised as more evidence is collected; they are a way to communicate ideas; and eventually they represent a consensus of the scientific community. Thus, developing and using models is an essential practice of scientist work. Additionally, other scientific practices are embedded in the practice of developing, revising, and using models. In order to make decisions about what to include in their models, students must ask questions, plan investigations, and gather and analyze data. Models are a way to communicate ideas to others, and students will need to engage in arguments based on evidence in order to evaluate and revise the models they are developing (NGSS Lead States, Appendix F, 2013; Passmore & Svoboda, 2012). Once a community generally agrees on the causal mechanisms within in a model, the model can even be used as a source of data to test relationships between components. Focusing on modeling does not mean that students are not working with the other science and engineering practices; rather, focusing on the practice of developing and using models inherently means that students will be engaging in a range of science practices as they develop, discuss, evaluate, and revise their own models. If we want students to be doing the practices of science we cannot leave out the practice of modeling.

While the practice of modeling is a core practice across sciences, in traditional science classrooms, students do not engage in the complex practice of scientific modeling (Giere, 1988; Griffiths & Preston, 1992; Stevens et al., 2010; Windschitl, et al., 2008). "In school, the word 'model' usually denotes a noun, the product of the modeling enterprise rather than a verb describing the practice of science" (Lehrer & Schauble, 2006, p. 177). In traditional classrooms, students are often just shown models rather than participating in the practice of making decisions about what to include in the model, about how evidence fits with the model, what relationships can help account for the mechanism that would explain observations, and evaluating how well models align with various phenomena. For example, students may be shown different models of atoms and be told about the evidence that led to each of these models, but students are not encouraged to analyze the evidence, to develop their own models, or to use those models to explain their observations. Thus, current classroom practice does not represent the type of three-dimensional learning that is argued for in the *Framework*

(NRC, 2012). In order to ensure that students are participating in scientific practices, including models, classroom interactions need to shift and students will need support with the more complex aspects of modeling.

Because models are by necessity simplifications, important decisions must be made about what to include in the model and what is insignificant (NGSS Lead States, Appendix F, 2013; Giere, 1988). If students only observe others' models they may not understand the complex conscious decisions that went into choosing what to leave out. As students learn to participate in the practice of modeling, they will need support in deciding what aspects of a phenomenon are important enough to include in the model. Students also need to learn how to evaluate models (Penner, Giles, Lehrer, & Schauble, 1997; Schwarz, et al., 2009). All models are incomplete simplifications, so they are not evaluated based on correctness but rather based on usefulness. Students need support to identify the purpose of a model and evaluate the relationship between that purpose and the model.

While modeling is complex and often not included in classroom work, others have shown that elementary and middle school students are able to engage in the practice of modeling to explain observations and make predictions (e.g., Hokayem & Schwarz, 2014; Lehrer & Schauble, 2006; Penner, et al., 1998; Schwarz, et al., 2009). Baek and Schwarz saw that in a class using curriculum that focused on modeling, even when students' ideas developed along different progressions, they could end up with similar and sophisticated modeling practices. This dissertation will build on research showing that students are able to develop modeling practices in elementary and middle schools. It is important to study the practice of modeling in a range of contexts and at different levels of schooling. The *Framework* (NRC, 2012) argued for three-dimensional learning throughout K-12 science classrooms. Students need to be engaged in three-dimensional learning as they develop a range of concepts and throughout all ages. How do high school students' modeling practices develop when studying abstract concepts like atomic structure?

Crosscutting Concept

Just as the practice of modeling fits well with a focus on the disciplinary idea of the atomic structure of matter, the crosscutting concept of cause and effect integrates naturally with the practice and idea that I will study. Students should be able to use models to describe the cause and effect relationships—or to provide causal mechanisms—that account for observations. Cause and effect relationships lead to understanding the mechanism that can explain *how* an event occurs and support the development of sound predictions (NRC, 2012). This provides an opportunity for analyzing students' mechanistic reasoning—or how students develop and use cause and effect relationships to account for observations of phenomena. Russ, Scherr, Hammer, and Mikeska (2008) argued for focusing on mechanistic reasoning as part of scientific inquiry in part as "both historically and for students, progress in scientific inquiry is characterized in part by a shift toward reasoning about causal mechanisms" (p. 500). They proposed a framework for analyzing students' mechanistic reasoning by noting the phenomena, conditions, entities, properties of those entities, and activities.

This dissertation will analyze the integration of the disciplinary core idea of matter and its interactions, the practice of developing and using models, and the crosscutting concept of cause and effect. I will analyze the development of students' models of electric fields and atomic structure and how students use those models to provide causal mechanisms to explain a range of phenomena.

Scaffolding

In order to meet the expectations described in the *Framework* and NGSS, classroom interactions will need to shift dramatically. Students are expected to process more of the information and participate in the practices rather than hear or read about them. This means part of designing learning environments and curricula that align with NGSS will need to include scaffolds to support students as they learn and build their own understanding and engage in the core ideas, scientific and engineering practices, and crosscutting concepts. Wood, Bruner, and Ross (1976) proposed the idea of scaffolding as a means of supporting students' development of complex and abstract practices and ideas. Instructional scaffolds are additional supports that are added during instruction. These can be breaking a complex task into smaller pieces, providing prompts or reminders, or adding discussions. Instructional scaffolds are similar to scaffolds that are used during the construction of a building. During construction, the scaffolds provide support for the building, but once the building is completed, the scaffolds are no longer necessary. As students develop their understanding of the content and/or practice, the instructional scaffolds are also removed. McNeil, Lizotte, Krajcik, and Marx (2006) demonstrated that students who worked with scaffolds that faded, or were slowly removed over the course of instruction, performed better on assessments that did not include the scaffolds. The goal is to get students to work independently.

Quintana and colleagues (2004) proposed a framework for features to consider when designing scaffolds. They suggest seven guidelines:

> 1: Use representations and language that bridge learners' understanding
> 2: Organize tools and artifacts around the semantics of the discipline
> 3: Use representations that learners can inspect in different ways to reveal important properties of underlying data
> 4: Provide structure for complex tasks and functionality
> 5: Embed expert guidance about scientific practices
> 6: Automatically handle nonsalient, routine tasks
> 7: Facilitate ongoing articulation and reflection during the investigation (p. 345)

Scaffolds also work best when the curriculum, teacher, and any technology supports work together to support student learning. Tabak (2004) called this "synergistic scaffolds," when the teacher uses the same language used in the scaffolds in the curriculum and readings to discuss complex practices and ideas, provide feedback, and have the students evaluate their own work. When a consistent language is used throughout instruction, the scaffolds reinforce the work students are doing rather than add confusion.

The literature has shown important aspects of scaffolding for supporting students' learning in science classrooms. However, since three-dimensional learning as argued for in the *Framework* (NRC, 2012) and the NGSS (NGSS Lead States, 2013) is new, we need to analyze what scaffolding looks like in this new learning and assessment environment.

Interactions Curriculum

In this section, I describe the curriculum development process for the Interactions Curriculum used in this study. I then describe the key features of the learning environment that are embedded in the design of the curriculum and the foundational theories about learning. Finally, I describe why and how specific scaffolds for modeling were added to the curriculum.

The Interactions Curriculum is being developed as part of a design-based research project funded by the National Science Foundation (#1232388). The project is a collaboration among CREATE for STEM at Michigan State University, the Concord Consortium, and the University of Michigan. The project team has been developing, piloting, and revising an introductory, semester-long, high school science curriculum aimed at developing understanding of the electrostatic forces that govern atomic interactions and macroscopic observations. A significant goal of the curriculum project is to prepare students for future learning in science classes and their life outside of school by building the foundational ideas of the electrostatic and atomic nature of matter and the interaction between matter and energy. These are foundational ideas that students can apply in biology, chemistry, and physics classes they take later in high school and college. Ideally, students will also be able to continue learning throughout their lives by asking questions, evaluating new information, and explaining observations they make outside science classes as well.

The Interactions Curriculum is delivered using computers. Students record their observations, data, and explanations; draw their own models; and explore simulations all on the same computer platform. Using computers means that all information, including the animated simulations, is collected in one place. Part of the reasoning for this is to help students integrate the information from multiple sources. The teacher can also display students' responses, including their drawn models, to facilitate discussions.

For design-based research, the goal is to contribute to both practice and theory by developing principled practical knowledge (Bereiter, 2014; Brown, 1992; Collins, Joseph, & Bielanczyc, 2004; Edelson, 2002). Therefore, it is important to build curriculum based on design principles that reflect theories of how people learn. The Interactions Curriculum is being developed and revised based on the *Framework* (NRC, 2012) and NGSS (NGSS Lead States, 2013). The curriculum development section below describes how the theories of learning that informed the development of three-dimensional learning in the *Framework* (NRC, 2012) were used to define design principles and features for the curriculum.

Curriculum Development

Design principles based on the theories of learning that also informed the development of the *Framework* were used to guide the development of the curriculum materials. Table 1 identifies the design principles used for developing the Interactions Curriculum.

Table 1: Design principles for Interactions Curriculum

Design Principles	Rationale	Design Features
Coherence	Ideas need to build on prior knowledge and other topics covered in the curriculum (Schmidt, Wang, & McKnight, 2005).	• Driving questions (Krajcik, Czerniak, & Berger, 1999) revisited throughout unit • Students revise models of the same phenomena • Investigations begin with discussions of students' initial ideas
Contextualization	Students need to connect ideas to real world problems and examples (NRC, 2007, 2012).	• Students observe several phenomena • Unit level driving questions relate to real-world phenomena
Driven by learning goals	Knowledge is organized around a framework (Medina, 2008; NRC, 2012).	• Learning goals are defined by blending, disciplinary core ideas, crosscutting concepts, and practices
Multiple representations	Experts can link multiple levels of representation together to explain phenomena (Nahum, et al., 2007; Stevens, et al., 2010).	• Use multiple representations—explanations, models developed by students, and simulations—to explain phenomena and observations • Multiple representations are delivered in the same computer platform to facilitate comparing information from multiple sources
Scaffolds	For complex ideas and practices students need additional guidance and support. As students develop an understanding of these ideas and practices, the support is slowly removed (Wood et al, 1976).	• Framework for developing, discussing, and working with models (Mayer & Krajcik, 2015) • Claim, evidence, reasoning framework for writing, discussing, and evaluating explanations (McNeil, et al., 2006)

Table 1 (cont'd)

Sociocultural	Meaning is developed as a group develops consensus about the connections between patterns they observe, possible causes, and ideas held by the larger community. These ideas are developed and negotiated through dialog and discussions (Lave & Wenger, 1991; Vygotsky, 1980).	• Every lesson begins and ends with a whole class discussion for students to share their ideas and questions at that point • Frequent stops are included in the curriculum to discuss simulations, labs, demonstrations, and other sources of evidence to develop consensus about what was observed and possible relationships • Students' models and responses are displayed and discussed as a way to develop ideas and reflect on each other's ideas • Teacher is encouraged not to evaluate students' responses, but instead to ask the students to evaluate their ideas based on the evidence that has been gathered
Educative materials	This is a new approach for teachers as well as students, so materials need to support both teachers and students (Schneider & Krajcik, 2002).	• Detailed introductions in teacher's material for each activity provide descriptions of how activities build and how the three dimensions from the *Framework* (NRC, 2012) fit together in the activity • Discussion boxes throughout materials highlight points for discussion and provide examples of specific content questions, general probing questions, and questions for eliciting ideas from a range of students

Using a construct-centered design process (Krajcik, McNeill, & Reiser, 2008; Pellegrino et al., 2008; Shin, Stevens, Pellegrino, Krajcik, & Geier, 2008), our group worked collaboratively to develop curriculum materials. The construct-centered design process starts with clearly identifying and "unpacking" a construct to study. We defined the constructs by evaluating and breaking down the disciplinary core ideas from the *Framework* (NRC, 2012). We described the ideas we wanted students to understand, how those ideas are linked to each other, and what background knowledge is needed to develop those ideas. Once each construct was clearly described and developed, we defined claims (Shin et al., 2008) in the form of performance expectations (NGSS Lead States, 2013). The claims describe the expectations for what students should be able to do by the end of instruction. In the Interactions Curriculum, we described our claims following the three-dimensional format from the NGSS by blending aspects of the disciplinary core idea, crosscutting concepts, and science and engineering practices. For a list of these claims, which are called learning goals in the teacher's materials that accompany the curriculum, see Appendix A.

With a clear description of what students will be able to do after instruction, the next stage in the construct-centered design process is to define what evidence will show that students have met the claim or performance expectation (Shin et al, 2008). The evidence can then be used to design tasks that inform the development of the student materials (questions and tasks students complete), teacher materials (supports for the teacher to lead the instruction and assessment), and assessment tasks (embedded assessments within the curriculum materials as well as summative assessments). While the construct-centered design process sounds linear, in fact it is a very iterative process. Each stage informs development and revision of the other stages. We engaged in this iterative process of defining learning goals, developing measurements of those learning goals, designing learning tasks, testing the materials in classrooms, and revising the materials.

To support students in building integrated understanding, the materials: 1) introduce each topic using a driving phenomenon, 2) ask elicitation questions to draw out students' prior knowledge before new instruction, 3) use driving questions (Krajcik, et al., 1999) that connect to real world contexts, and 4) revisit questions and phenomena repeatedly as new ideas can be applied to previous ideas. Students work on laboratory experiences in groups, discuss their models and responses within groups and with the whole class, and over time develop consensus through discussions and arguments based on evidence. Throughout instruction, students are integrating disciplinary core ideas, practices, and crosscutting concepts to develop more complete explanations of the driving phenomena.

Learning Environment

Since the Interactions Curriculum is aimed at preparing students to learn and build on their electrostatic and atomic model of matter in later courses and in their experiences in the world outside of school, embedded in the Interactions Curriculum is a pedagogical approach that encourages students to develop their own models to explain observations.

Students have an active and central role in the learning process because the aim is to help students engage in the process of science (NRC, 2007) and because learning happens in a social setting as members of the community negotiate the meaning, significance, and connections among ideas (Lave & Wenger, 1991; Vygotsky, 1980). This classroom environment aligns with some of the prinicples described by Engle and Conant (2002) for fostering a productive classroom, which they call a “community of learners.” Two key principles are that (1) students have the authority to solve problems while at the same time, (2) students are held accountable to each other as well as norms of the discipline. Thus, students should be sharing their ideas with each other in order to develop, clarify, and evaluate their own ideas. Students then use the evidence they gather to evaluate and refine their ideas. As students gather evidence, they engage in discussions with each other about how the evidence aligns with the initial ideas that were shared. As students gather and debate additional evidence, they should develop consensus around particular ideas that fit all the evidence best.

In a classroom environment in which students are expected to explore their own solutions to questions, it could be incorrectly assumed that the teacher plays a minimal role. However, as Kirschner, Sweller, and Clark (2006) point out in their critique of curricula that ask students to develop their own solutions to problems, without guidance many students struggle to simultaneously explore solutions and make connections to the content they are learning. Without guidance, students often learn little, and sometimes low-achieving students even perform worse on assessments after an open-ended learning experience. In their response to this critique, Hmelo-Silver, Duncan, and Chinn (2007) point out the importance of teachers’ careful scaffolding in classrooms that ask students to develop their own solutions to problems.

Teachers must have deep background knowledge of the content as well as pedagogical understanding in order to provide feedback and guidance to students. The need to understand both the content and how to support students learning of that content is what Shulman (1987) referred to as pedagogical content knowledge. Since the introduction of this concept, there has been significant interest in defining teachers’ pedagogical content knowledge as “it identifies the distinctive bodies of knowledge for teaching" (p. 8). Through video analysis, Alonzo, Kobarg, and Seidel (2012) identified some characteristics of science teachers' pedagogical content knowledge: flexibility, richness, and student-centered-ness. When interacting with students and leading discussions teachers need to be able to recognize students' scientific ideas—even if worded in non-scientific ways, to make decisions about how to respond to students, and to support students without misguiding or short-cutting the learning process. In order to successfully lead classrooms where students are inventing their own solutions and models, teachers must have strong, flexible, and rich content knowledge.

The role of the teacher is important in this type of classroom, but much of what the teacher is doing is supporting and guiding students. The classroom interactions required for the new science goals as described in the *Framework* (NRC, 2012) and NGSS (NGSS Lead States, 2013) represent a shift away from the type of interactions that students engage in during typical classroom instruction. In this classroom environment, the teacher is leading a "cognitive apprenticeship" (Collins, Brown, & Newman, 1987). Cognitive apprenticeship builds on the idea of a traditional apprenticeship, in which a worker learns a skill by studying with a master. In a cognitive apprenticeship, rather than learning a skill like shoemaking, the focus is on developing cognitive skills, such as preparation for future learning. Teachers do this as "they guide students in the learning process, pushing them to think deeply, and model the kinds of questions that students need to be asking themselves" (Hmelo-Silver, et al., 2007, p. 101). In this case, the teacher is a master learner, someone who can ask meaningful questions, reflect on ideas, and make connections to evidence. Hmelo-Silver and Barrows (2006) identified several specific strategies teachers used to facilitate these interactions including: asking open-ended questions, asking students to reflect on their own ideas, pushing students to support their ideas with explanations and evidence, revoicing or repeating ideas that students have shared, summarizing the range of ideas that have been suggested by the class, helping students identify gaps or remaining questions that need to be explored, and checking for consensus when ideas are recorded. The teacher is neither the source of answers nor the evaluator of ideas; rather, the teacher uses questions to push students to evaluate their own ideas, the ideas of others, the evidence they have gathered, and ideas that can be agreed upon or questions that still need to be evaluated before a consensus can be reached.

Teachers also have an important role in setting the tone of the classroom. Sharing ideas with peers can be scary, especially when students are uncertain about those ideas. The relationship between the teacher and student is important for learning (Assiter, 2014). This is particularly true in classrooms where students are being asked to solve problems by working with their peers. Teachers develop these relationships by listening carefully to students—showing students that their ideas are important and that all students have ideas to contribute to the class. Teachers can also model this by showing students that they are participating in the learning process along with students and showing students how the teacher—a master learner—reflects on his/her own ideas (Le Cornu & Peters, 2009). In classrooms where students are expected to discuss their ideas and use evidence to reflect on and develop those ideas, it is important that the teacher create a safe space for sharing ideas even if they end up changing. Teachers can do this by reflecting and repeating students' ideas and showing interest in students' ideas, while avoiding evaluating or critiquing those ideas.

Encouraging students to share their ideas does not mean that all ideas are equally valued throughout the learning process. As students gather evidence, the teacher also plays a role in pushing students to use that evidence to support or refute ideas. As the class gathers more evidence, students should be developing consensus around ideas that align with scientific ideas. Therefore, the teacher needs to analyze students' ideas as they are developing in order to assess if students need to gather additional evidence. Through all of this, the teacher is supportive of students and honors their ideas.

Students' Scientific Modeling

In previous work, I found that the models that students drew in response to prompts in the curriculum did not fully reflect their modeling practice (Mayer & Krajcik, 2014). The models students drew often seemed incomplete, were missing key components, and did not clearly indicate how their representations related to the phenomena. However, in interviews, students identified components they left out and could explain the relationship between what they had drawn and a variety of phenomena. Students just did not think it was necessary to include that information in their written models. Additionally, students did not use the dynamic models (simulations) provided in the curriculum as data sources that they could use to evaluate and revise their own models. Instead, students saw the simulations as an authoritative source of information, depicting the "correct" answer. In response to these findings, we added additional scaffolds to the Interactions Curriculum. Modeling and the disciplinary idea of atoms are both complex abstract ideas. As such, while in a three-dimensional learning environment in which students have the responsibility for developing and evaluating ideas, they will also need support with the topics of modeling and atoms.

Scaffolds for modeling

In order to address the concerns we identified regarding students' modeling practices, we proposed a framework for scaffolding students' development and use of models. The claim, evidence, reasoning framework is used to introduce and support students' scientific explanations based on evidence (McNeill, et al., 2006). We wanted to include a related framework to use as scaffolding for developing and using models. In order to develop a scaffolding framework for modeling, we needed to describe the practice of modeling. We used the following definition: Models are simplifications that highlight mechanisms and are used to develop and support explanations of phenomena, to make predictions, and to ask questions (NGSS Lead States, Appendix F, 2013; Penner, et al., 1998; Schwarz, et al., 2009). Lesh and Doerr (2003) broke models down by stating, "A model is a system consisting of (a) elements, (b) relationships among elements, (c) operations that describe how the elements interact, and (d) patterns or rules…that apply to the preceding relationships and operations" (p. 362).

One of the Quintana et al. (2004) guidelines is that scaffolds provide structure for complex tasks. Thus, in order to develop a useful scaffold for students, we need to be able to take the complex task of modeling and provide structure for students. Lesh and Doerr's description provides a clear starting point; however, the scaffold would need to simplify all of these aspects in order to support students as they develop and use models.

Framework for scaffolding modeling

We propose a framework comprised of three aspects of modeling to give students an introduction and support for modeling: components, relationships, and connection to phenomena (Mayer & Krajcik, 2015). In this framework, we use the term components in place of Lesh and Doerr's (2003) term "elements". The relationship among elements and rules and operations to describe how elements interact are all included under "relationships" in our framework. The "connection to phenomena" includes the patterns and how the interactions lead to specific observations.

Models are necessarily a simplification and, therefore, when making a model, you must make decisions about which components to include and which to exclude. However, the model should also provide a causal mechanism; therefore it may be appropriate to add some components that are not visible or do not look like the phenomena but provide an underlying causal mechanism that accounts for the observations (Penner, et al., 1997; Schwarz, et al., 2009). The interactions and relationships between components are also an important part of the causal mechanism and, therefore, when creating or working with a model, it is important to analyze and/or represent the relationships and interactions between the components. However, on their own, the components and relationships only provide a representation, for example, a diagram or simulation. Representations on their own are not models. A representation is only part of a model when it is used to explain or make predictions about phenomena. Therefore, the final aspect of modeling provided in the curriculum is "connection to phenomena." The relationships between the components should work together to help provide a causal explanation of observations or help form a prediction.

Use and possible drawbacks of framework for scaffolding modeling

This framework provides students with specific aspects of modeling to think about when they are working with a model. This reflects the scaffolding guideline: "organize tools and artifacts around semantics of the discipline" (Quintana, et al., 2004, p. 345). It is important to note that the goal of our modeling framework is to provide language and an organizing tool for discussing models; we are not trying to "proceduralize" the practice of modeling. The framework for modeling gives students language that they can use to discuss models that are embedded in the curriculum (simulations) as well as each other's models. Thus the modeling framework is aimed at supporting students with a complex task by giving them language to use to begin to describe that task, as well as aspects to think about when working with models so the complex task has some structure.

The modeling framework provides language and structure that may be helpful for introducing students to the complex task of modeling. However, the modeling framework does not include many important aspects of the practice of developing and using models. The practice of modeling is more complex than the product of modeling. For example, models are always simplifications and thus it is important to think about the limitations of any model that you are working with. Models are evaluated based on whether they are useful for the given purpose and the extent to which they fit with the given evidence. Models are also continuously updated and revised as new evidenced is gathered. Modeling is an iterative process through which models are developed, revised, and changed through the evaluation of new evidence and phenomena (Hokayem, & Schwarz, 2014; Lehrer & Schauble, 2000; Lesh & Doerr, 2003; Penner, et al., 1997; Penner, et al., 1998). The learning progression for modeling proposed by Schwarz et al (2009) included a progression for students' metamodeling knowledge which includes the components (p. 636):

- "Nature of models";
- "Purpose of models"; and
- Criteria for evaluating and revising models.

Baek and Schwarz (2015) highlighted the importance of multiple forms of support—from the teacher, technology, and the social setting in the classroom—working together to support students' as they learn the complex practice of modeling. The components, relationships, and connection to phenomena framework we propose provides some structure to support students work with models; however it does not include all the aspects of modeling. Thus, it is important to use this framework thoughtfully as one form of support when working with students on the practice of modeling.

In the Interactions Curriculum, the modeling framework is introduced by the teacher, reinforced using readings, and embedded in early questions that ask students to think about each aspect as they create their own models and as they work with early dynamic models (simulations) embedded in the curriculum. Throughout the teacher's guide, teachers are encouraged to display students' models and simulations and to use the language from the modeling scaffolds to lead discussions. Throughout instruction, students were asked to draw models several times.

This reflects the synergistic scaffolding approach suggested by Tabak (2004). By using the same language to discuss models in class, in the written curriculum, and in questions, these different supports work together to support students' modeling practices. Thus, the teacher and interactions among students are also important for developing modeling practices. The modeling framework is intended to introduce modeling and support discussions about models and modeling.

Since three-dimensional learning is a new vision for science classrooms and the framework for modeling proposed in our curriculum is a new structure for scaffolding this practice, it is important to study the affordances and constraints of this form of support and how to better support students with the practice of modeling and three-dimensional learning. It is important to assess how students use these scaffolds to develop and use models to provide causal explanations of phenomena and how the use of the modeling scaffolds impacts students' understanding of the practice of modeling more broadly. This dissertation addresses these needs by analyzing how students developed their own models, how students used their models to explain electrostatic phenomena, and how students evaluated and justified their models.

Chapter 3: Methods

In this chapter, I describe the methods used for this dissertation. I start with details about the context in terms of the teachers, school, classes, curriculum, and instruction. I then describe the data sources and finally the processes used for data analysis.

Context

I co-taught four sections of 9th grade physical science using the Interactions Curriculum. I worked with two different teachers; each teacher had two sections of physical sciences. I was the “lead teacher” in the first of each teacher’s classes of physical science, and in the second class, the teacher took the lead while I was a support. These classes were all in the same rural/suburban high school.

Teachers

After getting my teaching certification with a major in chemistry, I taught high school chemistry in the Bronx, New York, for two years. While in New York I earned my Masters in Science Education and completed an action research project, analyzing students’ ideas about gases and how specific labs affected those ideas (Mayer, 2011). I then moved to Seattle, where I taught high school chemistry and 9th grade physical science for four years in an urban school. While in Seattle, I participated in a long-term professional development program for science teachers. Part of this program included professional learning communities (PLCs). I met with my PLC once a month throughout the school year for all four years. At each meeting, one teacher would bring samples of student work. The goal of these meetings was to analyze student work in order to make informed decisions about what to do next with the students and about modifications for future years. Through this work, I drastically changed my approach to teaching in order to focus more on students' ideas and building on those ideas. Along with that new approach, I also re-structured my own chemistry curriculum. After teaching in Seattle, I started a PhD in Curriculum Instruction and Teacher Education and a Masters in Physical Chemistry at Michigan State University (MSU). As part of my work at MSU, I am working as a research assistant for the Interactions Curriculum: developing and revising lessons and assessments, visiting classrooms during implementation of the Interactions Curriculum, and interviewing students as they completed the curriculum.

KD majored in Earth Science and has general science and math endorsements for her teaching certification. The year we co-taught together, KD had over ten years of teaching experience. Before teaching in the school district, KD taught high school math and science elsewhere in the state. She taught at the district's middle school for several years before moving to the district's high school, where she taught high school math and 9th grade physical science.

CA majored in physics and has a general science endorsement. Prior to the year we co-taught together, he did his yearlong student teaching in the physics class at the district's high school and taught at the district's middle school for three years. This was his first year teaching 9th grade physical science and chemistry at the high school. In addition to teaching science, CA was also an assistant coach for the football team and coach for the wrestling team at the middle and high schools.

School

The high school enrolls about 650 students. Over 90% of the student body is white, and a low percentage (16.7%) of students are eligible for free-reduced lunch. Students at the school generally do well academically. Based on the Michigan Education YES Grades, the school is rated as an "A" school, the highest ranking. However, students' achievement in science has declined in recent years. In 2010, 82% of 11th grade students at the high school passed the Michigan state science assessment. The pass rate has steadily decreased since then; in 2012 (the most recent year reported) it was down to 37%.[1]

Classes

The 9th grade classes I worked in reflected the demographics of the school in general. However, two of the classes (2nd and 5th periods) had a high number of students on Individualized Education Programs (IEPs). These two classes had a paraprofessional assigned to provide additional support for specific students on IEPs. The same paraprofessional was assigned to both classes.

From the four participating classes, I randomly selected two to three students per class for the case studies. Table 2 provides an overview of the classes and the students selected for the case studies. The case study students represent the range of students in the four classes.

[1]Based on statistics reported on movoto (http://www.movoto.com/schools/) and niche for the school district (https://k12.niche.com/)

Table 2: Classes and case study students

Period	Co-teacher	Class	Case study students*
2nd	KD	8 Female 11 Male	Claire†
			Christopher
			Jonathan
4th	KD	11 Female 15 Male	Brittany
			Chase
			Mallory†
5th	CA	11 Female 15 Male	Fabrizio†
			Lily
			Tony
6th	CA	6 Female 14 Male	Aiden
			Nate

* Pseudonyms
† Chose own pseudonym

Curriculum

The learning goals for this curriculum focus on students' development of macroscopic and atomic models to explain phenomena involving electrostatic interactions. Each learning goal is expressed as a performance expectation by combining a disciplinary core idea, a crosscutting concept, and a scientific and engineering practice. The curriculum is broken into four Units; each Unit is broken into Investigations; and Investigations are broken into Activities. Each Activity lasts between one and four days depending on whether lab work is included and whether students design their own labs. Each Investigation and Activity has learning goals written in the form of performance expectations. The core ideas in the learning goals for the Activities are smaller pieces that build together to address the learning goal at the Investigation level. Each Unit is organized around one Driving Question.

In the classes that I co-taught, students completed Unit 1 and the first three Investigations in Unit 2 during the first semester of their physical science course. In Unit 1 the

Driving Question is “Why do some clothes stick together when you take them out of the dryer?” Students are asked to connect various representations (including simulations and models they construct) in order to explain observations of a range of phenomena, including various objects interacting with a Van de Graaff generator, balloons, and other objects that have been rubbed with fur. Students initially develop models of electric fields to explain these observations and then students used evidence from Thomson’s Cathode-Ray tube experiment and Rutherford’s gold foil experiment to develop atomic model that could explain their earlier observations in more detail. In Unit 2, students work to answer the Driving Question “How can a small spark trigger a huge explosion?” The students start by observing a demonstration in which a spark generated by a Van de Graaff generator is used to ignite a Bunsen burner. In Investigations 1 and 2, students add the concept of energy to their descriptions of how the Van de Graaff generator works. In Investigation 3, students analyze the relationship between chemical formulae and properties as well as energy and bond formation. Investigation 4 compares changes in energy to the process of a chemical reaction. While the students in these classes did not complete Investigation 4, we did have a brief discussion of these ideas in order to wrap up the Unit so students could prepare for their semester exams. See Appendix A for the Activity titles, learning goals, and brief description of each activity. The full curriculum can be found at interactions.portal.concord.org.

Instruction

In class, we started with observations of phenomena. Students were asked to develop their own models to explain those observations throughout the curriculum. Every time students created a model, I would project the models and use the modeling scaffolds to lead a discussion. I would use the modeling framework to structure discussions of models: asking the students what components they saw when comparing the models, what relationships were indicated, and how those relationships connected to our observations of the phenomena. Every time students were asked to draw a model, I would project the students' drawings and ask students: "What components do you see in these models? What relationships are shown? How does this model help explain our observations?" For example, students were asked to draw models to explain the interaction between a Van de Graaff generator and pie pans that had been stacked on top of it early in the semester. As students worked throughout the semester, they revised these models several times. As students revised their models, they could incorporate more evidence, but there was also information that students did not gather yet. For example, at one point, students had learned about charges and could use charges to revise their models of the Van de Graaff generator, but they did not know if the pie pans were charged or neutral to start and they did not know the charge of the Van de Graff generator. Therefore, students had to make some decisions about their models. When we displayed the models to discuss them, I asked the students to note what components they saw. Students noticed the different choices they made when completing their models. These differences led to questions and additional investigations to gather more evidence and make additional revisions to their models.

I used the modeling framework to discuss simulations as well. Every time students worked with a simulation, I would project the simulation and ask students: "What components do you see in this simulation? What relationships can we see in this simulation? How do these relationships relate to the observations we have been discussing?" The modeling framework was used to organize our discussion of all the models students drew and simulations students worked with. Asking about the components gave students a safe way to enter the discussion, but most of time during these discussions focused on the relationships and connection to phenomena.

Whenever we used a simulation, I would give the students time to explore the simulation with their partner and start to answer the questions. After students had some time to explore, I would display the simulation to discuss it as a class. In the same way that we discussed the students' models, I asked the students to describe the components and relationships included in the simulation then to connect those relationships to the evidence and observations of phenomena we had discussed in class. For example, when developing their own models of atomic structure, students explored three key simulations: two represent Thomson's historically significant experiment with Cathode-ray tubes and one related to Rutherford's gold foil experiment. In the first simulation about Thomson's experiment, students could change the type of metal in the Cathode-ray tube (https://lab.concord.org/embeddable.html#interactives/interactions/crookesElectrodes.json). Students could easily identify the components and type of metals. The discussion revolved around the relationship between the type of metal and the outcome. This relationship was difficult for students to identify because changing the metal does not change the outcome, so students tended to say "it does not make a difference." We had to continue to focus on the cause and effect and stating the relationship between the type of metal and the outcome. In the second simulation, students focused on the outcome of Thomson's experiment: that the ray of particles released from the metal always bent towards a positively charged plate. In this simulation, students could send atoms of different mass between the charged plates and the particles from the Cathode-ray tube (https://lab.concord.org/embeddable.html#interactives/interactions/electronProperties.json). Again, the students could quickly identify the components: different atoms, the particles from the Cathode-ray tube, charged plates, etc. Again, the discussion focused on the relationships students saw between the mass and the path of the atoms and particles. I then asked students to connect that relationship with Thomson's observations in order to make claims about the particles. Finally, students were told that Thomson's conclusion was that the particles were small negatively charged piece of atoms and students were asked to use the relationships from the simulations to evaluate Thomson's conclusion. A similar pattern was used to study Rutherford's gold foil experiment. The students were told about the experiment and the outcome. Students then explored a simulation that allowed them to adjust the concentration of positive charges within an atom and observe the impact on the path of alpha particles (https://lab.concord.org/embeddable.html#interactives/interactions/rutherford-no-electrons.json). Students could quickly identify the components. Again, starting with the components gave students a safe way to enter the discussion. For example, one student said there is a blue circle, I repeated that one of the components is a blue circle. The discussion then focused on the relationships shown between the concentration of the positive charges, the electric field, and the path of the alpha particles. I then asked students how those relationships connect with Rutherford's observations and what we can say about the structure of atoms based on those relationships and Rutherford's observation. These relationships and experiments were really complex, so we had discussions of the simulations over multiple days.

We would revisit them when looking at models students drew and evaluating conclusions about atomic structure.

Classes were generally driven by a lot of discussions. When we had class discussions, I consciously tried to respond to all student ideas with a neutral expression. I generally repeated students' statements and asked if I understood their idea, for additional details, or clarifications. As we worked through the investigations, I would also ask the students to connect their ideas to the evidence we gathered in class. Setting a classroom environment where students feel safe sharing and evaluating their own ideas takes intentional work by the teacher. On the first day of school, I told the students my class may be different than the science classes they have had in the past. I spent the first week setting up the expectations for the class. I told the students that I would not be giving them the answers and they would not get a textbook. Instead, students would need to analyze data, identify patterns, and use that evidence to develop and support their own conclusions. During the first week as we worked through activities we would also stop and talk about what the students needed to do in order to develop their responses. This focus on using data and observations to propose and evaluate ideas continued throughout the semester. For example, there were times when students did not know all the information for making a model of a phenomenon. When discussing students' models, rather than focusing on which ones were correct or best, we would notice similarities and differences. Having different ideas was not seen as a problem, instead, we used those differences to identify new questions to investigate and what additional data we needed to gather.

Data Sources

The data sources include both the written work students completed in class and recorded interviews. Including students' written work allowed me to see how students' responses to modeling questions in the curriculum changed during the course. I also interviewed these 11 students throughout the school year.

Models from Curriculum

Students were asked to draw models at several points throughout the curriculum. There are two series of models that I will focus on, because these two series of models are places in the curriculum where students were asked to develop and revise the same or similar models to incorporate additional evidence.

One of the first phenomena students experienced in the curriculum was observing what happens to pie pans when they are stacked on top of a Van de Graaff generator. The students made predictions about what they thought they might see before observing the pie pans fly off when the Van de Graaff generator was turned on. Throughout Units 1 and 2, students were asked to draw a model to explain this observation six different times:

1. In Unit 1 Investigation 1 Activity 1, students were asked to "draw two pictures to show what caused the pie pans to behave the way they did." These images were used to lead a discussion about models and introduce the idea of causal mechanism—a model should show the chain of events that lead to a particular outcome.
2. Students immediately redrew their models of the pie pans and Van de Graaff following this discussion.

3. Throughout Unit 1 Investigation 1, students explored the interactions between charged objects. At the end of Unit 1 Investigation 1 Activity 4, students were asked to use the ideas they had developed to draw another model of the pie pans and Van de Graaff generator.
4. In Unit 1 Investigations 2 and 3, students added to their understanding of how charged objects interact by exploring representations of electric fields and interactions between neutral and charged objects. Unit 1 Investigation 4 asked students to take these ideas and apply them to the phenomena they observed earlier as well as to new phenomena. In Unit 1 Investigation 4, students were asked to once again revise their models of the pie pans and Van de Graaff generator in order to incorporate ideas about fields and neutral objects.
5. Unit 1 Investigations 5 and 6 provided evidence that students used to develop the particle nature of matter and a model of atomic structure. In Unit 1 Investigation 7 students were again asked to revise their models of the pie pans and Van de Graaff generator, now to incorporate ideas of atomic structure.
6. Finally, students revised their models of the pie pans and Van de Graaff generator in Unit 2 Investigation 2 to incorporate the idea of energy in their models as well.

Unit 1 Investigation 6 focused on the development of a model of atomic structure. In this Investigation, students were asked to draw a model of atomic structure three different times:

1. In Activity 1, students were asked to draw their initial ideas about atomic structure.

2. Activity 2 reviewed the evidence J. J. Thomson collected through his experiments with Cathode-Ray tubes. Students were asked to revise their models of atomic structure in order to explain Thomson's observations.
3. Activity 3 focused on the results of Rutherford's gold foil experiment. Again, students were asked to revise their models of atomic structure in order to account for this additional evidence.

Appendix B provides the wording of the questions from the curriculum for the Van de Graaff and pie pan models as well as the models of atomic structure.

Brief Follow-up Interviews

Since it can be difficult to interpret students' representations, for the three selected modeling questions that focused on atomic structure, I also conducted brief follow-up interviews about the students' answers to the three questions that asked students to draw a model of atomic structure. I printed out the students' responses and—in individual interviews—asked the students to explain what they drew and how it related to evidence from the class. Students may not have volunteered this information when answering the associated questions, so comparing what they wrote and what they discussed in the follow-up interviews allowed me to identify what students spontaneously include in their models and what additional information or ideas they may have had but did not include on their own. This also allowed me to evaluate how students connected evidence and their models.

Full Interviews

I conducted four semi-structured interviews with each case study student: one at the beginning of the year, one after Unit 1, one at the end of the semester, and one at the end of the school year. Semi-structured interviews allowed me to focus on a set of standard scenarios, but also to ask follow-up questions to clarify what students were saying. In the interviews, I focused on scenarios to see how students related their ideas to explain observations. I followed an evidence centered design process (Behrens, Mislevy, DiCerbo, & Levy, 2012) to develop the questions. I carefully defined and elaborated the components of the disciplinary core idea, crosscutting concepts, and practices. I used those ideas to define claims that describe what students should be able to include in their models and evidence that would indicate if students had met those claims. Finally, I identified essential and variable task features and contexts to define the questions. In the interviews, I asked students about various scenarios (described below) and then asked about the concepts of fields and atoms and whether those concepts are related to any of the scenarios we had discussed (See Appendix C). I sent the questions to several science education graduate students to determine if the questions elicited the ideas I was looking for when experts answered them. The graduate students' responses included the ideas I was interested in assessing and thus the questions were not revised.

The scenarios included some that were discussed in class, some that were near transfer questions, and some that were predictions about upcoming topics that the students had not discussed in class at that time. In the first three full interviews, I asked about three scenarios:

1) Why does your hair stand up when you take a knit cap off in the winter?
2) The image (Figure 1) shows two balloons hanging from a ceiling. What could explain why the balloons are hanging as shown in the images?
3) A video showed a piece of magnesium that was added to a porcelain crucible. The magnesium had a mass of 0.26 grams. The magnesium was then set on fire and the

burning strip of magnesium was returned to the crucible while the lid was held above the crucible. In the end, the mass was measured again and was now 0.29 grams and there was a fine white crumbling powder inside the crucible. After showing students the video, I asked them what they noticed and if they could explain those observations.

After discussing the scenarios, I told students I was also going to ask about some topics we would study during the curriculum. If students did not mention fields or atoms during their response to the scenarios, I asked students if they had heard of electric fields or atoms. If yes, I asked follow-up questions about what those ideas meant and if those ideas were related to any of the three scenarios we discussed earlier. I asked students to draw representations of an electric field and an atom. I also showed students two images of electric fields (Figures 2 and 3) and asked the students to interpret the representations and to connect the representations to the scenarios we had discussed.

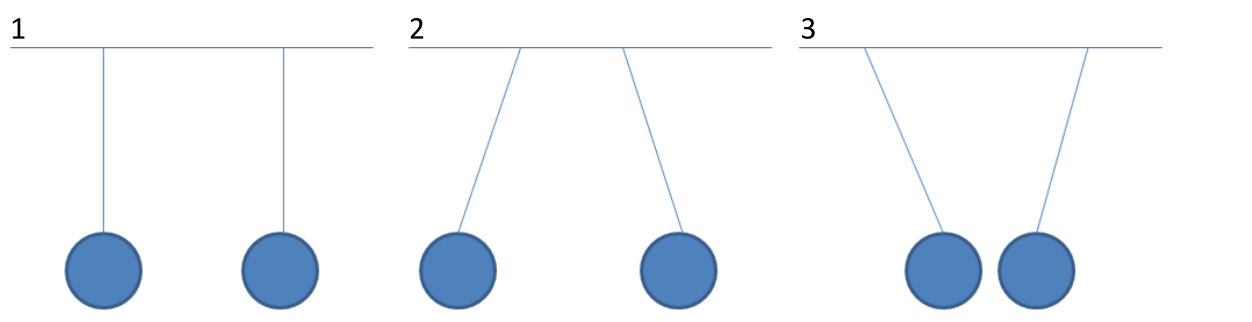


Figure 1: Balloon images for Scenario 2 in first three full interviews

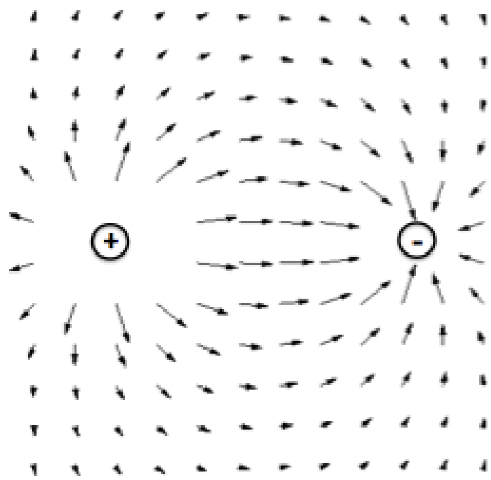
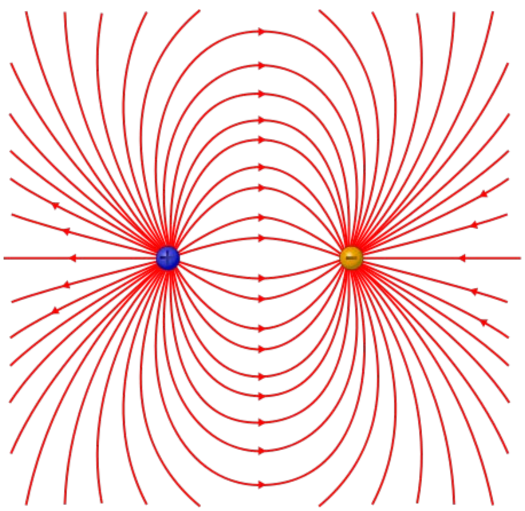


Image modified from: Srikant, Marakani. (2009). Electric and Magnetic Fields. Accessed from: http://srikant.org/core/node8.html#field2

Figure 2: First representation of an electric field used in full interviews



Source: By Sharayanan [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0-2.5-2.0-1.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

Figure 3: Second representation of an electric field used in full interviews

At the end of the school year, after students had continued working on other science topics, I returned to the school and conducted a follow up interview. In this interview, I was able to evaluate students' retention of their models and to ask students to apply their models to additional scenarios, including a biological application. The final interview was similar to the previous three full interviews. I asked students to explain three new scenarios. The first was the interaction between a circle of Mylar and a Teflon rod that had been charged by rubbing it with fur. I explained to students that I was going to have them charge the Teflon rod and that I would then drop the piece of Mylar on it. First, I asked students to predict what they thought would happen and to explain their predictions. After observing the phenomenon, I asked students to explain what they observed. There should have been a transfer of charge from the Teflon rod to the piece of Mylar, charging the Mylar. When the Mylar is charged, it repels itself, expanding the circle away from the rod to float in the air. However, it was raining on the day of the follow up interviews, and the moisture in the air affected the electrostatic interactions. Most students observed the Mylar clinging to the charged rod instead of it floating away. Regardless of how the interaction worked out, I asked students to explain what they observed. In the second new scenario, I showed students a video of a thin stream of hexane and a thin stream of water. In the video, fur was used to charge a rubber rod that was then brought near both the stream of water and the stream of hexane. The hexane does not interact with the rod, but the stream of water bends towards the rod. I asked students to explain what they observed, if they thought the ideas from the Interactions Curriculum were connected to the observation, and what questions they had about what they observed. Finally, I asked the students to make predictions about a topic they would learn when they took Biology the following year. I explained that proteins play an important role in our bodies and that the shape of the protein is important for how the protein does its job. I also explained that proteins are basically chains that are hundreds or thousands of atoms long. I made an analogy to origami: I can fold a flat piece of paper in specific ways to make a swan. Similarly, the long chain of atoms folds in a specific way to make the shape of the protein. I asked students to predict what could cause the protein to fold up. These new scenarios were added to the final interview to see how students applied their ideas of electrostatic interactions at the atomic scale to new contexts.

These scenarios were selected to represent both near transfer tasks and preparation for future learning. The first new scenario (interaction between the Teflon rod and piece of Mylar) is very similar to several interactions the students experienced in class: balloons and rods with various charges. The second and third new scenarios (interaction between the liquids and the rubber rod and protein folding) were applications related to future learning. The interaction between the liquids and the rubber rod is a task from Unit 3 of the Interactions Curriculum, about polar and non-polar substances. These students did not get to Unit 3, so this is a task that they had not encountered. Similarly, protein folding is a topic in Biology, a class most students would be taking in the following school year. I did not expect students to be able to explain this interaction but was looking to see if they could speculate about how the ideas they had learned might be connected to a new context. The purpose of this was to assess how students apply their models to novel situations to evaluate evidence of preparation for future learning.

Throughout the interviews, I asked follow-up and clarification questions, frequently asking things like, “Could you tell me more about that?” “How does that happen?” “What does that mean?” “Could there be another explanation?” “Anything else related to this?” These types of follow-up questions were used throughout all interviews, including asking students about their explanations of the scenarios, about the models they drew, and about the predictions they made. Table 3 summarizes the data sources, an overview of data analysis, and how this information relates to the research questions.

Table 3: Data sources

<table>
<tr><th>Research question</th><th>Data source</th><th>Data analysis</th></tr>
<tr><td>How do students' models of electric fields and atomic structure change over time through instruction based on a scaffolded curriculum designed to align with three-dimensional learning?</td><td>1. Seven models students drew regarding the Van de Graaff generator and pie pans
2. Four models students drew of atomic structure
3. Brief interviews with students after their drawings of atomic structure
4. Full interviews</td><td rowspan="4">Use modeling scaffolds to define rubrics for analyzing the models students drew in the curriculum to identify the components and relationships students include and how they explain observations using their models. I analyzed the drawn models to see how student models changed. I used the debriefs to supplement this analysis for the development of atomic structure.
Define coding schemes to analyze students' content ideas, modeling practices, and preparation for future learning in interviews and debriefs.</td></tr>
<tr><td>Are the models students develop retained after instruction?</td><td>1. Follow-up interview at the end of the school year</td></tr>
<tr><td>How do students use their evolving models from curriculum designed to align with three-dimensional learning to explain electrostatic phenomena?</td><td>1. Brief follow-up interviews after students' drawings of models of atomic structure
2. Full interviews</td></tr>
<tr><td>How do students apply their models of atomic structure to novel phenomena?</td><td>1. Full interviews</td></tr>
</table>

Data Analysis

I used the modeling scaffolds to develop rubrics to code the written models from the curriculum and used modeling practices and preparation for future learning to develop coding schemes to analyze the interviews. I combined these analyses to develop a case of each student. Finally, I identified themes across these cases. Below I describe the analysis of the models, interviews, and cases in detail.

Analysis of Written Models

I used the scaffolds included in the curriculum to define a general rubric for students' models shown in Table 4 (Mayer & Krajcik, 2015).

Table 4: General modeling rubric

Criteria	Levels		
	0	1	2
Components: Model includes identification and specification of appropriate and necessary components, including both visible and invisible	Diagram shows an image of the phenomenon	Model may include both visible and invisible components, but may be missing key components, or components are not clearly labeled leaving uncertainty in the interpretation of the model	Model highlights all necessary components, including both visible and invisible, that are needed for explaining the phenomenon. All components are clearly labeled or identified in description
Relationships: Model includes representations or descriptions indicating how various components within the model are related and interact with each other	Model does not indicate relationships or interactions between components of the model	Model is either missing key relationships or includes some inaccurate relationships between component	Model includes all appropriate relationships necessary for the explanation of the phenomenon.
The collection of relationships provides a causal account of the phenomena: The model is used to explain or predict phenomena or specific aspects of phenomena	Model is not used to explain phenomena	Model is used to try to explain phenomena, but there are some inaccuracies in the explanation of the phenomena	Model is consistent with available evidence and is used to explain phenomena.

For each of the series of models from the curriculum I wrote a series of rubrics. These rubrics specified what components and relationships students should include at that point in the curriculum and what students would need to do to connect their model to the phenomena. In developing the rubrics for the Van de Graaff generator and pie pans, I added additional levels to capture that students were expected to add additional details and mechanisms as they progressed through the curriculum (Appendix D). Another researcher on the Interactions Curriculum project and I used these rubrics to code several samples of students' models and used those to discuss and refine the rubrics. I also developed descriptive codes of the models students drew through an iterative process by describing particular aspects of each student's model such as the mechanism and justification students included.

Analysis of Interviews

Each interview was broken into responses to each scenario. A response included the student's initial ideas as well as his/her answers to any follow up or clarification questions. I analyzed each student's response as a whole using content, reasoning, and preparation for future learning coding schemes described below.

Content coding scheme

I created a list of content ideas students stated during their responses to the interview questions. The complete list is shown in Appendix E. Several of the ideas were commonly mentioned together. For example, if students mentioned that atoms had protons and a nucleus they also often included neutrons. I used these common groupings to define content themes. Table 5 summarizes the content themes and examples of ideas in each theme. Since each response was coded as a whole, these themes are not mutually exclusive. For example, a student could initially use charges to explain an observation then add an atomic-level explanation when asked a follow up question.

Table 5: Themes from students' ideas

Themes	Ideas
Charges	● Opposites attract ● Like repel ● Neutral and charge attract ● Friction leads to charges ● Charge depends on material ● Positive ● Negative
Atoms are pieces of matter	● Everything is made of atoms ● Atoms are the building blocks of matter ● [Object or material] is made of matter
Atoms have pieces	● Electrons ● Protons ● Neutrons ● Nucleus ● Rings ● Different atoms have different numbers of particles
Atoms have charged pieces	● The number of protons v electrons determines the charge ● Protons are positive ● Electrons are negative ● Same number of protons and electrons makes the atom neutral
Atoms have charged pieces that interact	● Rubbing materials makes electrons move ● Pieces in atoms (electrons/protons) shift due to interactions with other charges ● Electrons shift to form bonds ● Atoms repel if too close

Reasoning coding scheme

As I was interested in assessing three-dimensional learning, in addition to evaluating the students' content ideas—which can be thought of as elements of the disciplinary core ideas—I also needed to evaluate the nature of students' responses. Were students applying a model to develop cause and effect relationships, were students supporting their ideas using evidence, or were students recalling pieces of information from class? To assess the nature of students' responses and the justifications they used to support them, I adapted the Nature and Justification coding schemes from the *Supporting Scientific Practices in Elementary and Middle School Classrooms including Modeling, Explanation-building and Argumentation* project (NSF DRK-12 grant DRL 1020316). I adapted the codes to fit more closely with the specific content focus of this study. For example, I am particularly interested in whether students are using macro-level or atomic-level explanations and therefore I broke the categories under the nature of students' reasoning into macro-scale and atomic levels. I also modified the justification section from the original coding scheme. In the original coding scheme, there was one code to identify when a student referred to an activity from class. Several students referenced activities from class, but varied in the amount of detail they provided: some students only recalled that we did an activity, while others could describe the evidence from the activity, and ideally students would connect that evidence to support their models. All these responses would have been assigned the same justification code in the original coding scheme. I wanted to capture the differences in how students referred to class activities because it was important to me to see whether students were recalling ideas or using them to support their answers; therefore, I broke the justification code from the original coding scheme into several different codes. The adapted codes are summarized in Table 6. Again, students' responses were coded as a whole and, thus, these codes are not mutually exclusive. For example, a student could explain that balloons interacted because they were rubbed with fur that made them charged (a macro-scale explanation) and then continue to explain that rubbing them made them charged because electrons were transferred from the fur to the balloon (atomic-level explanation).

Table 6: Nature of students' reasoning and justifications

Nature of students' reasoning		
Category	Description	Example
Content ● Pieces of information ● Dynamic/interactions	Pieces of information–students' responses are composed of repeating pieces of information or terms. Dynamic/interactions–students build a response by describing cause and effect changes. Clarification: Student can use both pieces of information and dynamic/interactions in the same response.	Pieces of information: The hair stands up because of static. Dynamic/interactions: When you take off your hat, the friction makes electrons transfer so your hair all has the same charge.
Analogy ● None ● Macro-scale ● Atomic-level	Student answers a question or explains a scenario by comparing it to other situations.	Macro-scale: Static is like magnets. Atomic-level: The atom is like a ball.
Explanation ● None ● Macro-scale ● Atomic-level	Student provides cause and effects that build an explanation for an observation or scenario.	Macro-scale: The mass went up because the ash was heavier. Atomic-level: The mass went up because more atoms were in the cup.

Table 6 (cont'd)

Source – identification of the sources students refer to as they formulate their answers		
Category	Description	Example
None	Student does not say where their ideas come from and were not asked to explain.	NA
Authority	Student refers to an authority to support their answer. Authority is a broad term for any specific outside source students refer to as showing or telling the answer including: textbook, teacher, previous coursework, a parent, TV shows, etc.	I learned this in 7th grade. I saw it on TV.
Assumed knowledge/experiences	Student views the information as obvious and not needing support. These are ideas that students did not refer to a specific source. This often was enacted by students repeating their ideas when asked follow up questions about the meaning of a term. This was different from none in that the student was asked for the source of their idea and they simply repeated the idea.	That is just what static does.
Data (elaborate in justification)	Student refers to experiments, observations, and/or data—including hypothetical data—to support an idea or answer.	Scientist ran tests. We saw … in class.

Table 6 (cont'd)

Justification – elaboration on the type and use of data students use to support their answers or ideas		
Category	Description	Example
There must be experiments	Student states that experiments were done, but does not know what they were.	Scientist must have run experiments.
Experiments from class	Student states that we conducted or discussed experiments in class, but does not elaborate on what those experiments or observations were.	In class, we talked about different experiments that showed that atoms have electrons.
Conclusion and data	Student summarizes the conclusions and data from an experiment, but does not link the conclusions to the data because student's description of the claim is incomplete or vague.	Atoms have negative electrons because in the experiment, it was attracted to the positive charged plate.
Connected evidence	Student connects observations with claim or model by describing the observation and linking that with the claim or model.	I have negative pieces which are the parts that left the atom and made the ray. We know these pieces are negative because the ray was attracted to positive and repelled by negative.

Preparation for future learning coding scheme

Preparation for future learning research argues that—instead of focusing on whether or not students develop a correct solution to a new context—the questions students ask are a significant indication of how students transfer their knowledge to new scenarios (Bransford & Schwartz, 1999). Thus, I wanted to capture not only whether students had appropriate or inappropriate ideas but also whether students were trying to apply their ideas to the new contexts we discussed in the interviews by asking questions that would help them develop a more complete answer, and whether students could identify tests they could do in order to gather that new information. In order to capture these ideas, I developed a preparation for future learning coding scheme, summarized in Table 7.

Table 7: Preparation for future learning codes

Code	Description	Example
Application—student was asked to explain a situation that was connected to electrostatic interactions at the atomic level		
None	Student is not able to answer the question. This is not included if the opportunity never arose; it is included only if the student was asked to apply ideas to a new context and was unable to answer the question.	I don't know.
Speculation without class ideas	Student speculates about answers without using ideas from class to develop or support their ideas.	Maybe it has to do with the vitamins in the food you eat.
Application of class ideas	Student uses ideas from class to speculate about possible answers.	Charged atoms could attract or repel.
Question—questions the student asked while forming their explanation		
Unproductive	When prompted to, student asks questions that are similar to what they were asked by the interviewer.	How does it work?
Productive question	When prompted to, student asks a productive question that would give them relevant information that they could use to evaluate and/or revise their ideas and answer.	Can the atoms have different charges?
Productive question—unprompted	Student asks a productive question without being prompted.	Can the atoms have different charges? (without being prompted to develop a question by interviewer)

Table 7 (cont'd)

Test—description of a test that could be done to gather evidence that would answer questions the student defined		
None	When prompted to, student is unable to propose a test. This is not included if the opportunity never arose; it is included only if the student was asked what test they could do and was unable to answer.	I don't know.
Productive test	When prompted to, student proposes a test that would provide useful data to inform their answer.	We could use the pieces of tape to test if it is positive or negative.
Productive Test—unprompted	Student suggests a test that would provide useful data to inform their answer without being prompted.	We could use the pieces of tape to test if it is positive or negative. (without being prompted to develop a test by the interviewer)

I randomly selected a student response from each interview and debrief and had two other researchers from the Interactions Curriculum project code the responses. We compared our codes and while we agreed on most codes, the process of comparing and discussing codes was used to clarify the coding schemes.

Appendix F has transcripts of a randomly selected student response from each interview and from one of the atomic-model debriefs, along with the content ideas, content themes, justification and reasoning, and preparation for future learning codes to demonstrate how these codes were applied to the student responses. Throughout the transcripts in Appendix F and in the Findings chapter, when quoting students in the quotes, I use brackets to add descriptions of gestures and objects students are referring to when it helps clarify what the student is saying.

After reviewing all class models, the interviews, and debriefs, I wrote a case for each student. In the case, I summarized the student's written responses, the content themes, reasoning codes, and preparation for future learning codes for each interview and debrief. I then compared the content themes and codes across the cases. For each interview, I summarized the content theme each student expressed and whether or not each student applied his/her ideas to explain the scenarios, asked productive questions, or proposed tests in his/her explanation (Tables 8-11). In the tables, I used a single content theme to identify each student even though they may have included multiple themes in the interview. In the tables I identified the content theme the student used to develop the most complete explanation. I also focus on the content themes and preparation for future learning codes to identify patterns in students' responses because so few students provided any justification in their responses in the full interviews. Since the scenarios discussed in the interviews varied in terms of how closely they related to the activities done during different portions of the curriculum, the same scenario may have counted as a far transfer scenario in one interview but a close transfer scenario in later interviews.

Table 8: Summary of pre-interviews

Content	Application of ideas		
	Did not apply ideas	Applied ideas	Asked productive questions
Atoms are pieces of matter	Claire Mallory		
Atoms have pieces	Brittany Tony		
Atoms have charged pieces	Chase Christopher Lily Fabrizio Aiden		Nate

Note: Jonathan's interview was lost before analysis was completed

Table 9: Post-Unit One interviews

Content	Application of ideas to examples similar to class (close transfer)		Application of ideas to new context (far transfer)		
	Yes	No	Did not apply ideas	Applied ideas	Applied ideas and asked questions
Atoms are pieces of matter					
Atoms have pieces					
Atoms have charged pieces	All students		Claire Mallory Christopher – did develop reasoned hypothesis but not using class ideas	Jonathan Brittany Chase Tony Lily Fabrizio Aiden	Nate

Table 10: End of semester

Content	Application of ideas to examples similar to class (close transfer)		Application of ideas to new context (far transfer)		
	Yes	No	Did not apply ideas	Applied ideas	Applied ideas and asked questions
Atoms are pieces of matter	Claire		Claire		
Atoms have pieces	Brittany			Brittany	
Atoms have charged pieces	Christopher Jonathan Mallory Chase Lily Fabrizio Aiden Nate			Christopher Mallory Chase Lily Fabrizio Aiden	Jonathan Nate

Table 11: Follow up interviews

Content	Rod and Mylar (close transfer)				Rod and liquids			
	Did not apply class ideas	Applied class ideas	Applied class ideas w/ questions	Applied class ideas w/ test	Did not apply class ideas	Applied class ideas	Applied class ideas w/ questions	Applied class ideas w/ test
Macro scale charges		Claire Mallory				Christopher		Claire[‡]
Atoms are pieces of matter						Mallory Brittany		
Atoms have pieces								
Atoms have charged pieces		Christopher Jonathan Brittany Tony Lily Fabrizio Aiden		Chase Nate*		Jonathan Tony Lily Fabrizio Aiden	Nate*	Chase

Table 11 (cont'd)

Content	Protein folding (far transfer)			
	Did not apply class ideas	Applied class ideas	Applied class ideas w/ questions	Applied class ideas w/ test
Macro scale charges	Claire Mallory			
Atoms are pieces of matter		Brittany		
Atoms have pieces				
Atoms have charged pieces		Christopher Chase Tony Lily Fabrizio Aiden	Jonathan* Nate*	

**Student suggested test or question without being prompted by the interviewer.*

‡Interviewer pushed student to identify a test, because student was struggling to answer questions.

When comparing content themes and preparation for future learning codes, the students generally responded to the scenarios quite similarly. The exceptions were Claire, Christopher, Mallory, and Nate. I compared the students who were able to develop causal explanations to novel phenomena in the follow up interview to identify what was similar across those students. I also compared the students' responses over the course of Unit One. Finally, I contrasted the students who were able to explain novel scenarios to the students who did not match the general responses. Through this comparison and contrasts across the cases, I identified four themes: 1) the students were able to use the relationships between components in their models of atomic structure to apply their models to explain phenomena, including novel phenomena (explanation of phenomena); 2) students' struggled to use evidence to revise their models of atomic structure but in the end developed models that included relationships between the components (atomic model changes); 3) students developed models of atomic structure that they applied to explain phenomena, but they did not use models of electric fields in this way (models of fields versus atoms); and 4) too much focus on details interfered with students' ability to apply their models to explain new phenomena (focus on details). In the Findings chapter, I will review each of these themes.

Chapter 4: Findings

In this chapter, I start with a general overview from the data analysis in reflection to the research questions. I then review the evidence organized around the themes defined in the data analysis section of the Methods chapter. I end with a summary of the findings.

Findings Overview

Question One:

How do students' models of electric fields and atomic structure change over time through instruction based on a scaffolded curriculum designed to align with three-dimensional learning?

The students' models of electric fields and atomic structure both changed throughout the semester, however, they changed in different ways. Students were not familiar with electric fields before instruction. Students learned to interpret electric fields; however, in general, the students did not use the idea of electric fields to explain phenomena. In the pre-interviews, the students generally thought of electric fields as a sort of protective device that may be referred to in science fiction stories or video games. Students also discussed magnetic fields rather than electric fields. Once students had been introduced to electric fields in Unit One, they could interpret images of electric fields, noting variations in the strength and direction. However, students generally treated the arrows as showing a flow of something—such as energy, charge, or electricity—rather than an indicator of what would happen to a positive test charge at that point. Once students were introduced to electric fields, their ideas of these fields did not develop any further. In general, students could interpret a representation of an electric field to determine relationships; however, they did not include electric fields in their own explanations or models and instead used their atomic models.

The students in this study were aware of images of atomic structure before they started the Interactions Curriculum. Most of the students went to the same middle school and recalled a project they did in seventh grade as the source for where they learned about atomic structure. The students had similar representations of atomic structure before instruction: they drew concentric circles and focused on the number of protons, neutrons, and electrons in a particular atom.

During the curriculum, students were asked to develop revised models of atomic structure that could explain observations from Thomson's Cathode-Ray tube and Rutherford's gold foil experiments. Students struggled to connect observations from these experiments to their atomic models. Students recalled the conclusions made by the scientists and described the evidence that supported the scientists' claims, but they did not link the evidence back to their own models of atomic structure. For example, they might describe how Thomson concluded that atoms have small negative pieces based on the effect of charged plates on a ray of particles emitted from different metals, but they did not identify that the negative pieces in their models were the negative pieces in the Cathode-Ray.

Significant changes in students' models of atomic structure were more related to the relationships rather than to the specific components students included. In the pre-interviews, students generally knew that atoms have protons, neutrons, and electrons and that some of these pieces have different charges. During the semester, students were asked to use evidence to evaluate and revise their atomic models. Students all struggled to explain the evidence from the historical experiments we discussed and relate that evidence to their revised models. However, by the end of Unit One, students were able to use relationships and connections to phenomena in their models of atomic structure to build causal mechanisms to explain phenomena. During these explanations, students discussed electrons transferring from one atom to another, the ratio of protons to electrons affecting the charge of an atom or object, and electrons shifting due to attraction to protons or charged objects. The significant changes were related to interactions between the pieces of atoms and between atoms and other atoms or objects. Students shifted from focusing on the number of sub-atomic particles to discussing the movement of electrons and the attractive and repulsive forces among protons and electrons.

Are the models students develop retained after instruction?

The students were able to discuss and apply their ideas about atomic structure a semester after they finished the Interactions Curriculum. In the follow up interview, the majority of students continued to include relationships by describing the movement of electrons and the attractive and repulsive forces among protons and electrons. Students used these relationships to explain a range of phenomena including new phenomena.

Question Two:

How do students use their evolving models from curriculum designed to align with three-dimensional learning to explain electrostatic phenomena?

Students did not use models of electric fields to explain phenomena. However, after students developed more dynamic and interactive atomic models, they used these relationships in their models to explain a range of phenomena. In the pre-interview students explained electrostatic phenomena at the macroscopic scale. However, in subsequent debriefs and interviews, when I asked students about electrostatic phenomena, most of them discussed atomic-level causes without being prompted to do so. When asked to explain a scenario, students described how electrons could move from one object to another to make the objects charged and explained that neutral objects are attracted to both positively and negatively charged objects because the neutral object has both positive and negative charges that can shift around and attract to the charged object.

Question Three:

How do students apply their evolving models of atomic structure to novel phenomena?

Once students included relationships and developed a dynamic and interactive atomic model, they could use that model to make predictions about new phenomena. For example, before we discussed bonding, several students predicted that the electrons within two interacting atoms could shift. Students also used the idea that atoms with different charges within a protein could attract and repel, pushing portions of the protein into specific shapes. When students speculated about new topics, they often suggested multiple possible explanations or predictions and asked productive questions, indicating higher levels of preparation for future learning.

Explaining new phenomena was a significant shift for most students as students generally struggled to develop causal relationships to explain phenomena in the pre-interview. However, two students continued to struggle to apply their ideas to new phenomena through the semester and in the follow up interview. The shift to explaining new phenomena was correlated with including relationships in their models and with less emphasis on recalling details. Most students in the pre-interview and the students who continued to struggle with new phenomena in the follow up interviews focused on recalling pieces of information and did not speculate about how those ideas fit with new phenomena. However, even when students could not recall all the ideas in the post-Unit One and follow up interviews, they were able to use relationships to speculate about cause for new phenomena.

Themes and Evidence

Explanation of Phenomena

By the end of Unit One and throughout the rest of the interviews, students were able to use their models of atomic structure to develop and support explanations and predictions. In this section, I will give some examples from the interviews where students were explaining scenarios that were closely related to activities we did in class as well as scenarios that were new to the students. I will discuss these examples in chronological order based on when the interviews occurred. I have selected students who represented common responses among the students and highlight how students were applying their models of atomic structure to build their answers.

By the post-Unit One interview, most students were using relationships among components within atoms to explain phenomena. For example, when asked to explain why hair sometimes stands up after taking off a knit cap, in the post Unit One interview, Chase clearly used atomic-level causes to explain the phenomena. However, his answers were not completely accurate, and his self-corrections show how he was applying his understanding rather than memorizing information. For example, he initially said that the protons move from the hat to the hair to make the hair the same charges and repel. He corrected himself saying:

> Why did I say protons? It should be electrons, because usually protons don't move.

When I asked him why electrons instead of protons, he added:

> Because protons are in the nucleus, and they are attracting by the strong nuclear force, so do that [his previous explanation] but with the electrons.

By making mistakes and using his understanding of atomic structure and interactions to support his correction, Chase was not just memorizing answers but was applying his model to support his ideas. When he used the wrong word, he used his model (electrons on the outside and protons interacting through a strong nuclear force) to support his revised answer.

In the post-Unit One interviews, students also used their models to explain why neutral objects and charged objects attract. The students had very similar responses to Lily who said that the balloons in the third image could either be oppositely charged or one could be neutral and the other charged. When I asked Lily to explain this later scenario more she said:

> Lily: Well, the, um, in a neutral atom it has both negative and positive charges, so when something is charged negative or positive it is attracted to that aspect in the neutral atom.
> Interviewer: So let's say, for example, if this is like positive and that's neutral.
> Lily: The electrons in the neutral balloon are pulling the positive balloon towards it.

Lily is using the interactions at the atomic level to develop a mechanism to explain the scenario. She also developed multiple possible explanations (the balloons could have opposite charges or one could be neutral and one charged). This is very similar to the rest of the students. In the post-Unit One interview, they all used the ideas of atoms and movement of electrons to explain the interactions between the hat and hair and the images of the balloons without being prompted to use atomic-level ideas to form and support their explanations.

The students, with the exceptions of Christopher, Claire, and Mallory, also used an atomic-level cause to explain the video of the magnesium burning, a phenomenon that students had not studied in Unit One. The students had not covered bonding or reactions yet in class, so in this scenario, I was asking the students to apply their ideas to an upcoming topic. Jonathan's explanation represents the range of ideas shared by most of the other students. He started by saying, "It gains mass even though it's burnt, it confuses me I still don't understand that." Jonathan openly stated that he was not sure about what was happening in this scenario. He then said he thinks, "that maybe a chemical reaction of some sort is going on." After some follow up questions where I asked Jonathan to elaborate on what he meant and if any ideas from class might be related he came up with a possible mechanism stating:

> Jonathan: Maybe they gained electrons from the flame. And maybe they gained a bunch [laughs] which might make it heavier.
> Interviewer: Why do you say a bunch?
> Jonathan: Because I don't think gaining one electron would increase it that much because they [electrons] are smaller than the atom itself so I think you would have to gain a lot [of electrons] to gain any mass.
> Interviewer: Okay. So what about, any predictions about any properties, so we were left with that white powder at the end
> Jonathan: Yeah.
> Interviewer: So if you think that when it was burning it was gaining electrons, can you make any predictions about what that white powder would be like, any properties it would have?
> Jonathan: Mm, I think that it might be neutral, because all the electrons- NO! I think that it would have a very negative charge because it gained all those electrons to gain weight. Because we know that it wouldn't gain protons because that would change the whole substance itself, that would change what element it was, so it would be a very negative form of burned ash magnesium.

Jonathan's first mechanism was that perhaps the magnesium gained a lot of electrons from the flame. This is an unlikely explanation, since the mass of each electron is several orders of magnitude smaller than the mass of an atom. However, in class, students were using transfer of electrons to explain how objects become charged. Here, Jonathan is applying that model and idea to explain a new phenomenon. Next, I asked Jonathan a question where I was hoping to get him to summarize what he was thinking, since he had shifted some of his ideas during the explanation. Instead of summarizing his ideas, he developed an alternative explanation:

> Interviewer: So in the beginning it was kind of a coil of metal and in the end it was that ash, why do you think it looked so different in the end?
> Jonathan: Maybe it did gain protons? That's why it looks so different, it completely changed. Because when we were doing our simulation in the computer when it, when we added or took away protons it completely changed what it was. So, and now it looks nothing like it did in the beginning, so it might have gained or loss protons. Probably gained because it gained a bunch of, it gained some weight, so it might have gained protons and electrons which made it change its substance, form, appearance anyways, and it also gained weight. Just an idea.

By canonical ideas, this is an unrealistic answer. Protons are only added to atoms during nuclear reactions. However, Jonathan was applying his ideas to a new phenomenon and was speculating about multiple possible atomic-level causes that could account for his observations. He saw that the material looked different and that the mass increased after the reaction. He proposed that maybe protons were added, which would have added some mass and changed the material into a new element. His ideas may be unlikely, but they are consistent and logical, given his knowledge. These two explanations were common among the other students.

In addition to applying ideas to develop an atomic-level cause, students also started asking productive questions during the post-Unit One interview. When I asked Chase about the magnesium burning scenario, he started by asking productive questions:

> Chase: The element was the same, right?
> Interviewer: It was magnesium to start with.
> Chase: What was it afterwards? Still magnesium or something else?

Chase was asking productive questions: did the element change during the reaction? He realized that if he knew what material was left at the end of the reaction, he would be able to develop a more complete explanation. Thus, Chase was indicating preparation for future learning by applying his ideas to new phenomena and asking productive questions to inform his answer.

Students continued to develop atomic-level mechanisms to explain observations even after they finished the curriculum and moved on to other science topics. In the follow up interview, I asked the students about three new scenarios: the interaction between a charged rod and piece of Mylar, the interaction between a charged rod and thin streams of two liquids, and protein folding. The students' responses—with the expectation of Claire and Mallory—to the rod and Mylar and rod and liquid reflected the same ideas the students had shared when explaining the hat and hair and balloon scenarios. The students talked about electrons transferring and shifting to explain these interactions. Additionally, the students were able to explain a new and complex phenomenon: protein folding. Since proteins and protein folding was a topic students had not covered in any of their coursework, I used an analogy of folding paper into a swan shape when discussing this question. Again, the students—with the exception of Claire and Mallory—were able to apply the idea of atoms to develop a mechanism to explain this abstract phenomenon. For example, when I asked Fabrizio about what could make proteins fold into a particular shape, he quickly stated:

> Fabrizio: Probably the charge of the atoms. Uh, you know the DNA, it says which atoms to, you know, organize themselves in a certain, you know, way. And then, you know, those atoms have a certain charge and then they are either going to be attracted to each other, not attracted to each other, or have no interaction. So, I'd say, yeah just the positive or negative charges, or neutral charges, within the atoms, uh, change how it bends.
> Interviewer: So, the atoms within that chain
> Fabrizio: Yeah, the atoms within the chain

> Interviewer: Will bend to be attracted or
> Fabrizio: Yeah, so if this part of the chain was positive [picking up paper swan and pointing to the back] and this part of the chain was negative [pointing to the neck], you know from the flat piece of paper, it will be attracted to each other and form the shape that it does [folding the paper to push the back and neck closer to each other].

His answer is not complete if judged solely in comparison to canonical ideas. He did not include any interactions outside of the chain: his causal account relied solely on interactions among atoms in different parts of the chain. Yet since Fabrizio had not taken any Biology courses, his answer reflects his ability to identify atomic-level causes that include electrostatic interactions to explain a complex and abstract phenomenon he had not studied before. He continued to use and apply ideas even after he had moved on to different topics in his science class for a semester.

Chase had a very similar response to Fabrizio, stating that charged atoms in one part of the chain would attract to oppositely charged atoms in another part. He ended his responses by stating, “It’s pretty cool how they're just doing that.” While, like Fabrizio and many other students, Chase’s explanation is incomplete by canonical ideas, not only was he able to apply his ideas to develop a mechanism, he is expressing an appreciation for the phenomenon.

Students were indicating preparation for future learning by applying ideas to new phenomena and asking productive questions. For example, as Jonathan was developing this idea, he asked if proteins change their shape. We discussed protein shapes and how they can shift and he used this to develop a more complete explanation. He ended up saying that the protein could attract to other things because oppositely charged atoms in one protein are attracted to another protein. Then he thought that once they were close, similar charges could push other parts of the protein making its shape shift.

Christopher is an interesting comparison, given he had additional content background in Biology and knew more about proteins and protein folding. However, the causal explanation he gave about how proteins fold was similar to those given by other students: charged atoms interact and push or pull on different portions of the protein chain. When I asked Christopher about protein folding, he told me he was taking Biology at the same time as Physical Science. He recalled several pieces of information about how proteins are formed. He described the processes of translation and transcription and also recalled different types of errors that could occur during protein synthesis, or that sometimes they can “mess up,” but “sometimes you can get away with it because there’re different ones [codons] that code for the same protein.” When I asked him about what makes the proteins fold, he immediately said, “Uh, the charges of the atoms that are used to make up the amino acids.” When I asked him to explain more, he drew a model (Figure 4) and explained, “If it was a chain right here, it was like that. And then this was positive and this was negative, this [drawing an arrow from the negative to the positive] would want to move over there.” I asked him if he learned that, since he was so quick and confident in his answer, but he said he did not learn it and was just making a prediction. When we first started discussing proteins, Christopher listed terms he learned in Biology class. However, when I asked him to explain something he had not covered in Biology class, he responded confidently and, like Fabrizio and the other students, applied his model of the interactions between charges at the atomic-level to develop causes and effects that could explain the phenomenon. Christopher recalled lots of the facts covered in both Biology and Physical Science class and also applied ideas from Physical Science to explain observations.

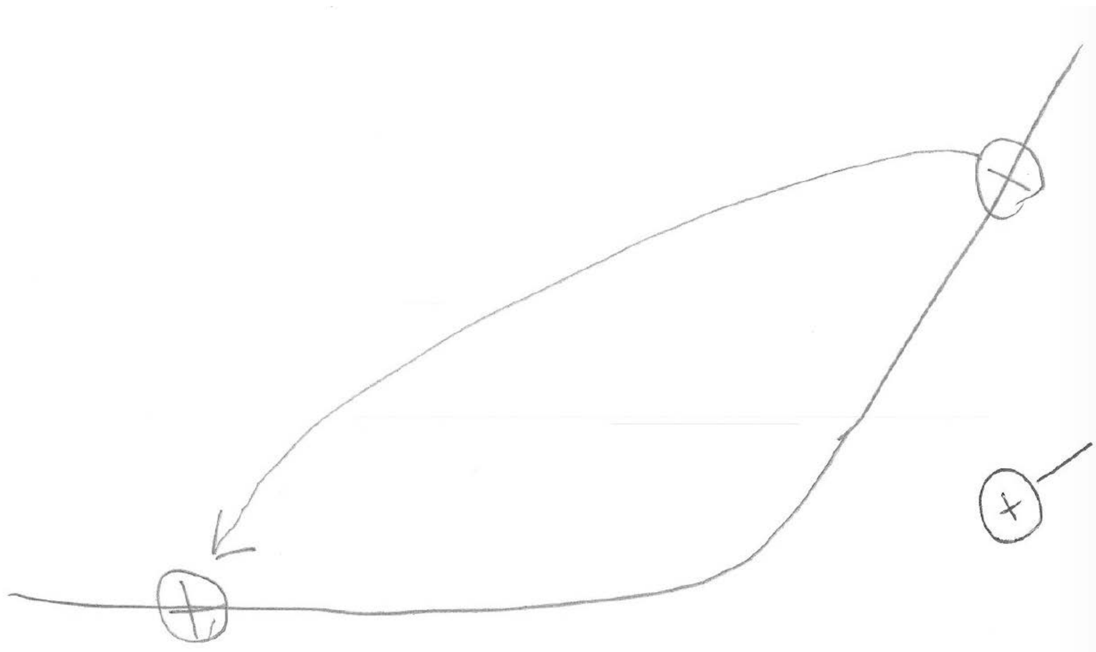


Figure 4: Christopher's model of protein folding

Mallory and Claire were not able to develop atomic-level causal explanations of the phenomena of protein folding. These two students could explain observations using atomic-level causes in the post-Unit One and end of semester interviews, but did not continue to use those ideas in the follow up interview. I will elaborate on this contrast more when discussing the fourth theme: focus on details.

Atomic Model Changes

The students had learned about atomic structure in seventh grade, except Jonathan who moved schools over the summer. In the pre-interview, the students already knew about atoms before starting the curriculum, but they could not use their ideas to explain any of the scenarios we discussed. In the curriculum, students were asked to use evidence from historically significant experiments to evaluate and revise their atomic models. Students generally struggled to do this, but by the end of Unit One, students had dynamic and interactive models of atomic structure that included relationships where components could move and react that they could use to develop causal mechanisms to explain phenomena. The components the students included did not change; what did shift is the students changed from recalling the structure of atoms to talking about the relationships and interactions between the components. This shift happened through struggling to explain evidence from historically significant experiments and, at times, seemed like students were making unproductive revisions to their models. In this section, I focus on Chase's models, debriefs, and interviews because his responses were consistently representative of the majority of the students. I have included a couple comparisons to other students to illustrate the patterns clearly.

In the pre-interview, Chase did not use understanding of atoms to explain any of the observations or situations we discussed. His understanding of electrostatic interactions was limited to the idea that they are caused by friction. He stated:

> Because it [hat] rubs around. It causes friction, and some type of, I don't know, friction, magnetic force, I don't know, it just when you go like this [moved hands to pantomime removing a hat], it [hair] tries to stick to it [hat] still.

He seemed to use "magnetic force" as a synonym for attraction, and the only cause he gave for this force or attraction was friction.

Chase had learned about atoms and knew that they had positive protons, negative electrons, and neutral neutrons, but he did not use atomic-level reasoning to explain any of the situations we discussed. When we discussed atoms, like many students, he only recalled pieces of information and told me about the project he did in seventh grade for which he picked an element and determined the number of protons, electrons, and neutrons in that atom. When asked to draw the atom, he drew a circle and stated that he would need to figure out how many protons, neutrons, and electrons would be in the atom in order to complete the drawing. When asked about atoms interacting, he again referred to an activity from seventh grade and said he remembered putting balls together to show how atoms combine to form molecules.

Chase's ideas were accurate, but he did not include relationships in his understanding of atomic structure. Further, he did not use these ideas to develop causal explanations of observations. When asked if there was a connection between atoms and the scenarios we discussed, he said, "I'm pretty sure all that is connected in one way…what we're trying to learn here is that it is all connected somehow." He seemed to deduce a connection from my questions. When I asked what the connection might be, he paused for a while and then speculated, "Maybe, something to do with the positive and negative charges that it might have?" He did not use these ideas to develop a causal account but rather was guessing that, since I was asking this series of questions, they were probably connected. Thus, his understanding of atomic structure indicated low preparation for future learning. He could recall the ideas he learned earlier, but could not apply them appropriately to new context or identify what he would need to learn to make the connection.

In general, while he speculated about a connection between atoms and observations, Chase's ideas in the pre-interview were discrete: facts such as atoms have protons, neutrons, and electrons, or simply the idea of 'friction' to explain the observation of what happens to hair after taking off a knit cap. Although he speculated that there might be a connection between atoms and the observations we discussed, he did not make descriptive or causal links across these ideas.

Chase's initial model of the Van de Graaff generator and pie pans (Figure 5) shows an illustration of the phenomenon. The only components he included are the visible components, and he did not include any relationships that could be used to explain his observations. While in class, we discussed these first models and the need to clearly connect the model to the observations, and students were instructed to add descriptions to their model, Chase did not make any modifications to his model after the discussion.

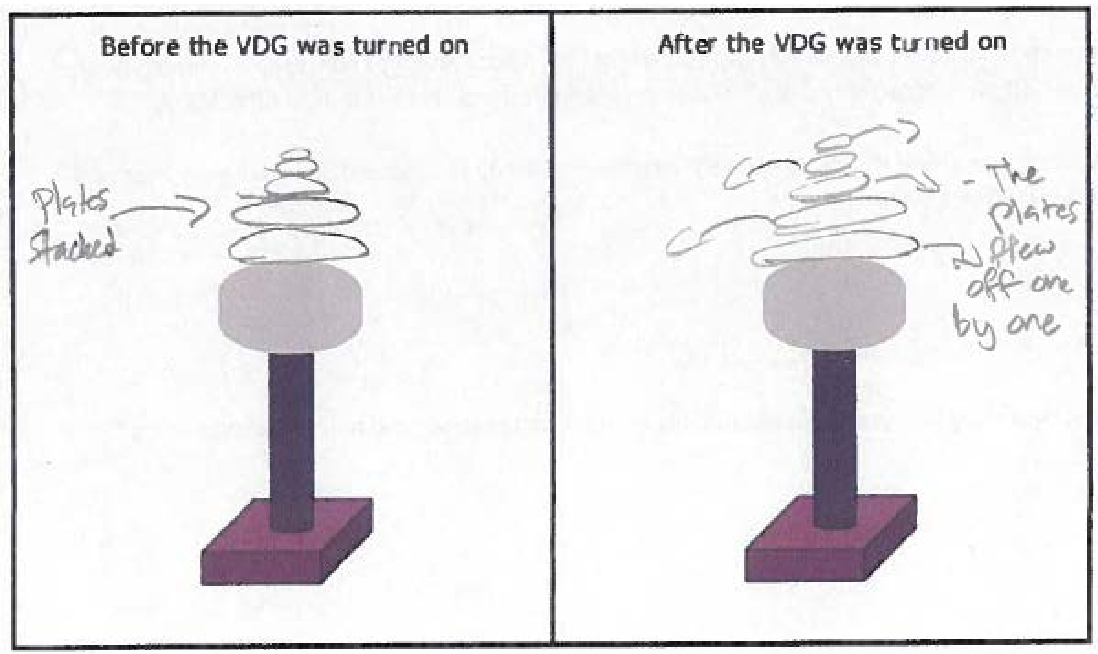
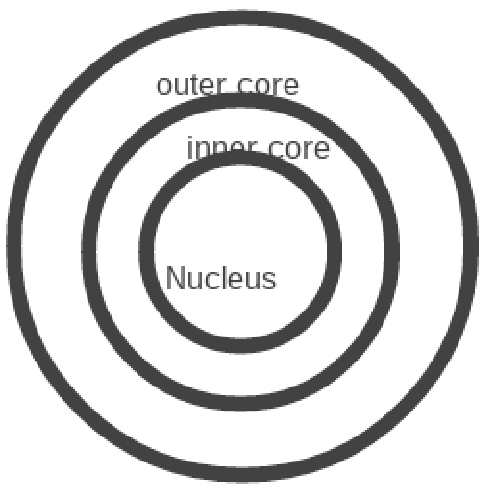


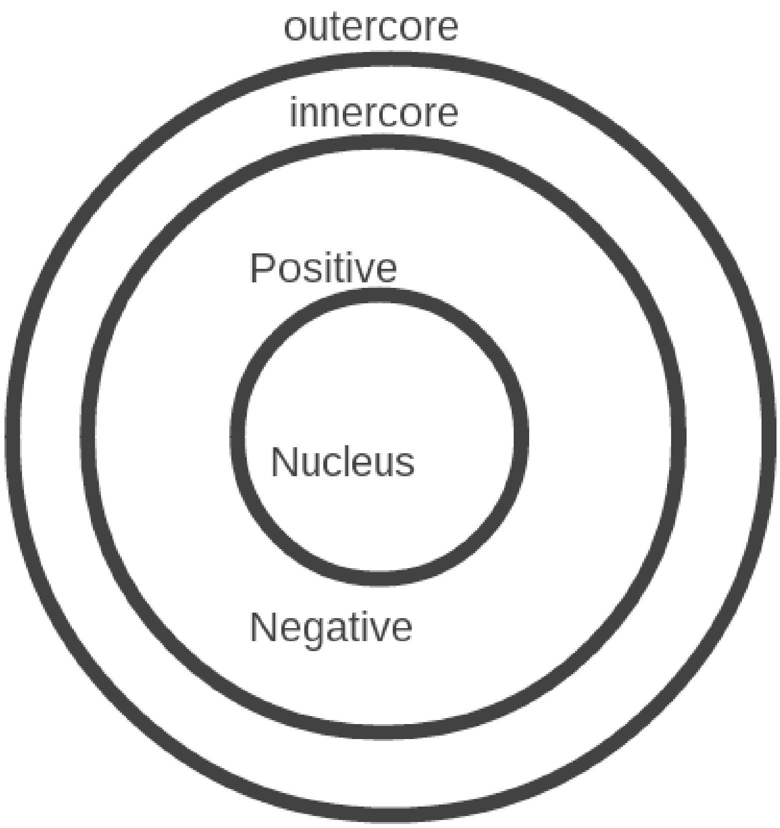
Figure 5: Chase's first model of Van de Graaff and pie pan

The second part of Unit One focused on developing atomic models, then using the atomic models to revise the models and explanations of phenomena discussed in the first part. Chase's initial model of an atom (Figure 6) resembled a model of the layers of Earth's interior: concentric circles with labels like "inner core" and "outer core." In the debrief he said these were details he remembered from when he studied atoms in middle school. His next representation of an atom (Figure 7) included charges that corresponded to the different layers or "cores." He said he added these charges because, "Well, we learned in the past week or uh few days, that an atom can have positive and negative charge." He said this idea came from the "models" (referring to the simulations). He described the simulation that showed that atoms coming from metal were attracted to a positive plate (Figure 8). He stated these ideas as discrete facts that were added to his model of the atom. He was not relating the observations Thomson actually made to the model he drew.



atoms make up the materials we have been working with

Figure 6: Chase's initial atomic representation



An atom has both charges because it can be attracted to negative and positive objects.

Figure 7: Chase's second atomic representation

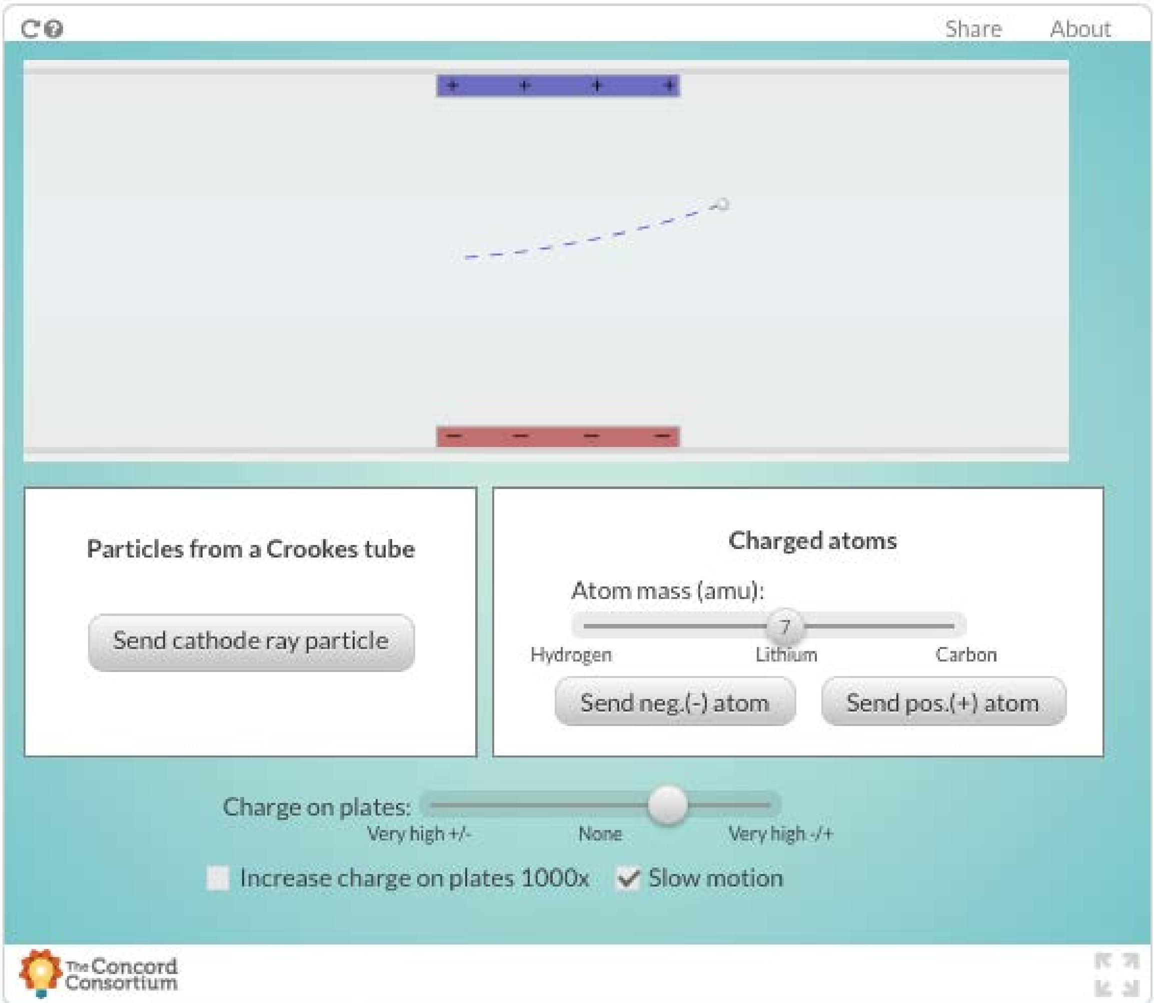


Figure 8: Image of simulation Chase discussed in debrief to justify adding charges to his atomic model

After studying Rutherford's gold foil experiment, students drew a revised atomic model in class, but, due to technical problems at the time, Chase's model did not save. Therefore, during the debrief, instead of discussing the model I printed from his report from class, I asked him to draw his revised model of the atom so we could discuss that. He drew a model of the atom that looked similar to a canonical representation of the Bohr atom (Figure 9). His nucleus took up a significant portion of his atom and included protons and neutrons; negative electrons were added around the outside.

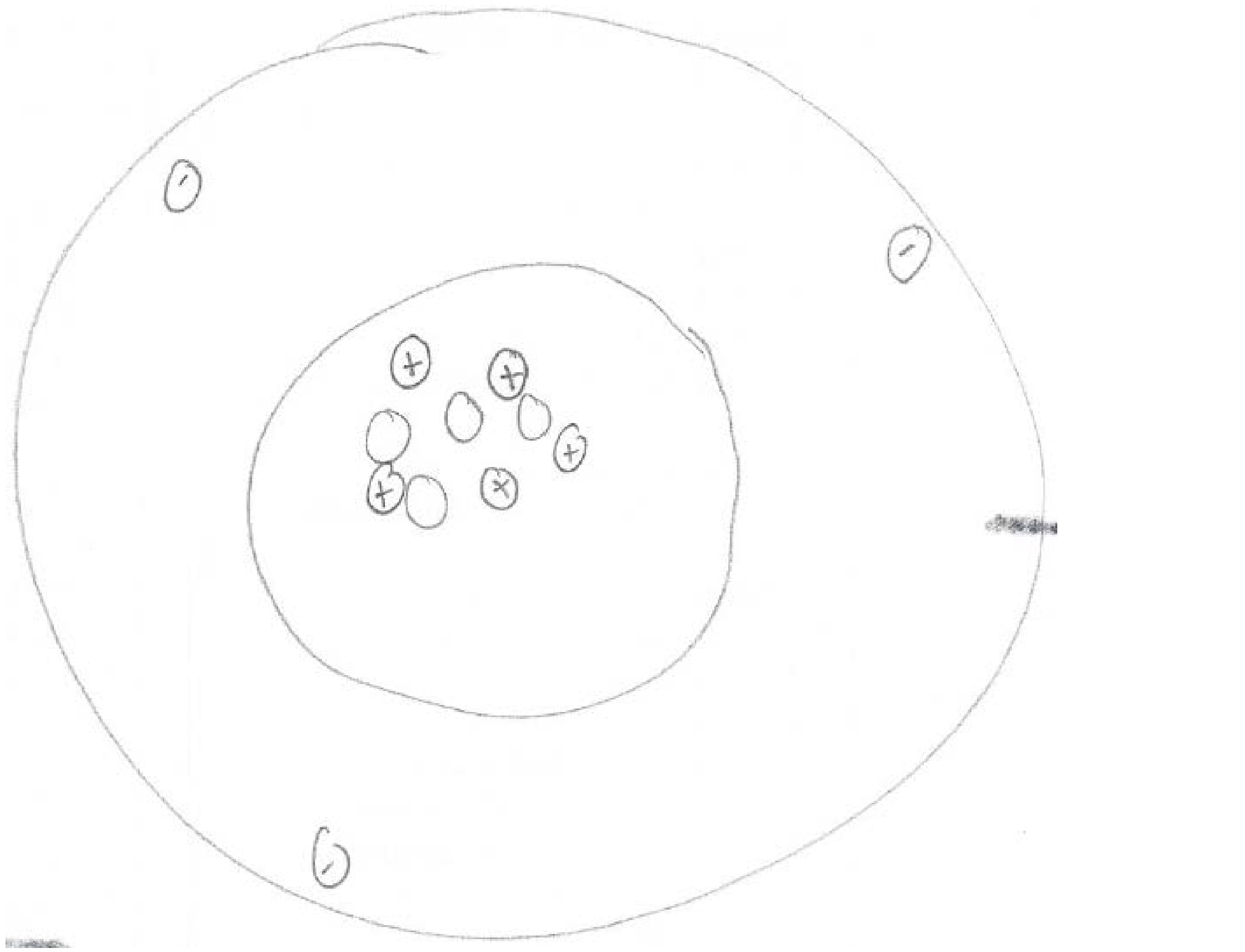


Figure 9: Chase's drawing of atomic structure from after Rutherford experiment debrief

In this debrief, as Chase was starting to draw his model of the atom, he stopped and asked, “What were we trying to figure out again?” This could be an indication that he was beginning to internalize the idea that a model is connected to phenomena or “figuring” something out or explaining some observation. Although, he did not talk about the purpose of a model being a significant aspect of modeling even in later interviews, at this point, he stopped drawing his model until he had determined what he was trying to “figure out” by drawing it.

As he drew this model, he said that Rutherford learned that there are more positives than electrons. Similar to the debrief after Thomson’s experiment, he struggled to accurately describe the relationship between Rutherford’s observations and the variables tested in the simulation. For example, rather than talking about the alpha particles bouncing off or going through the gold atoms in the gold foil, he said:

> Well, the gold foil was pretty, um it's light, and I think it has a charge, I think it was positive, I can't remember. And this [point to atom he drew], and this was heavier than the gold foil so it [atom] went right through it [gold foil].

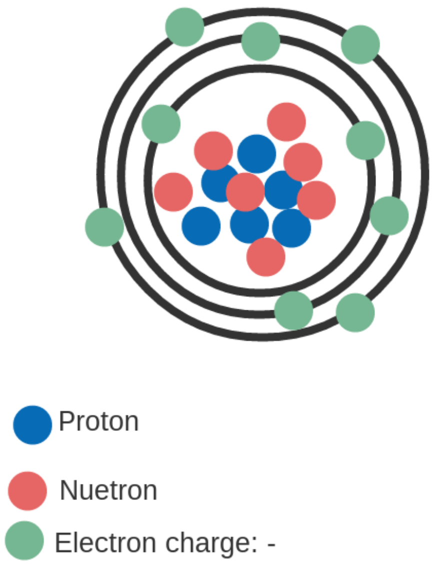
He had an idea of the observations Rutherford made and said those observations informed his latest model of the atom. He does not have an accurate understanding of the historic research, but understanding these historically significant findings was not one of our learning goals. Rather, these experiments and results were included in the curriculum to give students evidence to use to evaluate atomic models and apply their models to explain results. Chase does not build a strong connection between the historical evidence and his model, but it may not be too problematic that he does not accurately understand the details of these abstract historical experiments.

In this debrief, Chase was able to use his model of the atom to develop a causal account of the observations of electrostatic phenomena made earlier in the class. When I asked if the idea of an atom could explain any observations from class he said, "Well, probably, positive charged atoms were around the positive charged objects and like electric atoms, like electrons, on those, the electric charged." This explanation is incomplete in that he does not describe how his ideas link with his observations, but it does show that he is starting to connect atomic-level causes with macro-scale observations. When I asked him to explain the example of rubbing the balloon with fur, making the balloon negative, he thought briefly then said:

> Well the fur, you said it makes it negative, yeah okay, so the fur is probably negative and had negative charged atoms on it and the balloon was probably neutral so when you rubbed the fur on it, eh ele- uh negative charged atoms were on the balloon which made it negative.

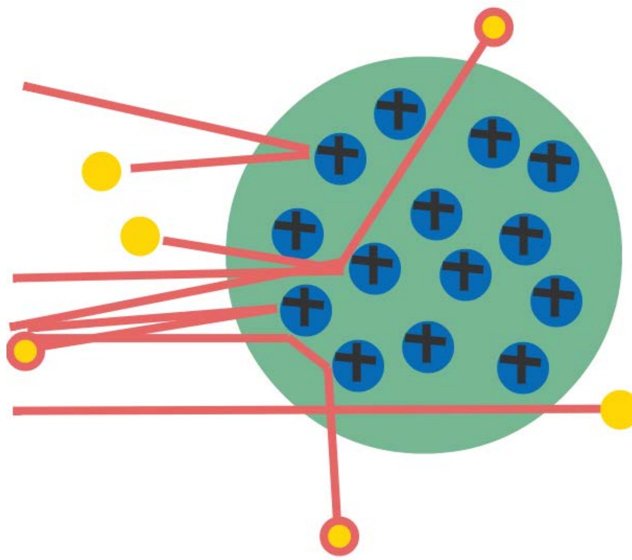
As he described this he also gestured, indicating the atoms were moving from the fur to the balloon. When I asked what that would do to the fur, he speculated that it might make the fur's charge "weaker or take it all." While he had observed the interactions between the balloon and fur, the class had not yet used atomic models to explain these observations. Therefore, these statements from the debrief show Chase, for the first time, applying ideas from his development of a model of atomic structure to phenomena he had observed. These statements also show stronger preparation for future learning. Chase is applying ideas to a context that was not discussed in this way before.

Like Chase, the other students struggled to fully link their atomic models to the evidence from the historical experiments we discussed. For example, when explaining Rutherford's results, Fabrizio changed his model from a nuclear model to a plum-pudding model (Figure 10), stating that Rutherford's observations could be explained by whether the alpha particle hit the charged "plums" or passed through the charged "goo." This is almost the opposite of Rutherford's conclusion, since he calculated that the positive particles in an atom had to be packed tightly together in order to have a strong enough electric field to cause the alpha particles to reverse their paths. Even though all the students did not understand the specifics of the historical experiments, most of the students were starting to change how they thought about the model of atomic structure. The students were transitioning from recalling the ideas they were taught in middle school to thinking of how their model might connect to evidence, even if they were confused about some of the details.



Protons are part of an atom, they have a negative charge.

Fabrizio's model before



It shows why the alpha particles bounce off the condensed atom.

Fabrizio's model after

Figure 10: Fabrizio's models before and after studying Rutherford's gold foil experiment

However, the students did link the interactions between charged sub-atomic particles to explain phenomena they observed in class and make predictions about upcoming topics. At the end of Unit One, when the students were asked to revise their models of the pie pans and Van de Graaff generator, Chase used charged particles or atoms to develop a model that could explain his observation (Figure 11). Chase did not include labels or descriptions on this model, so it is hard to tell if he is representing atoms or just using the circles to represent a charge building up on the objects. In the curriculum, the description of this task did not include a text box, and most students did not add text to explain their models, making these models generally more difficult to interpret as compared to the other models that included written descriptions. Chase is representative in that he included charged circles but did not clearly label or explain what he was showing. However, some of the students did more explicitly link their idea to atomic-level causes. For example, Brittany (Figure 12) clearly included protons and electrons and adjusted the relative number of protons and electrons to indicate the charge on the Van de Graaff generator and pie pans. The students' models could show that they are starting to use their models of charged sub-atomic particles to explain their observations, but since they did not include explanations or descriptions of their models, the connections between the causes and observations were not always explicit or clear.

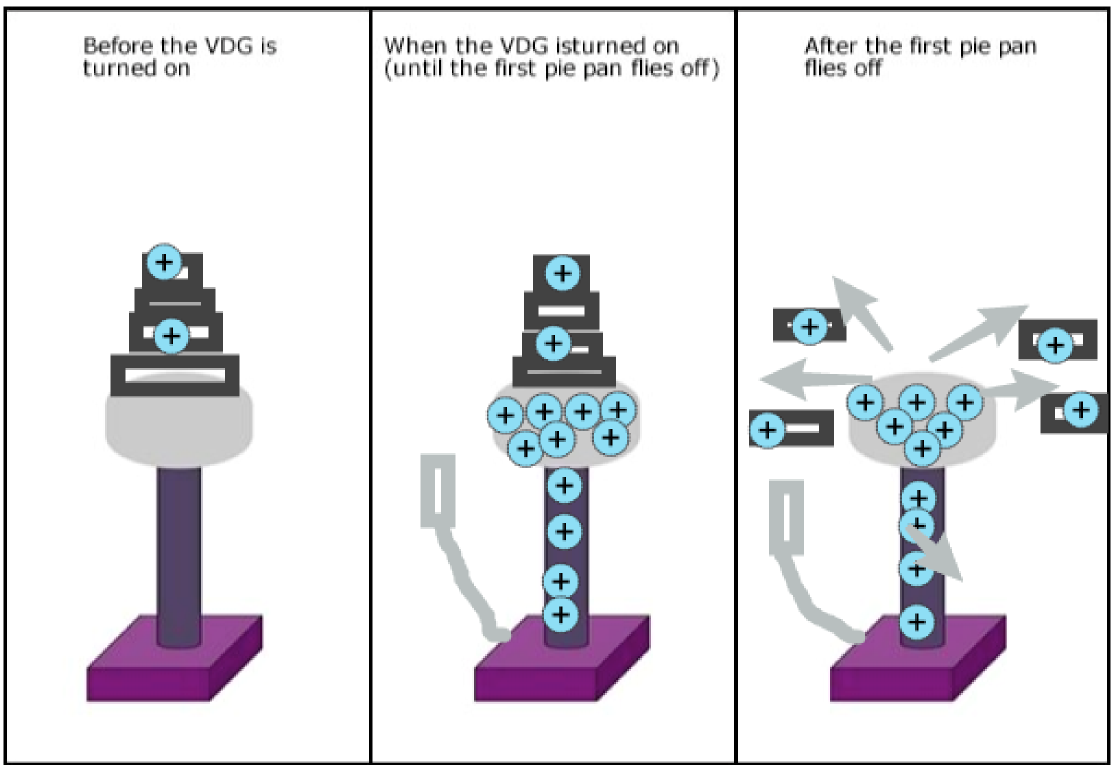


Figure 11: Chase's model of Van de Graaff generator and pie pans from end of Unit One

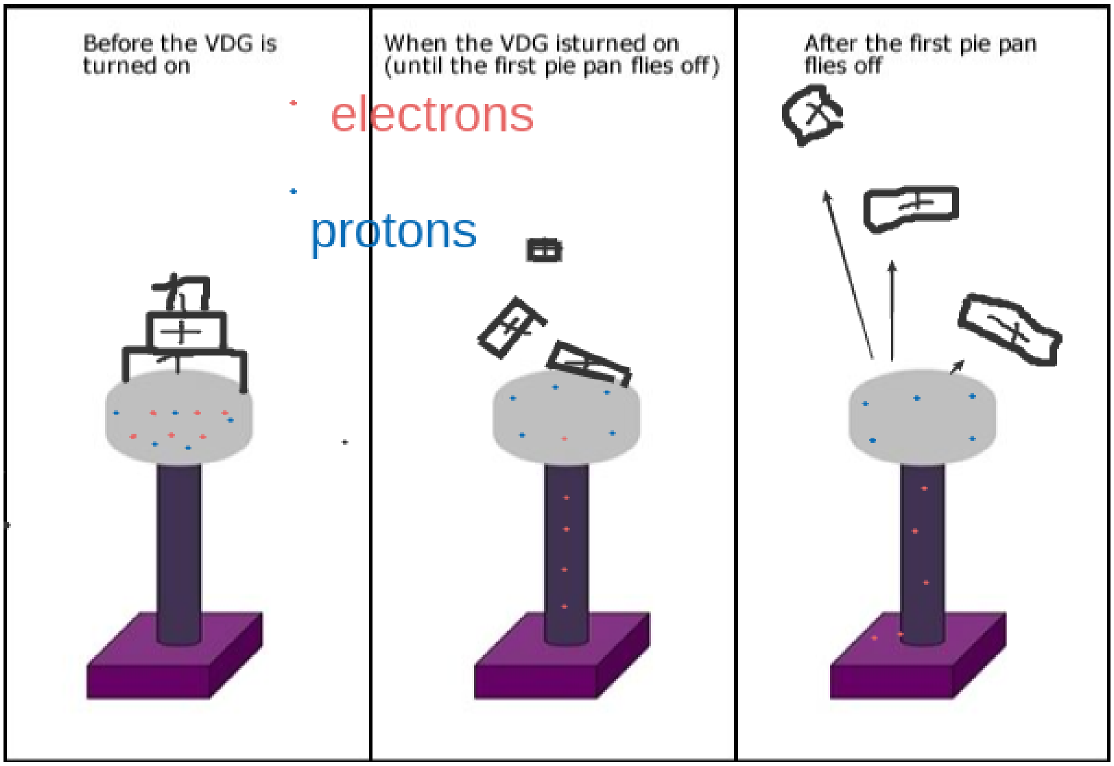


Figure 12: Brittany's model of Van de Graaff generator and pie pans from end of Unit One

In the post-Unit One interview, when I asked Chase what he thinks of when thinking of an atom, his model of atomic structure was more dynamic. Rather than focusing on the number of sub-atomic particles like he did in the pre-interview, or making revisions to what he recalled from middle school as he did during the debriefs, he now included relationships between sub-atomic particles. For example, he talked about how the neutrons balance out the protons because the protons would want to repel, and that the protons and neutrons are held by the strong nuclear force—indicated with arrows in his new drawing (Figure 13). He also described the electrons as closer to the nucleus but also moving all around. In contrast to the pre-interview, in which Chase stopped drawing because he needed to know how many protons, neutrons, and electrons to include, in this interview Chase “just” decided to include two of each.

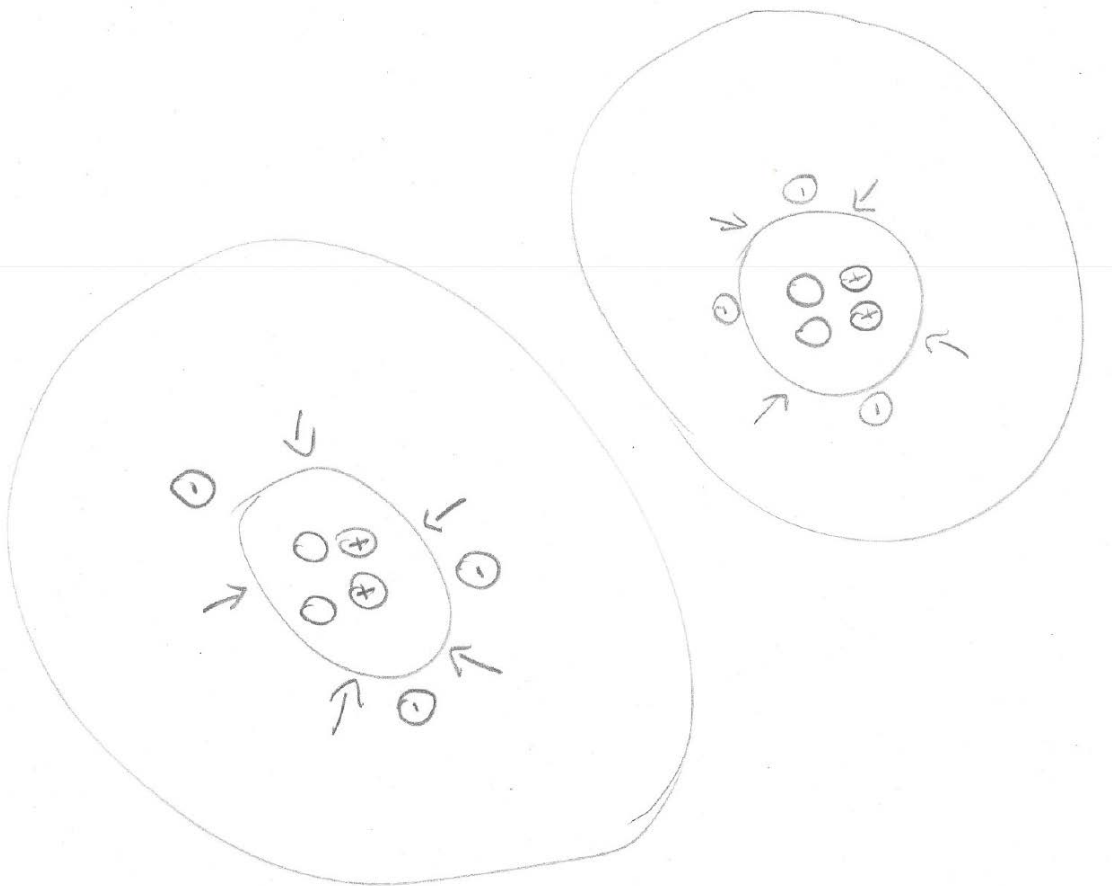


Figure 13: Chase's model of atomic structure from end of semester

In anticipation of working on bonding in Unit Two, I asked Chase to draw a second atom near his first one and asked how he thought the two atoms would interact. He said:

> Chase: Uh, yeah. These electrons [pointing to second atom] would probably go away from these electrons [on first atom] because they would repel. And that, yeah, so they would probably repel, actually.
> Interviewer: The whole atoms
> Chase [overlapping with interviewer]: because it's, it's
> Interviewer: would repel or its electrons would repel?
> Chase: Hm-mm. The whole, whole, um, I'm not sure about that. I'm gonna say the whole atoms.

Rather than focusing on the number of pieces, Chase discussed the relationships: forces and movement of the different sub-atomic particles, in addition to recalling information like where they are located and what charge they have. Again, this also indicates higher preparation for future learning, he is applying ideas to a new context and speculating about possible connections between his model and new phenomena.

Chase's model of atomic structure shifted from a static model in which he recalled facts to a dynamic and interactive model that included attractive and repulsive forces and that he could apply to explain observations and form predictions. Like most of the other students, Chase recalled learning about atoms from middle school. In the pre-interview, Chase could recall pieces of information about atoms; he recalled terms. Though Chase knew about atoms in the pre-interview, he got stuck when he could not remember details. He also did not apply his idea to develop causal explanations of phenomena. During Unit One, he made several different models of atomic structure as he studied evidence from significant historical findings. He did not understand the details of these historical experiments and struggled to connect those historical findings to the models of atomic structure that he drew. However, the details of atomic structure and the historical experiments were not the significant learning goals. Instead, the important shifts that happened during Unit One for Chase and the other students was starting to think about relationships and how the pieces of atoms are interacting with other atoms and objects. Once Chase thought about the pieces of atoms as interacting with other objects, he was able to apply his model of that atom to develop explanations and to form predictions about topics he had not yet learned about in class indicating his preparation for future learning.

The example of Chase represents the common development of the students in this study. In the middle of Unit One, the development of students' models seemed unproductive. Students really struggled to link the evidence discussed in class to their models and revisions to their models. At times, the development of students' models even seemed problematic in that they were making revisions that led them farther away from canonical ideas. However, by the end of Unit One, all of the students had models of atomic structure that included relationships among the components. Additionally, by the end of Unit One, all of the students were able to apply their models of atomic structure to explain phenomena that was discussed in class and to new phenomena that was similar to the phenomena discussed in class.

Models of Fields Versus Atoms

As described above, the significant shift in students' atomic models is that the students incorporated relationships between components and used interactions among pieces of atoms to explain phenomena and prepare for future learning. Students had already learned about atomic structure in middle school, so the students started by recalling the pieces of atoms and shifted to using dynamic and interactive models of atoms to build causes and effects that they used to explain or make predictions about observations. Students were not as familiar with fields in the pre-interviews and, while their ideas about fields did shift over the semester, students did not use these ideas to develop or support explanations.

In the pre-interview, when I asked Chase if he had heard of electric fields before, he said he learned about magnetic fields in seventh grade. I asked him what he thought the magnetic field is or what it does, and he said:

> Uh [long pause] I'm trying to think here. Um. If you take, like, I'm trying to think of something, like two magnets fit together but if you go to the other side they willn't let you touch. I don't know if that, it probably has something to do with it, but I know that's a field of magnetic stuff.

He had heard of magnetic fields before, but he was not sure about electric fields. He also said he "wouldn't even know how to draw" a representation of a field. Chase did say, "I guess" fields could be connected to the scenarios but just identified that there could be a connection; he did not use a connection to develop a mechanism. Brittany also talked about magnetic fields as the interaction between magnets and drew the image in Figure 14.

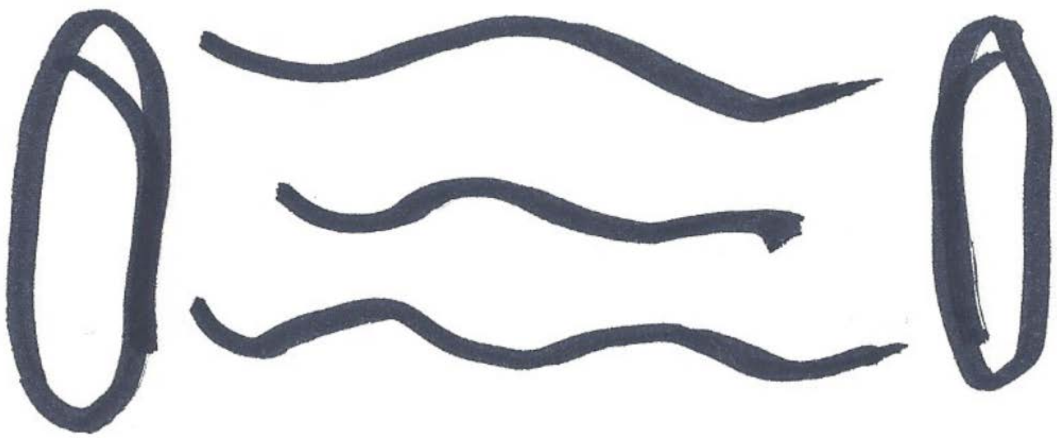


Figure 14: Brittany's image of field from pre-interview

Aiden, Christopher, Mallory, Nate, and Tony all talked about fields as defensive or protective devices. These students said a source created the field that acted like a protective barrier. Aiden drew the image shown in Figure 15 to show a source (small dot in picture) that creates a protective barrier. The students said this idea came from pop culture sources like video games or movies and were uncertain about whether these protective fields could exist in real life.

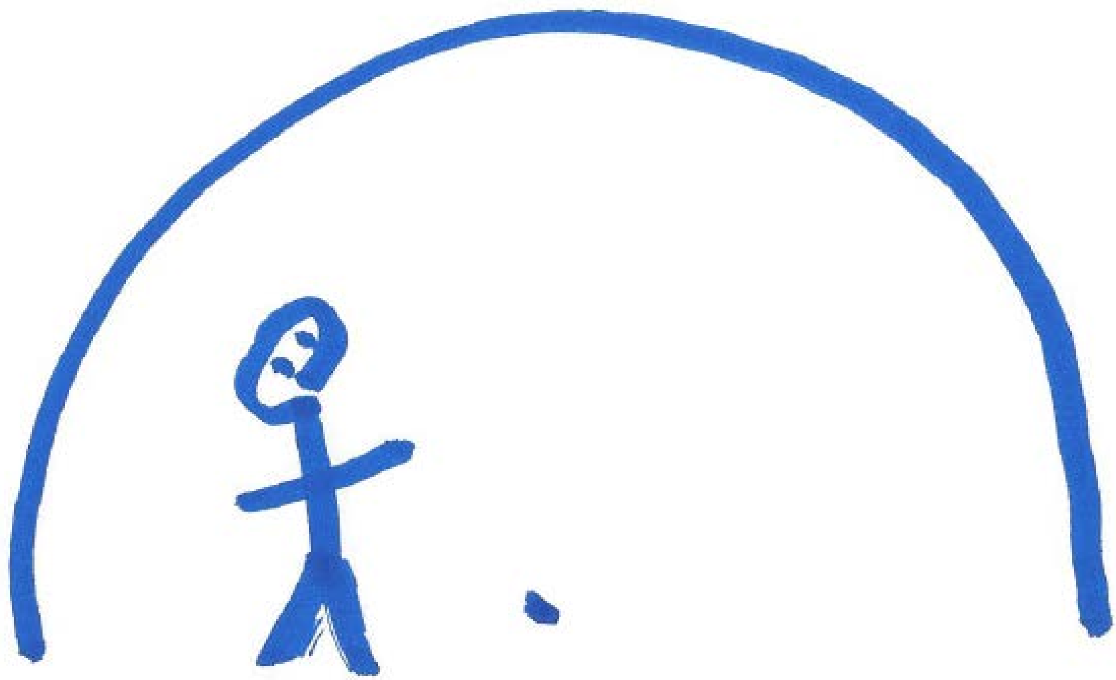


Figure 15: Aiden's initial model of a field

Fabrizio and Lily had ideas that were most closely aligned with canonical ideas. Fabrizio said there are different fields like gravity field, magnetic field, and force fields. When I asked what he thought those were, he said, "Like an invisible force that's there. Like gravity, you can't really see it, but it's there." Lily's idea was kind of a mix of magnetic fields and the protective barrier idea. She discussed magnetic fields, indicating that magnetic fields create a protective barrier for the Earth; she drew the representation of this shown in Figure 16. Her representation shows that the Earth has a magnetic field, created by the North and South poles, that protects the Earth from debris from space.

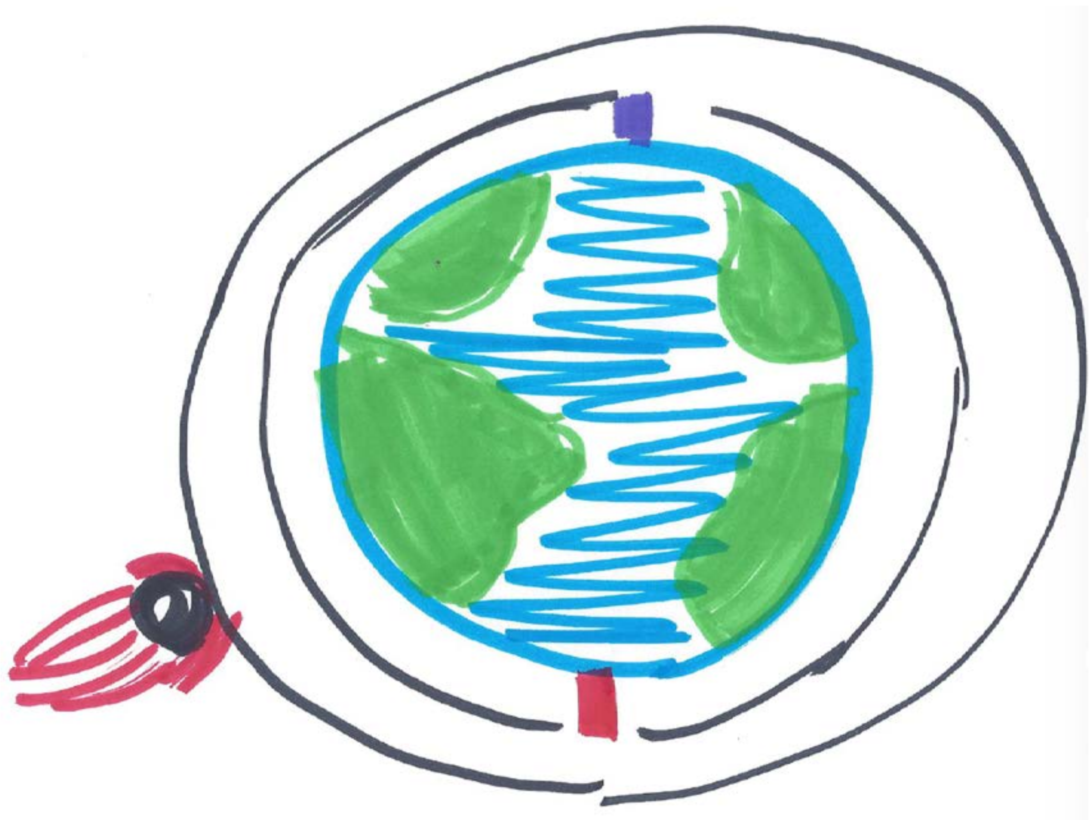


Figure 16: Lily's representation of field from pre-interview

In the post-Unit One interview, when I asked Chase about fields again, he recalled ideas from class:

> Chase: Um, a field is when there're two charged objects, right?
> Interviewer: Okay.
> Chase: I'm pretty sure, because a force. Well, um I know force is one or two and then field is one or two.
> Interviewer: They're like [making sign to indicate flip flopping with fingers]?
> Chase: So let's say, uh, say electric field is with two charged objects.
> Interviewer: Okay.
> Chase: It's making me think it's just one, but I don't, I forgot.
> Interviewer: So, let's not worry about the words, so if we just have one charged object, what can you say about that one charged object?
> Chase: Um there's like arrows that describe field[?] is like going towards and how like strong it is. There's arrows that represent that; they're dark or light. And they're strongest near the object and weaker away from the object.

He said that all of the charged objects we discussed had electric fields around them and were interacting through electric forces. However, these ideas did not really add anything to his mechanism or explanations of phenomena.

In the post-Unit One interview, the students all talked about using pointers to indicate the strength and direction of an electric field. For example, Lily drew the representation shown in Figure 17, stating that the darker pointers indicate the field is stronger closer to the charged object and that the lighter arrows show the field gets weaker farther away from the charged object. Lily also said that the arrows should go all the way around the charged object; she just did not want to draw that many arrows. This was a common response: students would draw some pointers and then explain the pattern that would be made by the rest of the pointers.

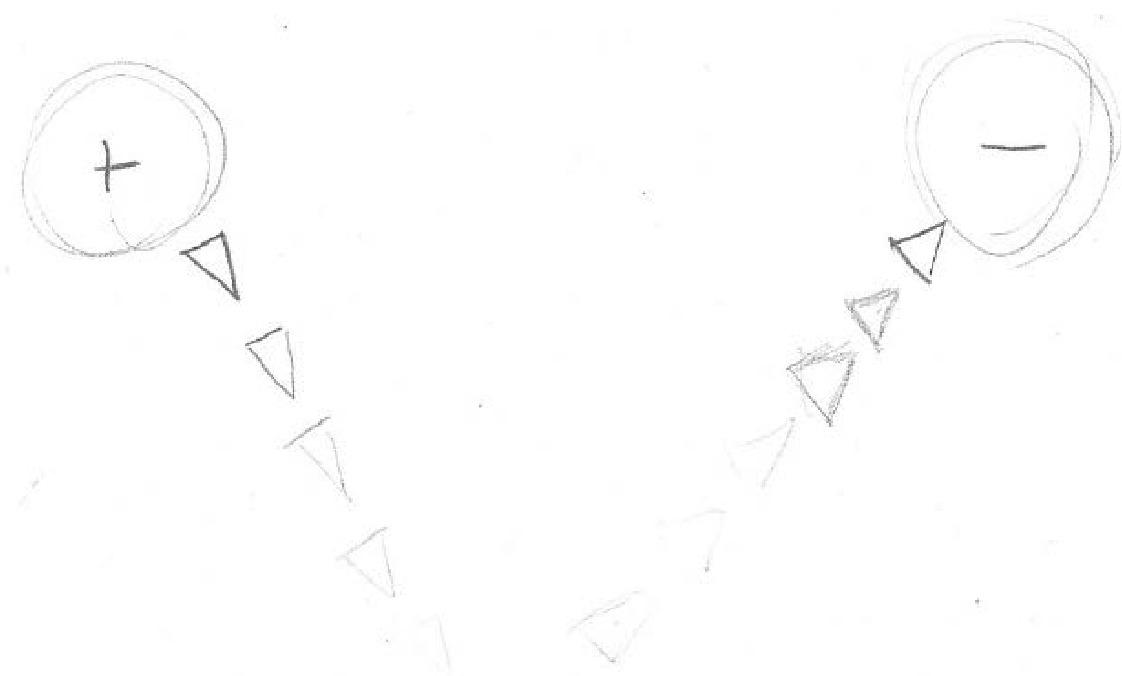


Figure 17: Lily's model of field from post Unit One interview

These drawings using pointers to represent fields resemble the representations used in the simulations from the curriculum. Students were able to interpret the meaning of the direction and darkness of the pointers. However, the students also interpreted the arrows or pointers as representing a flow of something. For example, in the post Unit One interview, Aiden said the representation of a field (Figure 18) shows “Like, you have a positive charge and a negative charge and it’s [arrows or pointers] the flow of electricity from one to the other.” Other students said it was a flow of energy or charge but all of the students except Claire talked about the arrows as indicating that something was flowing from the positive to the negative. Claire simply said the image “shows the positive is attracted to the negative.”

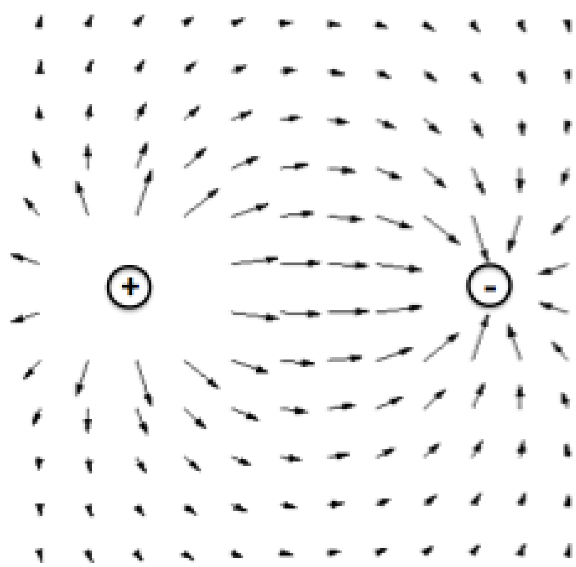


Image modified from: Srikant, Marakani. (2009). Electric and Magnetic Fields. Accessed from: http://srikant.org/core/node8.html#field2

Figure 18: Representation of fields shown to students in pre-interview, post-Unit One interview, and end of semester interview

The students understood the field represented information about the strength of forces in addition to having the inaccurate idea that the arrows represented a flow of something.

However, the students did not use this idea to explain the scenarios in the interviews, even though they did say yes when asked if fields were connected to the scenarios we discussed earlier in the interview. Fabrizio did go back to the hat and hair scenario and balloon images when I asked about fields in the post-Unit One interview. After I asked if the idea of fields related to the scenarios, Fabrizio added arrows to represent the fields around the balloons (Figure 19) and drew an image of three strands of hair on top of a head and the fields around those hairs (Figure 20). Fabrizio could use fields to explain these observations, but he did not include that idea until prompted to; initially he just used the idea of atomic structure to develop an explanation.

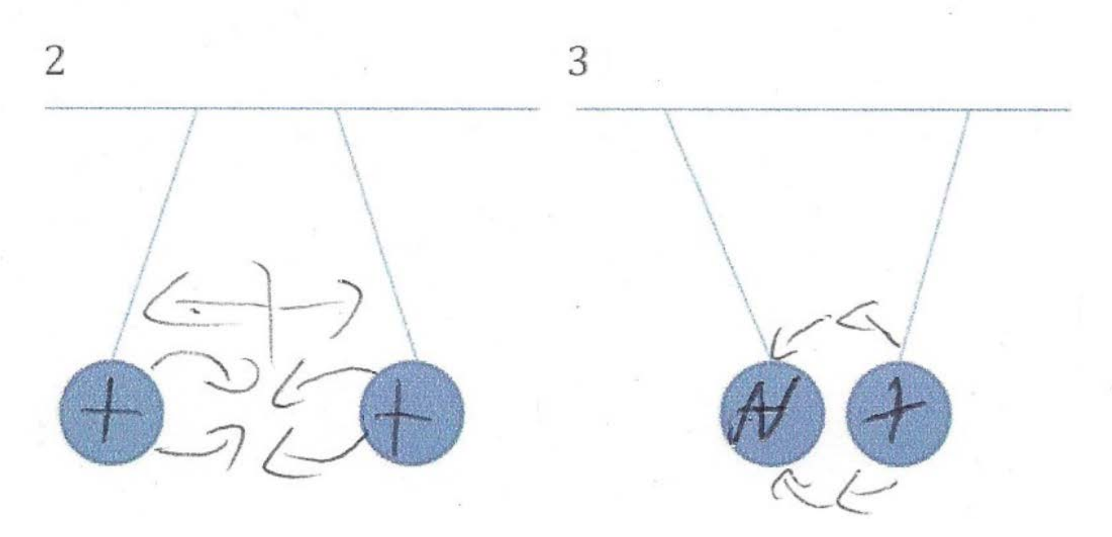


Figure 19: Fabrizio's model of fields and balloon images in post-Unit One interview

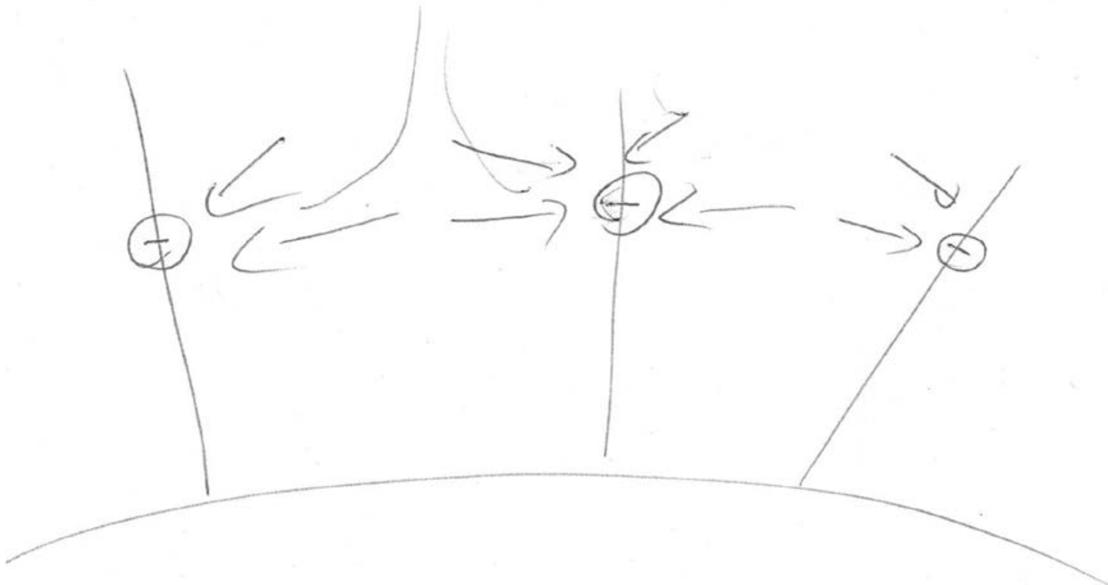
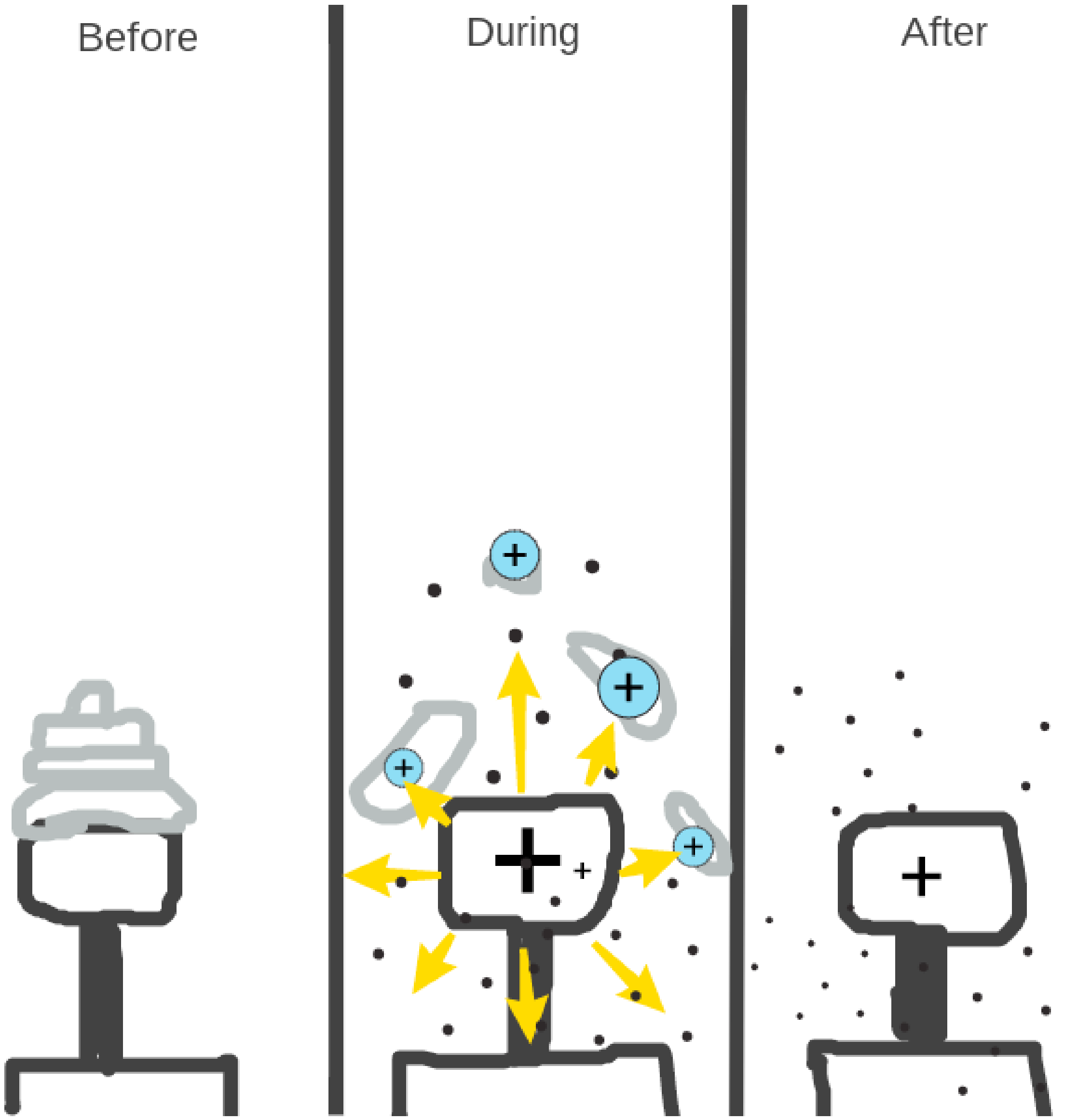


Figure 20: Fabrizio's model of fields and hair from post-Unit One interview

Jonathan was the only student who included the idea of an electric field in a model he drew in class. In the revised model of the Van de Graaff generator and pie pans phenomena that he made in the middle of Unit One, shown in Figure 21, Jonathan represented an electric field around the Van de Graaff generator. This model was created after students collected data for how charged objects interact and developed models of electric fields. Jonathan was the only student who tried to represent electric fields in his model. However, at the end of Unit One, Jonathan no longer included the idea of fields in his model for this phenomena (Figure 22). Once students developed models of atomic structure that they could use to explain their observations, they no longer included the idea of electric fields and instead only used their models of atomic structure and interactions.



Before the Van De Graaff was turned on, both objects (VDG and Pie Pans) were neutral. In our simulations, we learned that two neutrals do not affect each other. Once the VDG was turned on, it gained a strong positive charge. It put some of that charge into the neutral pie pans making them positive as well. We know that two like charges repel so it pushed the pie pans away. After the pie pans flew off, the electric field was left but the force was gone because it takes two objects for a force to be present; yet, only one for an electric field to be present.

Figure 21: Johnathan's revised model of Van de Graaff generator and pie pans from middle of Unit One

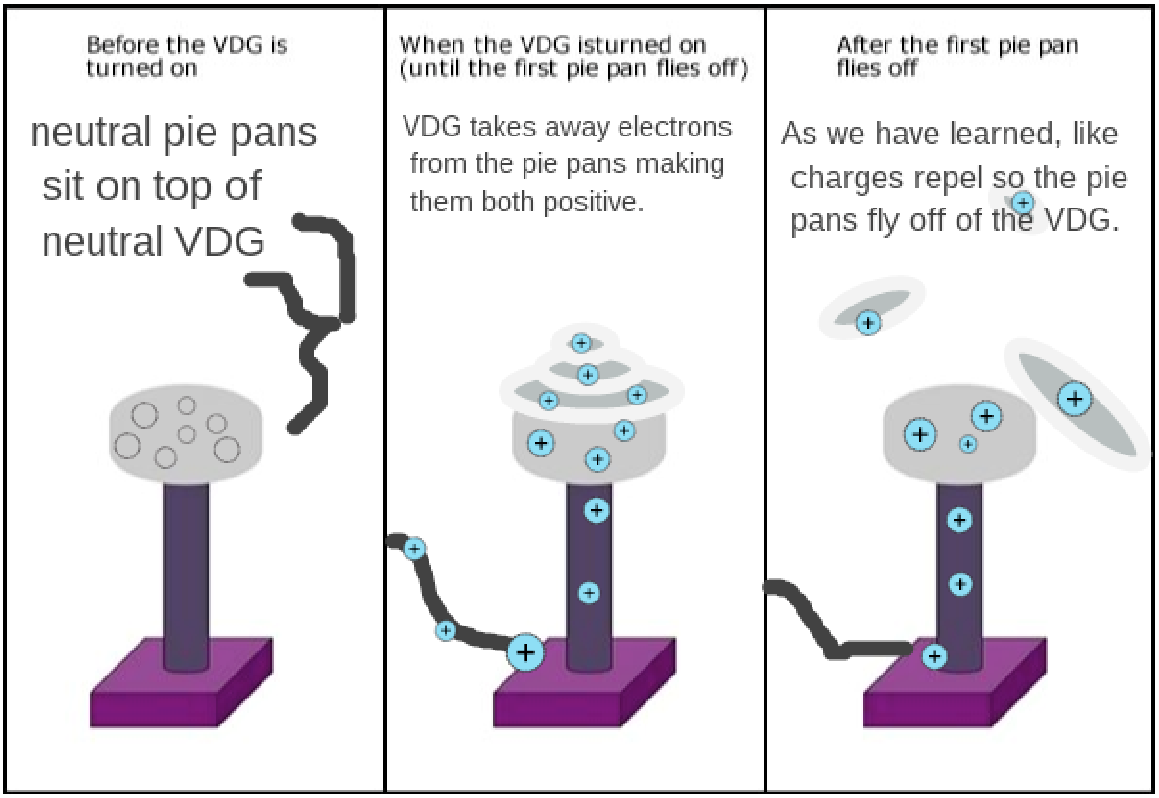


Figure 22: Jonathan's revised model of Van de Graaff generator and pie pans from end of Unit One

Focus on Details

The nature of most students' responses shifted significantly during the semester. In the pre-interview all the students—expect Nate—focused on recalling pieces of information but were not able to apply the ideas they recalled to explain the scenarios we discussed. In contrast, Nate was applying his ideas to phenomena he had not learned before. He was willing to speculate, propose different possible solutions, ask questions, and talk through ideas he was not sure about while the other students did not discuss things they were not sure about. Through Unit One, most of the students shifted to focus less on recalling specific ideas and could apply their ideas even when they were uncertain about those ideas. Thus, by the end of Unit One, most students were discussing ideas they were uncertain about. However, Claire continued to focus on recalling specific details and also struggled to apply ideas to explain the scenarios. In this section, I will use evidence from Claire's interviews to illustrate her focus on details and contrast Claire with the change in the other students and Nate.

Throughout the follow up interview, Claire frequently made the statement, "I don't remember that, I just remember…" She recalled how charged objects interact and other specific details from class, but when I asked her to apply those ideas, she repeated the general patterns she remembered.

After showing her the video of the charged rod and liquids, she kept saying she can't remember if the rod is charged or not. Several other students also said they were not sure about whether the rod was charged or neutral. However, they were able to develop possible explanations, explaining each option and working through which they thought was most logical. However, Claire did not develop any explanation and only focused on that she did not know whether or not the rod was charged. Because she kept repeating her uncertainty and therefore struggled to explain the liquid and charged rod video, I asked her if there was a way to figure out if the rod was charged or not. She said "just remembers" that we used tape in class to test the charge of objects, so I asked if she wanted tape. I was not worried about the charge of the rod, but since she was so focused on trying to remember whether or not the rod was charged, I thought testing the rod might allow her to decide if the rod had a charge or not and move on to discuss what might be causing the interaction. I allowed her to conduct the test and helped when asked. During this test, she volunteered, "All I remember is the t-tape [name we used for the piece of tape that was on top in experiment] was positive." We were conducting the test to determine if the rod had a charge or was neutral—whether it was positive or negative was not significant. Further, when other students were stuck recalling a detail like this, I would suggest looking up the data. Instead, Claire had memorized this detail. When I commented that I could never remember which tape strip was which charge, she explained that she developed a trick to remember because she also kept forgetting—the t is shaped like a positive sign. While this type of memory trick is common in science classes in which students are expected to memorize and recall a lot of information, it is not as useful in the Interactions Curriculum, in which we wanted students to support their ideas with evidence.

When asked to make predictions about protein folding, she said, “I have no idea. I don’t know,” and “I don’t know anything about cells and Biology.” After several follow up questions, she eventually said that maybe something else, like calcium, in the cells makes the protein fold but did not provide a mechanism for how this would work. When I asked her if she thought it had anything to do with atoms and charges or ideas we covered in this class, she said, “Maybe the charges, because, like, obviously we had to learn this stuff before we go into there [Biology].” Claire simply stated there is a very general connection between the Physical Science and Biology courses; she did not propose what that connection could be or use the ideas to propose a mechanism. Note, this is very similar to how Chase discussed the possible connection between atomic structure and the scenarios we had discussed in the pre-interview (p 90). They did not describe mechanisms but just stated that a connection probably exists.

While Claire was able to apply her model to develop atomic level causes to explain the hat and hair and balloon scenarios in the post-Unit One and end of semester interviews, throughout all of the interviews, Claire focused a lot on recalling details. For example, when we discussed her atomic model during the post-Unit One interview, she focused on recalling which experiment was done by Thomson and which experiment was done by Rutherford. She tried to remember who did the experiment with Cathode-Ray tubes and what was used in the other experiment:

> Claire: I think Rutherford was the one with the Cathode-Ray, I don't remember. I didn't study which one goes with which, 'cause she said we don't have to know which one goes with which. I don't remember, but I think Cathode-Ray tube was Rutherford's and then Thomson's was, maybe that one was the one—I like, have it in my head, there was like, the iron and the metal and the gold, no silver I think, or something like that. I don't know what that's called though, or something like that. I don't remember….I don't remember which simulation went with which person.
> Interviewer: That's okay, so the one was with different metals, you said. And do you remember what, like, whoever did the one with the different metals, do you remember what he saw?
> Claire: Mm, he saw that no matter what the material was, whether it was—I know silver was one, I think iron, it was either metal or gold, I don't remember.

Even when I prompted her to not worry about the name of the scientist, she focused on specifics she could recall rather than the general patterns, conclusion, and evidence. Note the difference between Claire's response and Chase's discussion of fields and forces (p. 106). When I told Chase not to worry about the words, he continued to share his ideas and was able to sort through his confusion. Claire, on the other hand, continued to focus on details.

Additionally, Claire was not the only student who struggled with the details of Thomson's and Rutherford's experiments. However, the other students were not as worried with recalling the specific details for the experiments. Recall that Chase and Fabrizio (p. 98) also struggled to describe Rutherford's experiment (p. 96). All of the students struggled with the details of this historical experiment, and they all mixed up some of the details

While most students did focus on details in the pre-interview and earlier in Unit One, most of the students also made a shift at some point during Unit One where they stopped focusing on recalling information and instead speculated about possible connections and interactions. For example, in the interview after the discussion of Rutherford, Lily even said, "Well, this time I figured I should use what we actually have rather than what I actually know." She went on to discuss the evidence from class rather than recall what she did in seventh grade. Her statement was vague, but she seemed to be communicating that she decided to shift from using the ideas she remembered from middle school to the evidence discussed in class. This point represented a significant shift in Lily's interviews—throughout the rest of these interviews, Lily's responses were focused on describing the relationships, evidence, and describing possible mechanisms to explain phenomena rather than recall ideas.

Nate, in particular, is a significant contrast from Claire; while Claire focused on recall throughout all the interviews, Nate was not worried about recalling specific details even in the pre-interview. Unlike the other students, in the pre-interview, Nate was able to make a prediction about how atoms could help explain the scenarios. When I asked Nate about atoms in the pre-interview, his responses were different from the other students. As Nate drew his initial model of the atom, he also discussed his memory of the seventh grade project. He drew three different sub-atomic particles, saying the "protrons or protons" orbit one way and the electrons orbit another way. He then described a third particle, saying:

> And then there's, I can't remember what they are, I think they're in the nucleus maybe, it's like electrobes?...I don't even know if that's the name. I think, I can't remember, we haven't learned about this in a long time.

Nate said he could not remember the name of the third type of sub-atomic particle, so he kind of made up his own name, "electrobes." He stated several times that he did not think that was correct, but he continued to use the name he created so he could communicate additional ideas. When I asked Nate if the ideas of atoms could be connected to any of the scenarios we discussed, he said:

> Maybe the atoms of the hat, like, attach to the atoms of your hair, and like, when you lifted the hat up and they would be, like, connected, and then once you took it off, the hair would be straight up still.

Nate speculated that maybe the atoms in the hat and hair connect, making the hair get pulled up with the hat. This does not explain why the hair stays up, but it does give a detailed mechanism to connect the idea of atoms with the observation of the interaction between a knit hat and hair.

In contrast to Nate, when Claire was uncertain about an idea, she did not form an explanation but instead recalled what she did remember. Nate was comfortable discussing ideas he was uncertain about. While Nate was comfortable sharing his uncertain ideas from the beginning of the school year, most of the other students started by recalling what they knew and then transitioned to be more comfortable speculating about things they had not studied. Claire did not ever really make this transition; this may explain why, in the follow up interview, while the other students were able to develop sophisticated explanations for abstract phenomena, Claire was not able to apply the ideas from class to explain novel phenomena. For Claire and others in the pre-interview, it seems that too much focus on recalling the correct information interfered with her ability to develop causal explanations of phenomena.

Summary

In general, the students really struggled to apply their ideas and models of atomic structure and electric fields to explain phenomena in the pre-interview. Most students were not sure what electric fields were and did not see how they were connected to the scenarios we discussed. Even though the students had learned about atomic structure, students could not use these ideas to build causal mechanisms to explain phenomena. In the pre-interview students could recall details they had learned, but these details did not help them make connections to phenomena.

Students did learn about electric fields through the semester, but they also developed some misconceptions about representations of fields and did not use their models of electric fields to explain phenomena. On the other hand, students did shift significantly in how they used their models of atomic structure. Students knew the components of atoms prior to instruction, but they did not include relationships, or connect those models to explain phenomena. By the end of Unit One, students included relationships in their models and used the interactions among protons and electrons and movement of electrons to explain phenomena. During Unit One, the students were asked to use evidence from historically significant experiments to revise their models of atomic structure. Students generally really struggled with this. They had a hard time describing the evidence from the experiments and linking those observations to the models of atomic structure they drew. Even though students really struggled with using the evidence to support revisions to their models, they ended up with models that included relationships and that they could use to explain a range of phenomena. Students retained these dynamic models a semester after finishing the Interactions Curriculum and could apply their models to explain new and complicated phenomena. Early on, students generally focused on recalling what they remembered. After developing models that included relationships, they could use those relationships to speculate about new phenomena, aligning with preparation for future learning.

Chapter 5: Discussion

In this study, I analyzed how students developed and used models to explain electrostatic phenomena. The students in this study were all in classes using a curriculum that was designed to align with three-dimensional learning proposed by the *Framework* (NRC, 2012) and the NGSS (NGSS Lead States, 2013). In this curriculum, students were asked to develop and revise models of atomic structure and to use models of electric fields and atomic structure to explain electrostatic interactions. In the Findings chapter, I identified four themes based on the models students developed in class and students' responses during interviews and debriefs: 1) the students were able to use the relationships between components in their models of atomic structure to apply their models to explain phenomena, including novel phenomena; 2) students' struggled to use evidence to revise their models of atomic structure but in the end developed models that included relationships between the components; 3) students used their models of atomic structure—but not their models of electric fields—to explain phenomena; and 4) when students focused on recalling details, they were not able to apply their ideas to explain observations. In this chapter, I start with the implications from the findings. I reflect on how the differences between students' use of the models of electric fields and atomic structure could relate to what happened in the classroom and implications from this contrast. This study also contributes an example of how students' ideas develop in a three-dimensional learning environment, and I reflect about this below. I end this chapter with a discussion of the limitations of this study and directions for future research.

Models of Electric Fields and Atomic Structure

While students' understanding of electric fields developed to align more closely with canonical ideas, when given a scenario in the interviews, students chose to use atomic models—rather than models of electric fields—to develop explanations. When specifically asked, students could add electric fields to their responses, but they did not initially include this model in their explanations. This finding aligns with what others have observed, that "students (even those in university) do not use, in a significant way, the concept of electric field within an electrostatic context" (Furio & Guisasola, p. 521).

However, this study differs from previous studies that have analyzed students' development and use of atomic models in high school science classes. While others have observed that students generally struggle to link atomic-level causes with observable phenomena (Griffiths & Preston, 1992; Stevens et al., 2010), the students I interviewed were able to use models of atomic structure to explain phenomena. Harrison and Treagust (2000) found that even one of their top students continued to have a static atomic model by the end of the year. Harrison and Treagust focused on discussing affordances and limitations of models of atomic structure that were presented to students. On the other hand, others have observed that in classrooms that focus on having students develop and revise their own models, students are able to develop models that they can apply to explain observations and make predictions about phenomena (e.g., Hokayem & Schwarz, 2014; Lehrer & Schauble, 2006; Penner, et al., 1998; Schwarz, et al., 2009). The students in this study developed dynamic models of atomic structure and students used these interactions to explain phenomena. This indicates that even as phenomena and disciplinary core ideas become more complex, students are able to use modeling practices to develop knowledge-in-use. However, the finding that students were able to develop dynamic and abstract models to explain phenomena is complicated by the limited way students used their models of electric fields.

There could be several possible explanations for why students used their models of electric fields and atomic structure differently. One possible cause for this difference is that I had taught models of atomic structures to students during six school years before starting the Interactions Curriculum project. I had experience with ideas that students find difficult, inaccurate ideas that students may have or develop, and activities that I had used in classes in the past. However, the emphasis on fields in the *Framework* (NRC, 2012) is a disciplinary idea that was not emphasized in previous science standards. Therefore, this was my first attempt at teaching the concept of fields. This study indicates some ideas that students develop when introduced to the concept of electric fields and some inaccurate ideas that can develop. Given this experience, moving forward, I would be sure to discuss how students are interpreting the arrows in diagrams of electric fields whenever these diagrams and models are used in the semester.

Additionally, the students in this study were familiar with atomic structure before starting the Interactions Curriculum but had not studied fields formally before instruction. While many of the students' previous work with atomic structure was problematic in that they were not able to apply those ideas, it could have provided a foundation to build on rather than teaching a new topic. The students' familiarity with the idea of atomic structure could have led them to rely more on this idea rather than the newer, less familiar idea of fields.

Further, the scenarios and phenomena we discussed in the interviews could be explained without relying on models of electric fields. Electric fields are helpful for explaining how charged objects interact without contact and are also useful when developing the relationship between energy and changes in the orientations of objects that are interacting through an electric field. However, it was difficult to identify phenomena that could be explained using electric fields that could not also be explained using other disciplinary ideas. Electric fields would have added details to the explanations of the interview scenarios, but the students were able to build complete causal explanations without including electric fields.

In addition, the students worked with the models of electric fields first and, thus, were still developing their modeling practice. Students could have been more comfortable with modeling by the time they were working with models of atomic structure. Further, in Unit Two of the Interactions Curriculum, students incorporate the concept of energy with interactions between atoms in order to explain additional observations. Fields are particularly useful when discussing energy changes and therefore fields are revisited in Unit Two. The students I interviewed did not complete Unit Two. In addition to adding the concept of energy, revisiting models of electric fields in Unit Two would have given students the opportunity to use these models once they were more comfortable with the practice of modeling. They may have used their models of electric fields more after completing Unit Two.

Finally, models of electric fields and atomic structure were covered in different ways in the curriculum. In both cases, an unanswered question led to the need to gather evidence and develop a model. The question of how charged objects could interact without touching led to the development of the model of electric fields, and the question of why a neutral object would be attracted to both positive and negative objects led to the development of atomic models of matter. In both cases, modeling was a central aspect of a range of practices, and the whole investigation was driven by explaining phenomena in alignment with the practices framework (Passmore & Svoboda, 2012). However, for models of electric field, the curriculum focused on helping students interpret canonical representations of fields. Students gathered evidence to establish relationships between charged objects and then were shown simulations that included models of electric fields and were asked to interpret those representations based on the evidence they had gathered. In contrast, when developing models of atomic structure, students were given evidence from historically significant experiments and were shown simulations in which they were asked to explore relationships among the components. Students then used those relationships to develop their own models of atomic structure that could account for the historically significant observations. After several iterations of developing their own models, students were then shown canonical representations of atomic structure and asked to evaluate those models based on the evidence. Thus, there was a significant difference between how models of fields and atomic structure were used in the curriculum: for fields the focus was on interpreting representations, while students were asked to create their own models of atomic structure and to revise those models multiple times before they were asked to evaluate canonical representations.

This could connect with Schwartz and Martin's (2004) argument that inventing solutions supported preparation for future learning as well as the contrast between my study and what Harrison and Treagust (2000) observed. Harrison and Treagust focused on including a range of representations of atomic structure in their class and discussed the benefits and limitations of these representations. In my classes, I asked students to develop their own atomic models to explain evidence. Students generally struggled to explain the relationship between their own models of atomic structure and the evidence, but by the end of the first unit, students had dynamic models of atomic structure that they could apply to explain a range of phenomena. Schwartz and Martin (2004) found that even though the students' solutions were not necessarily appropriate, by spending time trying to create their own solutions, students were able to appreciate solutions the teacher presented and apply the ideas they learned to new problems. Similarly, even though students struggled to connect their models of atomic structure with the evidence from the historical experiments we discussed, taking the time to go through the process of developing a model that could explain the results was important practice. Focusing on canonical representations too early could limit the usefulness students see in the models. Rather than focusing on the correctness of students' models, spending time on the process helped students identify significant aspects of the problem and appreciate the importance of the canonical solution.

Three-Dimensional Learning

The vision of three-dimensional learning argued for in the *Framework* (NRC, 2012) and NGSS (NGSS lead states, 2013) represent a new approach to science teaching. Because this new vision is so different from the previous standards and classroom instruction, we don't have examples of what this looks like, and we don't know if students are able to integrate the three dimensions to explain phenomena and solve problems. As argued in the *Framework* (NRC, 2012), there is a need for research to understand how students learn the disciplinary core ideas, crosscutting concepts, and scientific and engineering practices, as well as research on curriculum and instructional approaches that support students in three-dimensional learning.

Throughout the classroom instruction, whenever students worked with a simulation or drew a model, I used the modeling scaffold framework: components, relationships, and connections to phenomena to discuss the models. I asked the students what components and relationships they saw in the model and how those relationships connected with the phenomena we were discussing. This framework could be problematic if used as a definition of models that students are expected to recall; however, when I was teaching, I just used this as a structure to discuss the models. Initially, students' models were pictures of the phenomena, a common starting point in students modeling practices (Schwarz, et al., 2009). Through having students develop and revise their own models and using the modeling scaffold framework to discuss those models, students incorporated relationships in their models and developed dynamic models. When students incorporated relationships into their models rather than focusing on terms or details, they were able to apply those models to explain phenomena. Further, students were able to apply their ideas to speculate about topics they had not learned yet, including abstract topics.

Due to the illusive nature of evidence of transfer, Bransford and Schwartz (1999) proposed preparation for future learning as a framework for analyzing how students transfer ideas to new problems. The majority of students in this study were able to apply the model of atomic structure they developed to explain a range of phenomena including phenomena they did not cover in class. Bransford and Schwartz argued that rather than assessing only if students are able to develop accurate explanations or solutions to problems with novel context, it is informative to analyze the questions students ask as they are developing solutions to a problem. The students I interviewed asked productive questions that they could use to develop more complete explanations of the phenomena. Additionally, several students were able to identify tests they could do that would answer their own questions. Thus, in an idealized classroom environment—students have a teacher with a deep knowledge of three-dimensional learning and the curriculum—there is evidence that this learning environment supports preparation for future learning.

In order to develop models that students could apply to explain phenomena, students had to let go of always knowing the correct term or answer. For example, when students started revising their models of the Van de Graaff generator and pie pans, they did not know whether the Van de Graaff generator was positively or negatively charged. Therefore, some of the models had positives on the Van de Graaff generator while others had negatives. Similarly, the students were not sure about whether the pie pans were always charged and only repelled when the Van de Graaff generator was turned on and therefore charged, or if the pie pans started as neutral and became charged along with the Van de Graaff generator. In the models, students had to make decisions about these different possibilities. When we discussed these models, students noted the differences between their models and used those differences to develop new questions and tests. Students had to make similar decisions in the interviews. For example, students did not know whether the hair becomes positively charged or negatively charged when rubbed with a hat. However, when students did not focus on this detail, they were able to develop the idea that electrons would move either from the hat to the hair or the other way around. By working with the relationships among components students could develop an explanation even if they were uncertain about some of the details.

Given that many classrooms focus on recalling correct terms and answers, shifting to a classroom where students are comfortable proposing ideas when they do not have all the information requires intentional work. In my classroom, I set up specific expectations with students in the beginning of the semester. I also constantly used the language of the modeling framework and scientific practices to discuss students' ideas. My focus was on listening to students' ideas and asking them to use the evidence we had gathered to evaluate their own ideas. Through this semester, most of the students did shift from focusing on recalling specific ideas to being comfortable speculating about possible causal relationships. As students made this shift, their responses to the interview questions indicated higher preparation for future learning and more knowledge-in-use.

Three-dimensional learning as proposed in the *Framework* blends scientific and engineering practices, crosscutting concepts, and disciplinary core ideas. While this could be thought of as adding practices and crosscutting concepts to the earlier versions of content standards, from my results in this study, I would argue this approach would not work. The students needed to let go of "correctness" and a focus on details to use models and cause and effect relationships in order to apply their understanding to explain phenomena. This means that in three-dimensional learning environments, the focus needs to shift away from memorization of terms, definitions, and details. Trying to add practices and crosscutting concepts on top of a focus on recall does not support applying models, or knowledge, to explain new phenomena and solve new problems. Instead, students need opportunities to try out ideas that they are uncertain about and develop possible explanations. While this study is not an assessment study, these findings could also give us some information about developing three-dimensional assessments. In order to assess students' application of models and development of explanations of phenomena, it may be important to give some of the details to students on the assessments. Again, this aligns with the argument for preparation for future learning (Schwartz & Martin, 2004). Rather than asking students to recall information on assessments, it may be more informative to provide students with those details and see how students use them to explain phenomena. In this transition to NGSS, we will need to learn to let go of some of the focus on details and specific content ideas. By letting go of a focus on details and terms, the students were able to develop dynamic models that they could apply to explain a range of phenomena.

Limitations and Future Work

This study provides examples of how eleven students responded to a scaffolded curriculum designed to align with the NGSS and three-dimensional learning. The sample is small and does not represent a diversity of students. I interviewed eleven students who were all in classes using one curriculum that focused on the practice of modeling, the disciplinary core idea of matter and its interactions, and the crosscutting concept of cause and effect. This does provide a detailed example of what student learning could look like in a three-dimensional learning environment. However, this study does not provide a generalized account. My perspective as a member of the curriculum development team and teacher for these students also comes along with biases and commitments that could impact my understanding of what happened in the classroom and how the classroom activities related to students' ideas. My commitment as an educator that students' have important ideas impacts the way I run class, but also could play out in the interviews. Though I try to respond to students' ideas without judgment, students may pick up on subtle cues from me in the classroom and this could follow through to the interviews. This could have cued students to use the ideas from class to answer the interview questions. Further, my knowledge of classroom activities and interactions informed the follow-up questions I asked during the interviews, and thus the line of questioning I asked directed the interviews in particular ways. I chose new phenomena to discuss in the interviews. Since we were not discussing specific scenarios from class, even if students used my presence as a cue to use the ideas from class, they were applying them to novel phenomena. As a teacher in these classes, I do have deep knowledge of what happened daily during instruction. Thus, I am able to speculate about possible connections between what happened in the classroom and the development of students models, but I have not analyzed data from the classroom to support these speculations. Any discussion of classroom activities is not intended as researched claims but just as speculation about possible relationships and context for understanding students' interview or written responses. In order to identify connections between teaching practices and student learning, studies that compare different teachers implementing the Interactions Curriculum are needed to compare common teacher practices across classrooms where students have similarly successful results. Further, research is needed in additional elements of the dimensions of the *Framework* to identify common practices for teaching in classrooms that are aligned to three-dimensional learning separate from teaching practices that are specific for modeling, matter and its interactions, and cause and effect relationships.

This is not a causal study and while I was able to reflect on how the classroom interactions could be related to how students' developed and used their models I cannot make claims about these connections. In this study I showed what students could do in a three-dimensional learning environment, but further studies that analyze the relationship between the classroom interactions and the students' work are needed. Additionally, this study showed some struggles students had with models of electric fields. Since fields is a new focus in the *Framework,* it will be important to continue to study how to support students when developing and using models of electric fields to explain phenomena. Further, the Interactions Curriculum was designed based on the argument that an understanding of the electrostatic nature of atomic interactions would provide a foundation for deeper understanding of additional disciplinary core ideas in high school and future learning. In this study, I saw that students were able to use their dynamic models of atomic structure to make predictions about a complex Biological phenomenon. This is an indication that having students use electrostatic interactions to develop and revise models of atomic structure could prepare students for learning in future classes. However, additional studies are needed to follow students into other courses to see if and how they continue to develop and use their dynamic models of atomic structure as they encounter novel phenomena.

APPENDICES

Appendix A: Curriculum Overview

Table 12: Learning goals and activities for Unit One

Unit 1 – Why do some clothes stick together when they come out of the dryer?			
Investigation 1 – Why do some things stick together and other things don't?			
Activity	Question/title	Learning goal	Overview
1	What are some examples of things that stick together and things that don't?	Students will ask questions about phenomena observed in the classroom and in daily life that involve electrostatic interactions.	Students discuss situations where objects stick together (packing peanuts sticking to a cat) and fly apart (kid's hair sticking at the end of a plastic slide). Students make several observations of a Van de Graaff (VDG) generator including what happens when metal pie pans are stacked on top of it. Students write questions about the scenarios and draw an initial model of the pie pans and VDG. Students are introduced to the idea that models must provide a causal mechanism and revise their model.

Table 12 (cont'd)

2	What are some patterns in how things stick together or push apart?	• Students collect and interpret data to identify patterns in the way that charged objects interact with each other. • Students apply patterns observed in a computer simulation to develop a model for how charged objects interact. o At this point, students' models will only include interactions between two charged objects.	Students use charged pieces of tape to find patterns in the interactions between pieces with different charges. Students explore a simulation showing objects with opposite charges. The simulation is also used to introduce the modeling scaffolds: what components are shown in the model, what are the relationships between those components, how does this connect with the patterns we saw with the pieces of tape? Students draw models to explain the patterns they observed with the pieces of tape.
3	How do I know if something is positively or negatively charged?	• Students design and carry out an investigation to determine the charge of an object using an object of known charge as reference, based on their model of electrostatic interactions. • Students collect and interpret data to determine the type of charge an object has. o At this point, students' model of electrostatic interactions contains rules for interactions of charged objects (likes repel; opposites attract) that can be used to explain electrostatic phenomena.	Students are told that after rubbing a balloon with fur the balloon is negatively charged. Students use this standard to make observations of the charges of other objects. Students then use these materials to design their own test to determine the charge of each piece of tape.
4	How can we improve our model?	Students revise and apply a model of electrostatic interactions to explain a range of phenomena.	Students apply their ideas and use the information they have gathered to revise their models of the pie pans and VDG.

Table 12 (cont'd)

Investigation 2 – What are the factors that affect how strongly objects interact with each other?			
1	How can charged objects have an effect on each other without touching?	• Students will develop a preliminary model of an electric field by describing the direction of the force acting on a charged object in the presence of the electric field. o Clarification: The region of space surrounding an electrically charged object that has an effect on another object contains an electric field. The concept of an electric field helps explain how electric force acts at a distance. o Representations of electric fields will be depicted using pointers to show the direction of force that a positive charge would experience. The color intensity of the pointers represents the strength of the field at that point in space.	Students observed that tape interacts with the VDG from all different sides. Students draw a representation of this space. Students explore a simulation showing a representation of this space using a pointer. Students then revised their models using this common representation.
2	How does the distance between charged objects affect the strength of the interaction between them?	• Students will qualitatively explain and predict how the distance between two charged objects affects the strength of the electric force between them. • Using an electric field model, students will explain the relationship between the distance separating two charged objects and the strength of the forces experienced by those objects. o Clarification: The strength of the electric force decreases with increasing distance, and vice versa. The electric force can be described by direction and the strength (magnitude). o Students will identify the direction and qualitative strength of an electric field surrounding a charged object. However, students do not need to calculate the magnitude of fields based on distance.	Students observe the interaction between a piece of paper and a VDG as the paper is moved closer and farther away. Students explore a simulation, discuss and answer several questions to identify the relationship between electric fields, electric forces, the number of objects, the distance between objects, and the strength of the field and forces.

Table 12 (cont'd)

3	How does the amount of charge on two objects affect the strength of the interaction between them?	Students will design and conduct an experiment to determine the relationship between the amount of charge and the strength of the force between two charged objects. • Clarification: Up to this point, the student model should include that o Opposite charges attract, and like charges repel. o The strength of the interaction between two charged objects depends on the distance between them. • Clarification: The amount of charge can be controlled by changing the type of material of the charged object, the number of similarly charged items, and/or the surface area of the charged object.	Students are given a set of materials and experimental set up then, through a discussion, students define possible ways to test how changing the amount of charge would affect the strength of the interaction. After collecting evidence that more charges lead to stronger interactions, students explore a simulation to explore the relationships between electric field, amount of charge, and electric forces in a simulation.
4	Wrap-up	Students will apply a model of electrostatic interactions to explain and make predictions about electrostatic phenomena. • Clarification: Up to this point, the student model should include that o Opposite charges attract, and like charges repel. o The strength of the interaction between two charged objects depends on the distance between them and the amount of charge on each object (a qualitative understanding of Coulomb's law). o Electric fields help explain how objects can interact with (exert a force on) each other without touching.	Brief activity where students apply their ideas to answer questions and complete games.

Table 12 (cont'd)

Investigation 3 - How do interactions between charged objects compare to interactions between charged and uncharged objects?			
1	What effect do charged objects have on uncharged objects?	• Students will determine whether an object is neutral or charged. o Clarification: At this point, students' definition of neutral will just be "uncharged" or "no charge." • Students will predict what will happen when a neutral object is close to another object (either charged or neutral). o Clarification: Neutral objects are attracted to charged objects, but two neutral objects do not seem to attract or repel each other. At this point, the type of charge is not specified.	Students observe that a plastic bottle and pieces of paper do not interact. Then students charge the bottle and observe that the pieces of paper are attracted to the bottle. Students answer questions about whether or not the pieces of paper and bottle are charged. Students conduct a similar experiment using their hand and the plastic bottle.
2	How does the charge of an object affect how it interacts with a neutral one?	Students will further develop a conceptual model of electrostatic interactions by generalizing the patterns of interactions between charged and neutral objects. • At this point, the student model should include the following: o Objects with opposite charges attract each other; objects with the same charge repel. o Neutral objects and charged objects are attracted to each other.	Students test several objects that they believe are neutral with both positively and negatively charged objects. Students observe that both positive and negative objects induce an attractive interaction with neutral objects.
Interaction 4 – Explaining phenomena with a model of charge interactions			
1	Applying and refining our model of charge interactions	Students will apply their models of electrostatic interactions that illustrate the principles about how objects become charged and about how charged objects interact with other objects to explain phenomena and make predictions.	Students apply the ideas they have learned to make a revised model of the pie pans and VDG as well as a model of a new phenomenon: a representation of Franklin's bell made with the VDG and soda cans.

Table 12 (cont'd)

Investigation 5 – What are all materials made of?			
1	Can the same piece of paper be cut into pieces indefinitely?	• Students will ask questions about the building blocks of materials and how they are involved with interactions between charged objects. • Students will make predictions about the building blocks of materials.	Students discuss remaining unanswered questions about why friction creates charge and why a neutral object would be attracted to both positive and negative objects which leads to a need to explore the nature of materials. Students discuss what would happen if a piece of paper were cut into smaller and smaller pieces. Students are introduced to the continuous and particle nature of matter ideas from ancient Greek philosophies. Students use these ideas to evaluate their ideas about the paper.
2	Does 5 + 5 always equal 10?	Students will evaluate whether the continuous or particle model of matter best accounts for their observations of a mixture. • When water and ethanol are mixed, the total volume is less than the sum of the volumes of the original liquids. The particle model can explain this loss in volume because in a mixture, smaller particles are able to fill in the spaces between larger particles.	Students make observations of mixing ethanol and water to mixing water with water and ethanol with ethanol. Students observe that when water and ethanol are mixed the volume does not add up. Students then explored a simulation and discussed how the particle model versus the continuous model explained these observations.

Table 12 (cont'd)

3	Is the particle model always better?	Students will use the particle model of matter to explain their observations of the characteristics of gases. • Clarification: Gas has mass, so it must be made of something. Gas can also be compressed. The particle model can account for both of these phenomena. o Gas particles have mass but are spread apart and too small to be seen. Since gas particles are spread out, gas can be compressed by reducing the space between the particles.	Students make observations of gases sealed inside a syringe and a simulation to use the particle model to explain those observations.
4	Which model best supports our observations?	Students will use evidence obtained in this investigation to support the theory that matter is made of particles too small to be seen. • The observations of mixing water and ethanol, and of measuring gases in a syringe, are best explained using the particle model.	Students use the evidence they gathered to revisit the question about cutting paper.
Investigation 6 – What are nature's building blocks?			
1	What are the particles that make up all substances, and how small are they?	Students will use atoms or groups of atoms to illustrate the underlying structure of materials. Students will describe in a qualitative or semi-quantitative way the relative size of atoms by using macroscopic objects to represent microscopic ones.	Students draw their initial representation of atomic structure. Students use analogies to develop an understanding of the size and scale of atoms relative to other small objects (blood cell, virus, strand of hair).

Table 12 (cont'd)

2	If you can't see it, how do you know it's there?	• Students will communicate the benefits and limitations of using indirect evidence for studying atomic structure. o Atoms cannot be directly observed, so using indirect evidence is the only way to investigate atomic structure. o Indirect evidence can provide some information about an object that cannot be observed directly, but it cannot provide an exact image of that object. • Students will use historical evidence to develop and defend a model of atomic structure that explains the results of experiments done historically to better understand the nature of matter. o By the end of this activity, students' models of atomic structure should include the following: ▪ Atoms have positive and negative parts. ▪ The negative parts, called electrons, have very little mass. o Evidence for the model should include the following: ▪ Thomson showed that negatively charged particles are part of all atoms. He determined that the mass of each negative particle was approximately 1/2000 the mass of a hydrogen atom. The particles were attracted to positively charged plates. (Students will not see this specific quantity in their experimentation, but they will see that electrons have a much smaller mass than the least massive atom—hydrogen.) ▪ Because atoms have negative parts, atoms must also have positive parts to balance out the charge, or everything would repel and fly apart.	Students analyze the limits and benefits of indirect evidence by using indirect evidence to determine what is inside a "black box." Students use this understanding of indirect evidence to explore two simulations that represent Thomson's Cathode-Ray tube experiments and then test relationships in order to explain his observations and evaluate Thomson's claims that he discovered small negatively charged pieces of atoms. Students revise their model of atomic structure in order to account for this evidence.

Table 12 (cont'd)

3	How do we know what's inside an atom?	Students will use evidence collected from simulations to develop and defend a model of atomic structure that explains the results of historically significant experiments. • By the end of this activity, students' models of atomic structure should include the following: o Atoms are made of smaller particles: electrons, protons, and neutrons. o Atoms have a small, dense, positively charged center called a nucleus. • Evidence for the model should include the following: o Thomson showed that atoms of all materials contained particles that were attracted to positively charged plates; therefore, the particles were negatively charged. He also determined that the mass of each particle was much lower than the mass of a hydrogen atom. o Rutherford found that when positively charged alpha particles were shot at a thin sheet of gold foil, most of the alpha particles passed straight through, but some were deflected back. This deflection suggested that the positive part of a gold atom was concentrated into a small, dense volume and had an intense electric field. This dense, positive center of the atom is called the nucleus.	Students use a simulation to explore the relationships between the concentration of positive charges within an atom and the path of alpha particles that pass through or near the positive charges. Students use this simulation to explain the results of Rutherford's gold foil experiment and revise their own models of atomic structure.
4	Where are the electrons?	Students will use mathematical thinking to describe probability and to analyze cloud representations of electrons in atoms.	Students explore probabilistic relationships and representation of electron distribution within atoms.

Table 12 (cont'd)

Investigation 7 – What is the effect of changing the composition of an atom?			
1	What is the effect of changing the composition of an atom?	• Students will use a simulation and the periodic table to identify the number of protons in any element. o Atoms of different elements have different numbers of protons; the number of protons identifies an atom as a particular element. • Students will interpret information from a simulation and use their model of atomic structure to explain the effect of changing the composition of an atom. o The number of protons determines the type of atom and can affect its charge. o Changing the number of electrons changes the charge of an atom. o There may be different numbers of neutrons in the same type of atom. The number of neutrons does not affect the charge of an atom. • Students will use the mechanism of electron transfer to explain how atoms become charged. o Protons are not easily added to or removed from an atom, so their number does not change when an atom becomes charged. o Electrons can move relatively easily between atoms. Therefore, the movement of electrons from one atom to another is responsible for changing the charge of atoms.	Students analyze basic information available on a Periodic Table and connect that to a simulation that allows them to explore what happens to an atom when the number of protons, neutrons, or electrons are changed.

Table 12 (cont'd)

2	How do objects become charged?	To explain how objects become charged, students will develop a more sophisticated model of atomic structure that includes electron transfer and conservation of charge. Students' models should include the following: • Electrons can transfer from one atom to another. The atom that loses one or more electrons becomes positively charged, and the atom that gains one or more electrons becomes negatively charged. • When two objects are rubbed against each other, electrons transfer between them. After being rubbed, if one object has an increase of electrons, then the number of electrons that object has gained will be the same as the number of electrons the other object has lost. • Charge is conserved. This means that the particles that have charge can be moved, but they cannot be created or destroyed.	Students test several materials before and after they were charged by rubbing them together. Students used the observation that one object changed from neutral to positive and one object changed from neutral to negative in order to develop a model to explain how objects become charged.
3	What causes neutral objects and charged objects to interact with each other?	Students will create models that incorporate atomic structure and electric fields to explain how neutral objects and charged objects (both positive and negative) can be attracted to each other. Students' models should include the following: • The electron distribution within an atom can shift in the presence of an electric field to create a separation of charge in which one end of an atom becomes slightly positively charged and the other becomes slightly negatively charged. • Neutral objects contain an equal number of positive and negative charges; charged objects contain an unequal number of positive and negative charges.	Students used simulations to explore what happens to electron distribution when neutral objects interact with different charges. Students use their model to explain why they observed attractive interactions between neutral objects and both positive and negative objects.

Table 12 (cont'd)

4	Revising our models of charge interactions	Students will apply their models of atomic structure and electrostatic interactions to provide a causal mechanism for explaining various electrostatic phenomena. • Students' models of electrostatic interactions should include electrons transferring between objects, attraction between charged and neutral objects, and repulsion of like-charged objects. • Students' models of atomic structure should include an electron cloud of electron density. (They will refer to the electron clouds as a region of high probability for finding an electron.)	Students revise their models of the VDG and pie pans and the Franklin's bell based on the additional ideas they have developed about atomic structure and nature of matter.

Table 13: Learning goals and activities for Unit Two

Unit 2 – How can a small spark start a huge explosion?			
Investigation 1 – What is happening when a spark occurs?			
Activity	Question/title	Learning goal	Overview
1	Can my finger start a fire?	Students will ask questions about how their current model of electric charge explains their observations of sparks and ignition of flames, leading them to consider what might be missing from their model.	Students observe a spark from the VDG start a Bunsen burner. Students discuss their ideas about energy and ask questions about energy.
2	What happens to energy when objects collide?	• Students will develop a model of energy that allows them to track the transfer of energy. • Students will develop model of energy that includes conservation of energy. • Students will identify necessary components to define a system and its surroundings.	Students observe a demonstration to determine how mass and speed impact the amount of kinetic energy an object has. Students use a simulation and colliding marbles to track the changes to kinetic energy. This is used to establish the rule of conservation of energy.

Table 13 (cont'd)

3	If moving objects have kinetic energy, do moving atoms have kinetic energy?	Students will further develop their atomic model by relating thermal energy to kinetic energy.	Students time food coloring as it spreads through water at different temperatures. Students use this observation to establish an understanding of kinetic energy at the atomic level and relate this to temperature and thermal energy.
4	If energy cannot go away, why don't things move forever?	• Students will develop a model of energy that includes energy conversion, energy transfer, and conservation of energy. • Students will track energy throughout a process using the ideas of energy transfer and energy conversion between kinetic and potential energy.	Students observe a pendulum as it stops swinging and explore a simulation to explain what happens to the energy from the pendulum as it comes to a stop.
Investigation 2 – How can a small spark start a huge explosion?			
1	How does potential energy change when things are pushed or pulled?	• Students will analyze and interpret data to define the relationship between force and changes in potential energy • Applying a force to move something from a stable state increases the potential energy of the system. • Students will apply a model of conservation of energy to describe and make predictions about mechanical processes. o Energy can transfer from place to place. o Energy can convert from one form to another. o NOTE: The predictions and descriptions involve the energy of the system and its surroundings.	Students use springs to move objects to build the idea of potential energy. Students explore simulations and use bar graphs to represent the changes in energy and energy conservation.

Table 13 (cont'd)

2	Where does the energy that was used to charge the Van de Graaff generator go?	• Students will develop their model of potential energy by describing the potential energy of a system in terms of fields. o Gravitational, magnetic, and electric potential energy are stored in fields. o Potential energy only exists in a system made of two or more interacting objects.	Students compare pushing and pulling springs to pushing and pulling two magnets. Students explore a simulation of charged objects to develop a relationship between potential energy and objects that interact through a field.
3	Why is lightning so much bigger than a spark from the Van de Graaff generator?	• Students will build on their models of electric interactions to relate electric force and electric potential energy. • Using a force to change the relative positions of interacting objects in a system changes the amount of energy stored in the system/field. • Students will explain and make predictions about the effect of changing the amount of charge and the distance between charges on electric potential energy. • Changing the electric field changes the amount of electric potential energy stored in the field. o The electric field is affected by changing o Force (amount of charge) o The position of charged particles	Students compare a stiffer spring and weaker spring as well as changing the distance they compressed the spring to how far or fast the spring will launch a toy car. Students then use this experiment to develop their own experiment to compare different strength magnets. Students use these experiments to make claims about the potential energy stored in the spring or field between the magnets. Students use a simulation to compare potential energy in the field between charged objects as the amount of charge and distance is changed.

Table 13 (cont'd)

4	Why do I get shocked if I am too close to the Van de Graaff generator?	Students will make predictions about the motion of objects in a system based on a model of energy that includes the natural tendency of systems to move toward more stable states. • Clarification: A more stable state means the energy is more evenly distributed and the potential energy has been minimized. This investigation focuses on minimizing the potential energy.	Students try to drop a pencil so that it will land and balance on the end. Students explore simulations and observe that if things are allowed to move they will naturally move toward a state where the potential energy is lower. Students explore a simulation of the VDG and use energy to explain the observation of the spark.
Investigation 3 – Why does an explosion not start spontaneously?			
1	What makes materials different from each other?	• Students will measure and use properties to characterize and distinguish between substances. • Students will use models to explain how substances are different from each other. o A molecule is a collection of two or more atoms that are linked together. o Molecules of the same substance have the same composition and ratio of atoms. o At this time, we don't expect students to know about chemical bonds—how and why atoms are held together.	Students observe flame tests used to test different gases. Students conduct electrolysis of water and test the gas produced using flame tests. Students compare the amount of gas and the properties of the gas to make claims about the composition of water molecules. Students are introduced to chemical formula and explore the relationship between the chemical formula and properties of materials.

Table 13 (cont'd)

2	What holds the atoms of a molecule together?	• Students will use a model to explain what happens when two atoms get close to each other in terms of changes in the electric forces and changes in the electron probability map between the atoms. • Students will construct an explanation of how atoms are held together in a diatomic molecule. o In a stable molecule, the repulsive force between the positive nuclei is balanced by the attractive force between the positive nuclei and the negatively charged electrons. o When the attractive and repulsive forces between two atoms are balanced, and the electron probability distribution of the atoms overlaps significantly between them, a bond forms between the atoms. o Atoms in a stable molecule are held together by the sharing of electrons. • Students will evaluate the purpose, usefulness, and limitations of different types of molecular representations.	Students work with simulations to explore the interaction between two atoms, noting the shifts in electrons and forces between the atoms.

Table 13 (cont'd)

3	When atoms get close to each other, what happens to their potential energy?	Students will use their conceptual model of atoms to explain, in terms of relative potential energy, why a molecule forms. • A molecule has less potential energy than the same set of individual atoms. • Binding energy is the difference in potential energy between the "optimal distance" where atoms form a molecule and a "too far distance" where no interaction occurs	Students explore simulations to add changes in energy to the interactions and shifts in electron when two atoms bond.
4	Why is a spark needed to start an explosion?	• Students will be able to construct an explanation and develop a model to describe the relationship between energy and molecules breaking and forming. o When a bond is formed, energy is released. o When a bond is broken, energy is absorbed. o The amount of energy that is needed to break a bond is exactly equal to the binding energy of the molecule. • Students will be able to use conservation of energy to explain that energy conversion takes place between potential energy and other forms of energy, and that energy transfer also occurs when a molecule forms or breaks.	Students use simulations to explore changes to energy when atoms bond, break bonds, and when bonding atoms interact with surrounding atoms.

Note: Unit 2 includes a fourth investigation (where does the energy in an explosion come from?) in which students develop a model of reactions that includes breaking bonds, rearranging atoms, and then forming new bonds. We did not have time to complete this last investigation during the semester. Instead, we spent a few days exploring some reactions (burning isopropyl alcohol vapor in a jug, electrolysis, and combustion of hydrogen gas) to develop the ideas that energy must first be added to start a reaction, that energy breaks atoms apart, the atoms then rearrange to form new bonds which releases energy. The amount of energy that is added to break the bonds has to be compared to the amount of energy released when new bonds are formed. If more stable bonds are

Table 13 (cont'd)

formed, then more energy is released than absorbed; if the bonds that were broken are more stable than the ones that were formed, more energy is absorbed than released in the end.

Appendix B: Modeling Questions from Curriculum

Unit.Investigation.Activity.Question#

Van de Graaff generator and pie pan model questions

1.1.1.2 Now that you've seen what happens to the pie pans after turning the Van de Graaff generator on, draw two pictures to show what caused the pie pans behave the way they did. Label your drawings and explain what is happening at each step so that anyone can understand your drawing.

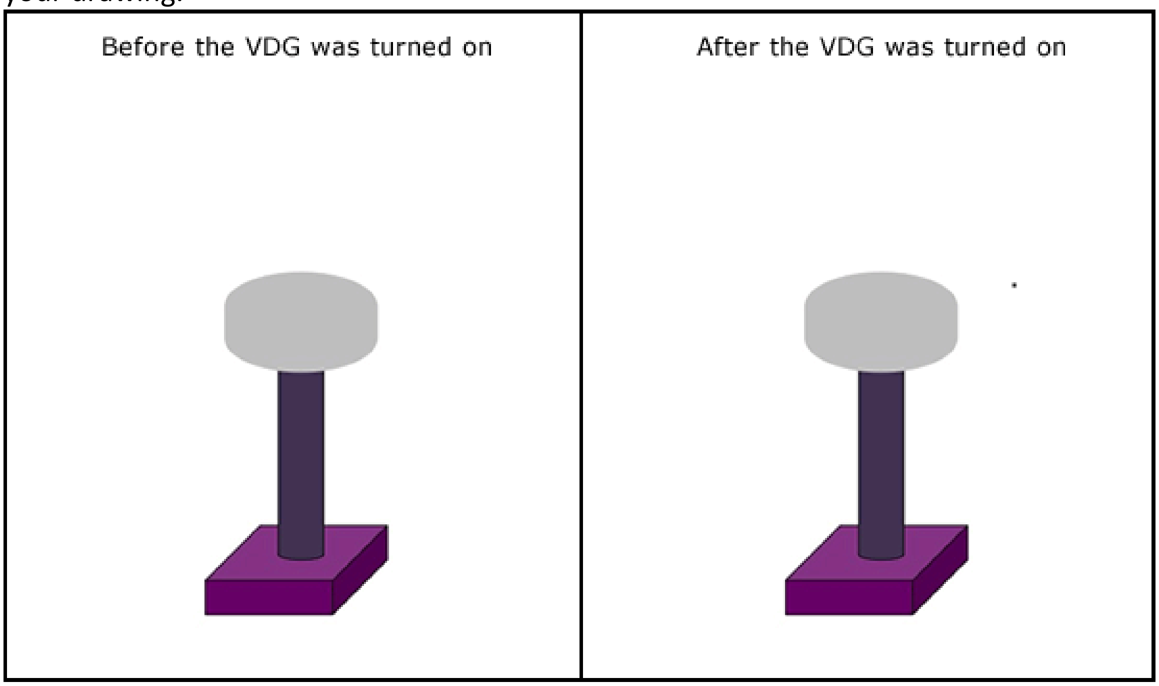


Figure 23: 1.1.1.2 prompt

1.1.1.3 Following the class discussion of your classmates' models and scientific models, revise your model of the Van de Graaff generator and the pie pans. Be sure to explain what cause the pie pans to fly off the Van de Graaff generator (the mechanism).

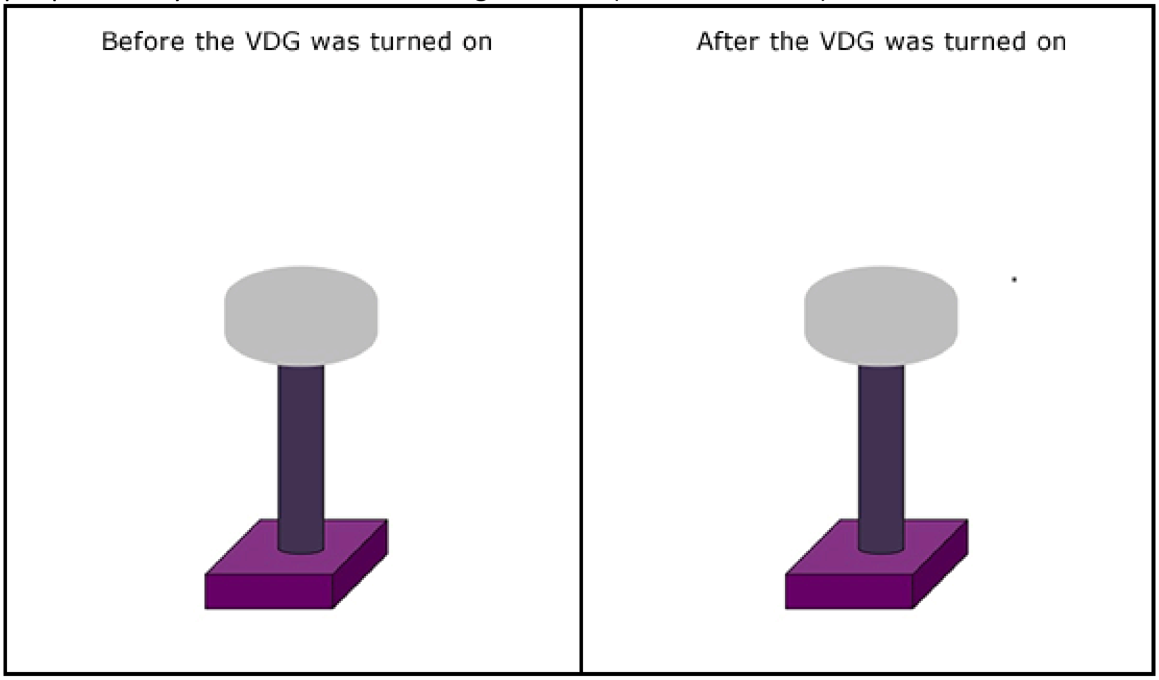


Figure 24: 1.1.1.3 prompt

1.1.4.2 [Students had the option to review the Van de Graaff generator and pie pan demonstration using a link to a video].
Think about what you've done since you first saw this demonstration and how you might be able to explain what cause the pans to behave like they did.
Create a series of pictures that show why the pie pans behaved the way they did.
Label your drawings and explain what is happening at each step.

1.4.1.13 Create a series of drawings to describe what happens to the aluminum pie pans from the time before the Van de Graaff generator is turned on until after the pie pans fly off. Label your drawings with descriptions of what occurs at each step. [text prompt] How does your model explain your observations of the pie pans?

1.7.4.1 Review your model of the pie pans and Van de Graaff generator from Investigation1, and revise it by adding ideas that you have learned since then. Create a series of drawings that show why the pie pans behaved the way they did. Be sure your new drawings include some atomic-level details. Keep in mind the three aspects of models: components, relationships, and connections to phenomena.

If you want to see the demonstration again, click on the following link: [link to video]

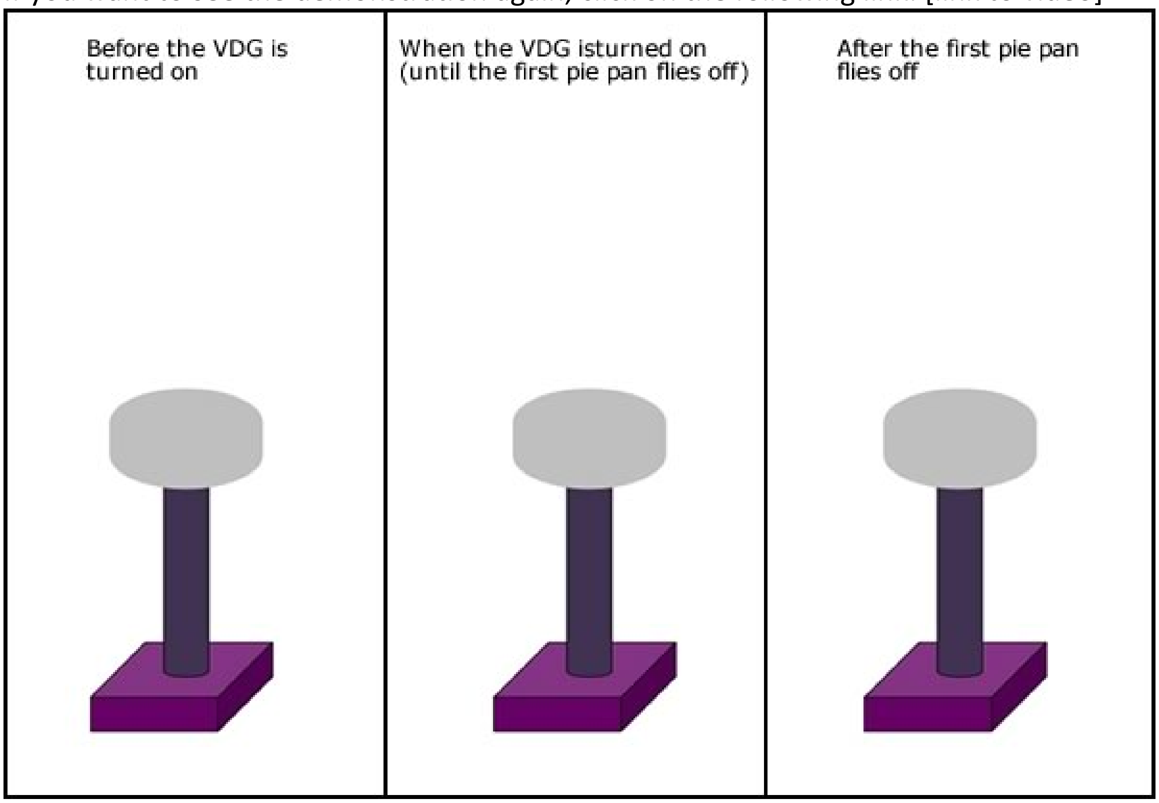


Figure 25: 1.7.4.1 prompt

2.2.4.14 Add energy to your previous model that explains why the pie pans fly off the Van de Graaff generator. In your model, indicate the amount and type of energy for the following: 1) when the generator is turned on but before the pie pans start to fly away, 2) as the pie pans are flying through the air, and 3) after everything has stopped moving. Draw an energy graph for each of these points in time.
[text prompt] Describe how this model explains your observations of the pie pans and the VDG. Be sure to include your new ideas about energy in your explanation.

Before the pie pans start to fly off (Van de Graaff is on)	As the pie pans are flying off	After the pie pans have flown off
Energy graph	Energy graph	Energy graph

Figure 26: 2.2.4.14 prompt

Atomic structure questions

1.6.1.1 Draw what you think an atom looks like. Make sure to label your model so that anyone can understand it.
How does your model explain your observations of substances?

1.6.2.12 Draw a model of the atom that could explain the evidence from Thomson's experiment.
Describe how your model explains Thomson's evidence.

1.6.3.7 Draw a model of the atom that could explain Rutherford's observations.
Describe how your model explains Rutherford's observations.

Appendix C: Interview Development, Questions, and Analysis

Steps of evidence centered design process (Behrens, Mislevy, DiCerbo, & Levy, 2012)

1) Select and unpack the Performance Expectation or Learning Goal
    a. Content analysis
        i. Elaboration of Ideas
        ii. Boundary
        iii. Prior-Knowledge
        iv. Student Challenges
    a. Unpacking Core Ideas
        v. Elaboration of Ideas
        vi. Boundary
        vii. Prior-Knowledge
        viii. Student Challenges
    b. Unpacking Practice
        ix. Elaboration of Ideas
        x. Prior-Knowledge
        xi. Student Challenges
2) Develop Instructional Level Learning Performances (ILLP)
    a. These are claims (what you hope students will be able to do)
    b. Specify the evidence you will accept that students have met the claim.
    c. What additional Knowledge, Skills, and Abilities will students need to respond to the item.
    d. Characteristic Task Features
        i. i.e., motivating task features
    e. Variable Task Features
        i. i.e., level of scaffolding provided
3) Write assessment tasks based on the information.

Interview questions:
Materials for pre-interview:

- Knit hat
- Balloon images
- Strip of magnesium ribbon (approximately 2 cm long)
- Crucible with cover
- Scale
- Lighter
- Blank paper
- Images for pre-interview paper
- White board and dry erase markers
- Video camera

Pre-interview
Scenario 1
Have you ever noticed your hair standing up when you remove a knit hat in winter?
- Interviewer will demonstrate using hat.

What do you think is happening to make your hair stick out?
Follow up questions:
How did your hair get that way?
What did the hat do to your hair?
What did that do to the hat?
Can you think of any other examples of things that happen in a similar way?

Possible probing questions (to be used as appropriate throughout interview)
Do you have any additional ideas?
Could there be a different cause?
What do you mean when you say _____?
(If student draws a diagram) Could you explain this to me? What does this represent?
How are these related/how do these interact?
Have you seen anything similar? What do you think is the relationship between these examples?

Scenario 2
- Show student images of balloons.

Imagine you had two balloons hanging from the ceiling near each other. If it is helpful, you can draw on the picture as part of your answers.
What do you think would make the balloons hang the way they are shown in the second picture?
If the balloons were hanging like they are shown in the first picture, what could you do to the balloons so that they would hang like the ones in the second picture?
What do you think would make the balloons hang the way they are shown in the third picture?
What could you do to the balloons to change them from the way they are shown in the first picture to the third picture?
Could you make other things behave this way?

Scenario 3

- Measure the mass of a piece of magnesium (approximately 2 cm) in a crucible
- Burn magnesium and collect white powder in crucible
- Measure mass of the white powder in the crucible

What did you notice when I burned the magnesium?

How would you explain those observations?

What do you think happened to the magnesium when I burned it? How does that explain your observations?

Now I'm going to ask you about a few specific ideas that will be discussed in class. I just want to get a sense of what you know or think about these ideas at this point. If you have not heard of some of these terms yet that is fine.

Have you heard of magnetic or electric fields? (If no, do not ask follow up questions)

What do you think a field is?

Do you have any ideas about how the idea of a field could help explain any of the things we have observed?

(For any scenario the student identifies as related to fields): Could you draw a diagram to represent your idea of a field? Explain your diagram to me.

Do you have any ideas of how this representation could help explain some of your observations?

What have you included in your diagram?

How do those pieces relate to each other?

How does this help explain your observation?

That's okay, fields often are not taught in school. Fields are related to forces, or how objects interact with each other. There are two really common ways to represent fields. I'm going to show you each and I just want to hear what you think is being represented. You may not have seen these before, in which case I just want to hear about how you would interpret the diagram.

(Alternatively, if student had heard of fields and drew a representation: Here are two other ways to represent fields. You may not have seen these before, in which case I just want to hear about how you would interpret the diagram.)

Field image 1:

What do you think the arrows are showing or telling you?

Does the size of the arrow mean anything?

Lets say we could insert the balloon we used earlier into this picture, do you think we could predict how the balloon would interact with these other pieces in the image? What would happen to the balloon?

Field image 2:

What do you think the lines are showing or telling you?

Is this representing the same idea as the picture with the arrows or different?

What if we inserted the balloon into this picture? What would happen to the balloon?

Could either of these pictures help explain any of the scenarios we discussed earlier? (Ask follow-up questions).

Another thing we will talk about this year are atoms. Have you heard of atoms before? (If no, do not ask follow up questions).

> What do you think of when you hear the word atom?
>
> Could you draw a diagram that represents what you think an atom looks like? Explain your diagram to me.
>
> > What have you included in your diagram?
> >
> > How do those pieces relate to each other?
> >
> > What if we had two atoms right next to each other? How would they interact?
> >
> > Why would they behave that way? Does your diagram help explain how the atoms would interact?
> >
> > Does the diagram or idea of atoms help explain any of the scenarios we discussed earlier?

Images for interview

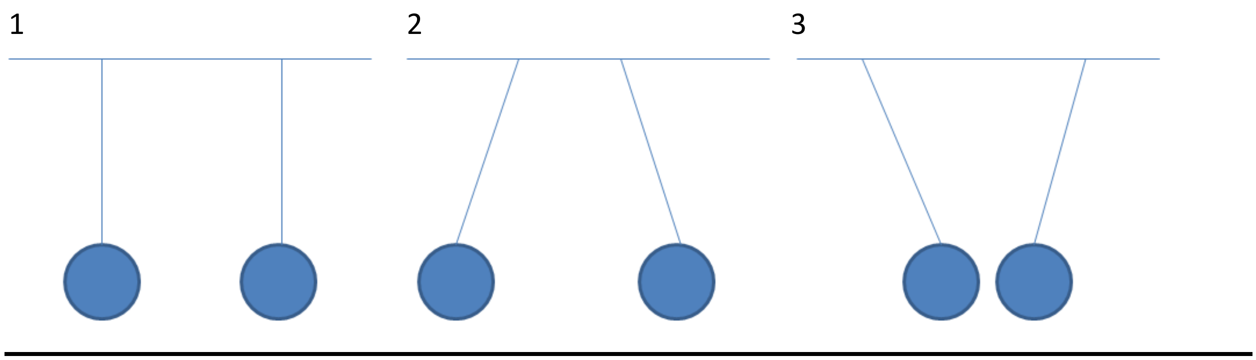


Figure 27: Scenario 3

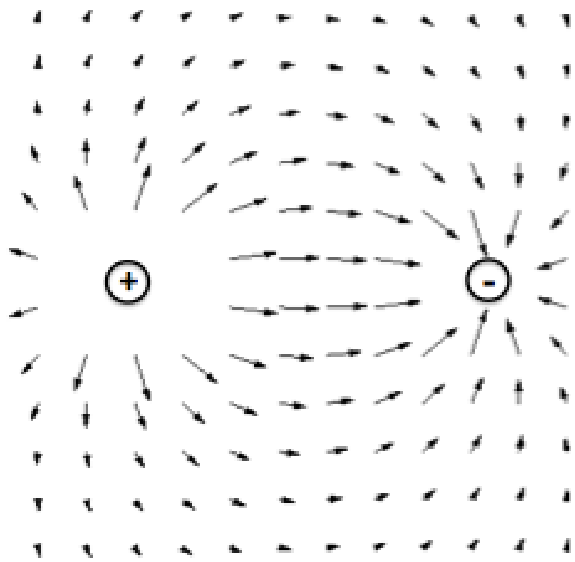
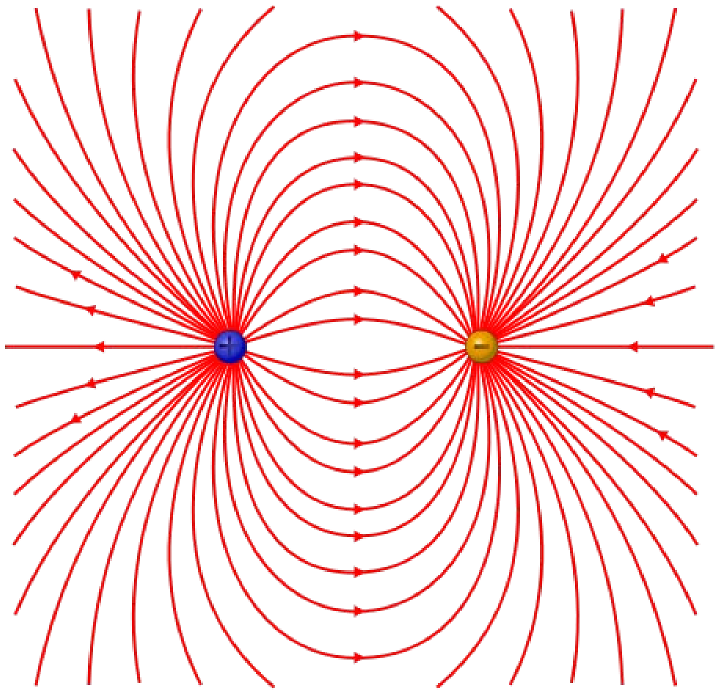


Image modified from: Srikant, Marakani. (2009). Electric and Magnetic Fields. Accessed from: http://srikant.org/core/node8.html#field2

Figure 28: Field image 1



Source: By Sharayanan (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0-2.5-2.0-1.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Common

Figure 29: Field image 2

Appendix D: Rubrics for Van de Graaff and Pie Pan Questions

1.1.1.7 & 1.1.1.8

These questions were meant to elicit their initial ideas. Students completed these models before learning about charges and interactions. Rather than define specific expected components, to evaluate these models, list the components students added and indicate if students drew a picture of their observation, or if they attempted to include a cause.

Table 14: Rubric for questions 1.1.1.7 and 1.1.1.8

Criteria	Description of what student includes	Code
Components		
Relationships		
Connection to phenomena		

1.1.1.7 & 1.1.1.8 coded as: A = attempt to include a causal mechanism or NA = picture of phenomena

1.4.1.13 Create a series of drawings to describe what happens to the aluminum pie pans from the time before the Van de Graaff generator is turned on until after the pie pans fly off. Label your drawings with descriptions of what occurs at each step. [text prompt] How does your model explain your observations of the pie pans?
1.7.4.1 Review your model of the pie pans and Van de Graaff generator from Investigation1, and revise it by adding ideas that you have learned since then. Create a series of drawings that show why the pie pans behaved the way they did. Be sure your new drawings include some atomic-level details. Keep in mind the three aspects of models: components, relationships, and connections to phenomena.
If you want to see the demonstration again, click on the following link: [link to video]
2.2.4.14 Add energy to your previous model that explains why the pie pans fly off the Van de Graaff generator. In your model, indicate the amount and type of energy for the following: 1) when the generator is turned on but before the pie pans start to fly away, 2) as the pie pans are flying through the air, and 3) after everything has stopped moving. Draw an energy graph for each of these points in time.
[text prompt] Describe how this model explains your observations of the pie pans and the VDG. Be sure to include your new ideas about energy in your explanation.

Table 15: Rubric for Van de Graaff and pie pan models

Criteria	Levels		
	0	1	2*
Components: Model includes identification and specification of appropriate and necessary components, including both visible and invisible	Diagram shows an image of the phenomenon – no charges indicated in the image or description	Some components are charged, OR charges are not included in the image and description is incomplete	The image or description clearly identifies the charge of each object.
Relationships: Model includes representations or descriptions indicating how various components within the model are related and interact with each other	Model does not indicate relationships or interactions between components of the model	Relationships are indicated in images, but does not explicitly state that same charges repel	Objects with the same charges repel
The collection of relationships provides a causal account of the phenomena: The model is used to explain or predict phenomena or specific aspects of phenomena	Model is not used to explain phenomena	Student uses model to explain observation, but it is incomplete or implied	Student uses pattern that objects with the same charge repel to explain why the charged pie pans fly away from the charged Van de Graaff generator

Table 15 (cont'd)

Criteria	Levels			
	3	4[†]	5	6[‡]
Components	Model indicates VDG and pie pans become charged, but the model does not specify that the neutral charge is an equal number of positives and negatives. No indication of changes in energy.	Student indicates that the pans and VDG are made of positive and negative particles; when the pie pans move, both the pie pans and VDG have excess of the same type of charge.	Model indicates charge building and that the objects have the same charge; however, the model is missing forms of energy that are necessary to account for the movement of the pie pans.	Students would indicate charges as described in level 4, potential energy and kinetic energy.
			Level E1—model uses energy as a mechanism but no charges or atomic structure: Model does not include charges and the energy that is included is insignificant for explaining observations.	Level E2—model uses energy as a mechanism but no charges or atomic structure: Model includes appropriate changes in energy, but does not include charges.
Relationships	Model indicates that neutral objects become charged through contact, but does not specify that this happens as electrons move.	Student shows that objects with an excess of the same charge repel and that charge builds through the movement of negative particles.	Model indicates that objects become charged as electrons move and that objects with the same charge repel. The relationship between energy and the set-up is inaccurate or incomplete.	Student shows that objects become charged through movement of negative particles and as objects near each other build up an excess of the same type of charge, the potential energy increases. As objects move kinetic energy increases.

Table 15 (cont'd)

Causal account of phenomena	Student explains how objects change from neutral to charged and how the charged objects interact but there are some missing steps or inaccurate ideas.	Student uses the connection between charge building up on nearby objects and the pattern that like charges repel to account for why the pie pans flew away from the VDG.	Student explains that charges build up and changes in energy to explain why the pie pans fly off the VDG; however there are some inaccuracies or incomplete ideas.	Student uses the connection between charge building up on nearby objects, increase in potential energy, and pattern that like charges repel to account for why the pie pans flew away.

*Highest level expected for question 1.4.1.13 is level 2

† Highest level expected for question 1.7.4.1 is level 4

‡ Highest level expected for question 2.2.4.14 is level 6

Table 16: Qualitative descriptions of models

Category	Descriptions
Mechanism for charging objects	• NA – is not included • Static electricity • One object makes another object same charge • Neutral particles change to charge • Turn on/plug in/motor
Mechanism for flying	• NA – is not included • Like charges repel (students don't need to use that language) • Potential energy converts to kinetic energy

1.6.1.1 Draw what you think an atom looks like. Make sure to label your model so that anyone can understand it. How does your model explain your observations of substances?

Table 17: Rubric for question 1.6.1.1

Criteria	Description of criteria in student's model
Components: Model includes identification and specification of appropriate and necessary components, including both visible and invisible	
Relationships: Model includes representations or descriptions indicating how various components within the model are related and interact with each other	
The collection of relationships provides a causal account of the phenomena: The model is used to explain or predict phenomena or specific aspects of phenomena	

1.6.2.12 Draw a model of the atom that could explain the evidence from Thomson's experiment.
Describe how your model explains Thomson's evidence.

Table 18: Rubric for question 1.6.2.12

Criteria	Levels		
	0	1	2
Components: Model includes identification and specification of appropriate and necessary components, including both visible and invisible	Diagram shows an image of the phenomenon	Model shows an atom – not the phenomena – but there are no clearly labeled charged components or only one type of charge is accounted for	Model represents an atom that includes negative particles and some positive charge
Relationships: Model includes representations or descriptions indicating how various components within the model are related and interact with each other	Model does not indicate relationships or interactions between components of the model	Implies that charged objects interact, but relationship between charged objects is not explicit.	Interactions between charged objects is explicitly stated or drawn: Opposite charges attract, similar charges repel
The collection of relationships provides a causal account of the phenomena: The model is used to explain or predict phenomena or specific aspects of phenomena	Model is not used to explain phenomena	Student connects model to explain the observations of the cathode ray, but the causal relationships are not clearly described, for example student explains attraction between cathode-ray (not necessary that students use this term) and charged plates but not that the pieces in the ray are smaller than atoms.	Student explains that atoms must have negative particles. These negative particles leave the atom and make up the cathode ray. The particles are negative because they are attracted to the positive plates and were repelled by the negative plates in the Cathode-Ray tube. It is not necessary that students use the term "Cathode-Ray"; however students do need to explicitly connect the negative electrons drawn in their atom to provide an explanation for why the ray bent toward positive and away from negative.

1.6.3.7 Draw a model of the atom that could explain Rutherford's observations.
Describe how your model explains Rutherford's observations.

Table 19: Rubric for question 1.6.3.7

Criteria	Levels			
	0	1	2	3
Components: Model includes identification and specification of appropriate and necessary components, including both visible and invisible	Diagram shows an image of the phenomenon	Model includes concentrated positive particles, but is missing negative particles. Positives are not packed together	Model includes positive particles concentrated in the center surrounded by negative particles. Positive alpha particles—in image or description.	NA
Relationships: Model includes representations or descriptions indicating how various components within the model are related and interact with each other	Model does not indicate relationships or interactions between components of the model	Student uses a "classical" model to explain why a few alpha particles returned toward the source, for example, they "bounced off" the nucleus (students are not expected to use specific terms)	Student uses an electrostatic interaction, for example, positive alpha particles are repelled because of the strong force that is exerted by the positive nucleus (similar charges repel), but does not include electric fields.	Concentrated charges create a stronger electric field. Positive alpha particles are repelled by a strong electric field.

Table 19 (cont'd)

The collection of relationships provides a causal account of the phenomena: The model is used to explain or predict phenomena or specific aspects of phenomena	Model is not used to explain phenomena	Model is used to explain why alpha particles bounced back, but connection between path of the alpha particles and the cause is incomplete	Student explains that a small number of particles bounced back in the direction they came from because those few alpha particles were affected by the strong field created by the concentrated protons	NA

Appendix E: Common Ideas Across Interviews

INC = incorrect idea, i = incomplete idea

Table 20: List of common ideas across interviews

Charges:		
• Opposites attract	C1	C1 INC
• Like repel	C2	C2 INC
• Neutral and charge attract	C3	C3 INC
• Friction -> charge	C4	
• Similar to magnets	C5 i	
• Friction/rubbing	C6 i	
• Static/shock/electric	C7 i	
• “attracted”	C8 i	
• Material	C9 i	
• positive/negative/charge	C10	
• fibers of material intertwine, tangle or stick together	C11 i	
Atomic:		
• Atoms = pieces of matter	A1	
• 7th grade project	A2	
• atoms have pieces	A3	A3 INC
o atoms have protons	A3a	
o atoms have electrons	A3b	
o atoms have neutrons	A3c	
• protons are positive	A4	A4 INC
• electrons are negative	A5	A5 INC
• neutrons are neutral	A6	A6 INC
• protons v electrons determines charge	A7	
• protons packed in center	A8	A8 INC
• electrons smaller	A9	A9 INC
• electrons move within atoms	A10	
• electrons move between things to charge	A11	
• electrons attracted to protons	A12	
• pieces in atoms shift due to interaction	A13	
• protons in middle	A14	
• protons held with strong force	A15	
• protons determine element	A16	
• add protons to make heavier	A17i	

Table 20 (cont'd)

• add electrons to make heavier	A18i		
• types of atoms similar to subatomic part	A19 i		
• same # protons & electrons = neutral	A20		
• neutrons in middle	A21		
• electrons in outside	A22		
• Different atoms have different properties	A23		
• Electrons are in rings/paths around middle	A24i		
• Rings can have a certain number of electrons	A25i		
• number of protons and electrons matter	A14 i		
• atoms form bonds	A15 i		
o atoms connect	A15a i		
• atoms make molecules	A16 i		
Atoms interacting/reacting			
• Electrons shift to form bond	R1		
• Energy to surroundings	R2		
• Bond is stable point	R3		
• Reaction = change in bonds	R4		
• Reaction = change	R5 i		
• Burning is evidence of energy change	R6		
• Burning consumes things	R7 i		
• Burning changes things	R8 i		
• Bond = connecting atoms	R9 i		
• Atoms form molecules	R10 i		
• Light connected to energy	R11 i		
• Atoms interact depending on charge	R12 i		
• Atoms repel b/c electrons	R13 i		
• Objects interact = atoms interact	R14 i		
• Mass incr b/c air/smoke trapped	R15 i		
• Mass incr = ash heavier	R16 i		
• Mass decr b/c ash less than Mg	R17 i		
• Atoms/molecules make matter	R18		
• Flame makes atoms move more	R19 i		
• Atoms in ash spread out	R20 i		
• Losing air or light stuff makes it heavier	R21 i		
• Reaction/burning changes atoms (ie Protons)	R22 i		
• Atoms bond b/c octet – ie "want" to "complete' or "fill" shell/level etc (does not need to be eight)	R23 i		

Table 20 (cont'd)

Fields:			
• electric charge interacts with electric field	F1		
• one object "creates" field	F2		
• stronger indicated in representation	F3		
• stronger closer	F4	F4 INC	
• weaker indicated in representation	F5		
• weaker farther	F6	F6 INC	
• in line arrows indicate attraction	F7		
• opposing arrows indicate repulsion	F8		
• arrows show what a positive test charge would feel	F9		
• arrows show energy/force moves from positive to negative		F10 INC	
• Fields are protective devices		F11 INC	
Other initial ideas			
• unable to answer	U		

Appendix F: Sample Student Responses with Codes

Pre-interview, Claire

Question – after discussing scenario 1 (hat and hair) and scenario 2 (balloon images)

Interviewer: Um, do you think there is any connection between the balloons and the hair and the hat?
Claire: Well, the material [rubbing fingers], the material that's, like balloons [rubbing fingers], like if you rub it on your head [pantomiming rubbing a balloon on head] then your hair gets big too
Interviewer: Okay, like same with, like your hair does the same thing
Claire: Yeah your hair goes frizzy.
I have no idea
Interviewer: Okay, but so it seems like you kind of have this idea that it has to do with the materials?
Claire: Hm-mm. Or like the fabric [rubbing fingers], or not the fabric because fabric is like cloth [pantomiming laying out cloth on table] but like [rubbing fingers] yeah.
Interviewer: Like what its' made out of?
Claire: Yeah, what its made out of.
Interviewer: Any ideas of what that would be, how that would make a difference?
Claire: Like the material?
Interviewer: Yeah?
Claire: Rubber, plastic, anything really. Or, I don't know what's in hair [rubbing hair between fingers], that's the thing. I feel like it has to do with hair, but I have no idea what's in hair.
Interviewer: You don't know what's in hair? Okay, okay.
Claire: No
Interviewer: So, you feel like it's the rubber and plastic with the hair?
Claire: Hm-mm [agreeing].
[throughout when she said 'material' she would rub fingers and thumb together, pantomiming rubbing fabric or material between her fingers]

Table 21: Codes for Claire's pre-interview sample

Coding scheme	Coding scheme category	Codes	Evidence
Content	N/A	Macro/observable	Lines 3 -7; Lines 11 – 19
Reasoning	nature	Pieces of information	Lines 3 – 7; Lines 11 & 12
	Source	None	
	Justification	None	
Preparation for future learning	Application	None	
	Question	None	
	Test	None	

After Rutherford debrief, Nate

Question – how does your model link to the evidence

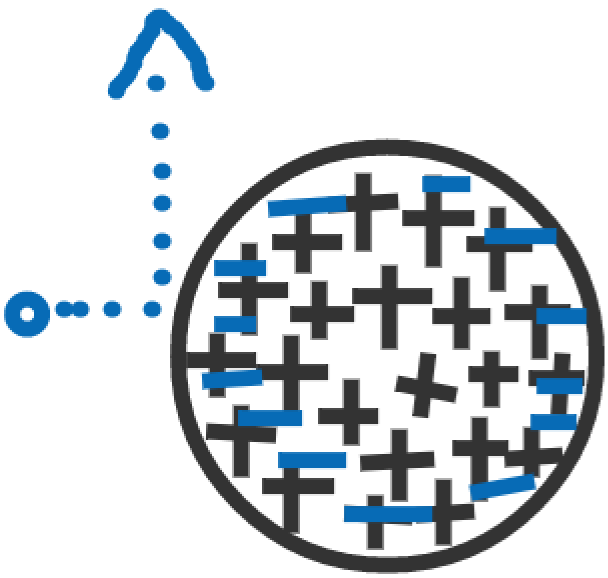
Interviewer: Um, so how does this kind of like explain what Rutherford saw?

Nate: I don't really remember

Interviewer: You don't remember? So Rutherford was the one with the gold foil. Where the alpha particles, a lot of them went through and some of them bounced back.

Nate: Um, maybe, um the electrons are so small and the atom's so much bigger than it, that um, it [alpha particle] would go and it [alpha particle] would like hit like the like glob of the atom which is positive, but sometimes it [alpha particle] would like go and there would be an electron close to the edge and it [alpha particle] was like deflected, that's what I think.

[throughout, "it" refers to the alpha particle]



the positive protons in the atom deflected some of the alpha particles while others pass through it

Figure 30: Nate's model of atomic structure after discussion of Rutherford's gold foil experiment

Table 22: Codes for Nate's after Rutherford debrief

Coding scheme	Coding scheme category	Codes	Evidence
Content	N/A	Atoms have pieces	Line 5
Reasoning	nature	Pieces of information	Lines 3 - 6
	Source	None	
	Justification	None	
Preparation for future learning	Application	None	
	Question	None	
	Test	None	

Post-Unit One interview, Jonathan

Question – scenario one: hat and hair

Interviewer: So, the first scenario is, actually very appropriate right now. So, a knit hat, you're wearing one, and you take it off and sometimes your hair stands up. Any ideas about why that happens?

Jonathan: Yes! Friction, when you're wearing it [hat], it rubs against your hair. And electrons are transferred. I don't know which way they're transferred, probably from, it takes some away from your hair maybe. And then it makes everything the same charge. And then when you take it off, your hair is all the same charge and so it wants to repel and it pushes away from each other and it sticks up.

Interviewer: Okay, uh what do you think that does to the hat?

Jonathan: The hat is now the opposite charge of your hair.

Interviewer: Okay.

Jonathan: And then it [hat] attracts it [hair] and that makes it stick up and then from there they [hairs] just repel away from each other.

Table 23: Codes for Jonathan's post-Unit One interview

Coding scheme	Coding scheme category	Codes	Evidence
Content	N/A	Charges	Lines 5 & 6 Lines 10 - 12
		Atoms have charged pieces that interact	Lines 4 - 8
Reasoning	nature	Pieces of information	Line 4
		Dynamic	Line 4 – 6 Line 10
		Atomic-level explanation	Line 4 – 8
	Source	None	
	Justification	None	
Preparation for future learning	Application	None	
	Question	None	
	Test	None	

Follow Up Interview, Chase

Question – follow up scenario two: charged rubber rod with hexane and water

Interviewer: So then the next situation is, um, kind of similar, only this time it's looking at liquids with the rod and the fur, um I think it's a rubber rod instead of Teflon. So the first liquid is called hexane, and it's a clear liquid. So this tube is filled with hexane and then there's a really thin stream of it.

Chase: Yeah, I see it.

Interviewer: You see it? Okay. So and hexane is, you know how finger nail polish remover is really smelly?

Chase: Hm-mm [agreeing].

Interviewer: Hexane is kind of similar to that, it's really smelly, um, it's used for cleaning. It's kind of a pretty nasty, it can cause cancer and stuff, so it's not used very much.

Chase: Oh, okay.

Interviewer: Um, so we're gonna look at hexane with the rubber rod after it's been rubbed with the fur and then same thing, only with water. [watched video] Did you see it?

Chase: So water moved, and the hexane didn't.

Interviewer: Okay. So what do you think's going on there?

Chase: So hexane, did it move at all?

Interviewer: Do you want to watch it again? [Replayed video]. It happens pretty quickly, so it's kind of hard to see.

Chase: [watching video closely] Doesn't move, and the water goes towards it. So, the water could be the opposite charge of what the Teflon is. Or, it actually, it could be this [rod] is neutral and the hexane is neutral, so they don't attract at all. And this [rod] could be neutral and the water could be positive or negative, and this [rod] is neutral so it attracts.

Interviewer: Okay, so if this [rod] is neutral and the water is either positive or negative, what's going on there, why would that attract?

Chase: Well, say that the water is positive, so it has more protons, um sorry [coughs], the protons they would be attracting to the protons that are in the Teflon, or no, sorry the electrons that are in the Teflon, because opposites attract.

Interviewer: Okay, okay. So the water has more protons and the Teflon has

Chase: Equal, equal amount.

Interviewer: And then the electrons in the Teflon and the protons in the water are attracted?

Chase: Hm-mm [agreeing].

Interviewer: Okay. Um, so it could be the water is charged and then everything else is neutral?

Chase: Hm-mm [agreeing].

Interviewer: So, with that, how could you test if that's what's going on?

Chase: You could, let's see, water is positive and Teflon is neutral, you could take another positive object and put it next to the water and see if it repels or a negative and see if it attracts.

Interviewer: Okay. So, how about, could there be any other explanations? Other than the water being charged, or the water being positive and everything else being neutral?

Chase: Um, yeah probably. Um, hexane didn't move, so probably, um.

Interviewer: So there could possibly be a different explanation, you're just not sure what it is?

Chase: Yeah. Yeah.

Interviewer: Okay. How about any ideas why water would be positive? What would

make it positive and hexane would be different?
Chase: I guess it just has more protons than electrons.

Table 24: Codes for Chase's follow up interview

Coding scheme	Coding scheme category	Codes	Evidence
Content	N/A	Charges	Lines 22 - 25
		Atoms have charged pieces that interact	Lines 28 - 30
Reasoning	Nature	Pieces of information	Line 28 Lines 38 & 39 Line 51
		Dynamic	Lines 21 - 25 Lines 28 - 30
		Atomic-level explanation	Lines 25 - 27
	Source	None	
	Justification	None	
Preparation for future learning	Application	Application of class ideas	Lines 22 - 25 Lines 28 – 30 Lines 41 – 42
	Question	Productive question - unprompted	Line 18
	Test	Productive test	Lines 41 – 42

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