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Impact of historical science short stories on students’ attitudes and NOS understanding

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This study examines the impact of historical short stories on upper and lower level high school chemistry students in the second semester of a two-semester course at a large Midwestern suburban school. Research focused on improved understanding of six fundamental nature of science (NOS) concepts made explicit in the stories, recollection of historical examples from the stories that supported student NOS thinking; student attitudes toward historical stories in comparison to traditional textbook readings as well as student attitudes regarding scientists and the development of science ideas. Data collection included surveys over six NOS concepts, attitudes towards science and reading, and semi-structured interviews.

Analysis of the data collected in this study indicated significant increases in understanding for three of the six NOS concepts within the upper-level students and one of the six concepts for lower level students. Students were able to draw upon examples from the stories to defend their NOS views but did so more frequently when responding verbally in comparison to written responses on the surveys. The analysis also showed that students in both levels would rather utilize historical short stories over a traditional textbook and found value in learning about scientists and how scientific ideas are developed.
CHAPTER 1. INTRODUCTION

The Nature of Science and Science Education

The current quality of science education has been in question for some time, as the majority of the United States citizenship is not scientifically literate. A survey conducted by the National Science Board reports that “64 percent of the American public effectively have no knowledge of how science works” (National Science Board, 1996). This statistic is sobering, as it reflects school sciences’ emphasis on factual recall instead of the knowledge generating process necessary for a scientifically literate society. To move towards this desired state, science instruction must include a critical context for understanding science.

Many science education scholars agree that a deep understanding of the NOS will help students’ better understand science content, gain appreciation for its study, and increase crucial science literacy (Matthews, 1994; McComas & Olson, 1998). The National Science Education Standards (NRC, 1996) state that scientific literacy hinges on understanding the NOS, while the latest Next Generation Science Standards add emphasis to the importance of NOS by stating “science is both a set of practices and the historical accumulation of knowledge…students should develop an understanding of the enterprise of science as a whole” (NRC, 2013, p.1, Appendix H).

This context is the nature of science (NOS), which includes topics such as what science is, what scientists are like and how science works. The NOS combines various aspects of the social studies of science to create a view of the scientific community and how science functions. A few examples of NOS concepts include how science knowledge is accepted, the difference
between private and public science, what scientists are like, the effect of culture and society on science, and how hypotheses, theories and laws function in science.

NOS as a goal in science education first appeared in a 1907 reform document when the Central Association of Science and Mathematics Teachers recognized the need for students to develop accurate conceptions of NOS to understand the process by which scientific knowledge is derived. Since then, NOS has appeared in many science education reforms as well as in all contemporary reform documents (AAAS, 1989 & 1993; NRC, 1996 & 2013). However, even with the constant acknowledgment that students need to comprehend the nature of science, the state of science education is far from achieving this goal. As Lederman & Niess (1997, p. 1) write “the longevity of this educational objective has been surpassed only by the longevity of students’ inability to articulate the meaning of the phrase ‘nature of science’ and to delineate the associated characteristics of science”.

Societal misconceptions of NOS, perpetuated through poor teaching, have very real implications for a democratic society. These consequences include, but are not limited to poor attitudes in science class and towards science careers (Tobias, 1990), superficial understanding of many science ideas (Clough, 2006), and poorly informed and problematic thinking regarding socio-scientific issues (Allchin, 2011; Herman, 2015; Mitchell, 2009; Rudolph, 2007; Zeidler et al., 2013). To move closer to the goal of scientific literacy for all, the NOS must be incorporated accurately and consistently into science education (AAAS, 1989; Matthews, 1994; McComas & Olson, 1998), thereby keeping students engaged to potentially pursue a future science career (Tobias, 1990).
Effectively Teaching the NOS

While the current state of NOS teaching is not particularly effective, much is known about effectively teaching the NOS in the science education literature. Extensive research makes clear that NOS instruction is most effective when it features an explicit and reflective character (Adb-El-Khalick et al., 2000; Abd-El-Khalick & Lederman, 1998). Explicitly teaching the NOS involves deliberate design and implementation of lessons to address NOS issues (Lederman, 1998; Khishfe & Abd-El-Khalick, 2002); whereas reflective NOS teaching involves helping students make connections between an experience (e.g., inquiry activity, classroom discussion, videos, etc.) and NOS ideas (Khishfe & Abd-El-Khalick, 2002).

Effective NOS instruction also demands that such instruction occur in a variety of contexts with extensive scaffolding back and forth between those contexts (Clough, 2006). These contexts occur along a continuum of decontextualized, moderately contextualized, to highly contextualized settings (Clough, 2006) creating a foundation for students to work from that links to science content understanding (Driver et al., 1996; Ryder et al., 1996; Brickhouse et al., 2000). Clough (2006) describes decontextualized settings as isolated examples of NOS issues devoid of science content. A decontextualized activity creates a base of knowledge through ideas that are familiar and concrete to the student, but do not feature science content, such as black box activities. The moderately contextualized setting features students reflecting upon the process of science as conducted in their lab experiences. Decontextualized and moderately contextualized settings are important to introducing students to NOS concepts. However, they rarely force students to evaluate their NOS conceptions and are divorced from authentic scientific investigations. This is not to say they do not have value, as they are crucial in creating analogies
for students that will benefit in creating conceptual change (Clough, 2006; Dagher, 1994; Tyson et al., 1997).

Highly contextualized settings occur when NOS and science content are seamlessly connected. The incorporation of highly contextualized NOS activities requires historical and contemporary science examples (Clough, 2006) such as stories where NOS ideas are explicitly discussed. The AAAS (1990) states that, “The teaching of science must explore the interplay between science and the intellectual and cultural traditions in which it is firmly embedded. Science has a history that can demonstrate the relationship between science and the wider world of ideas and can illuminate contemporary issues”. Due to the deep entanglement between content and the NOS featured in historical examples, the teaching of science content and NOS ideas happens seamlessly. Historical short stories with embedded questions that encourage reflection and intentionally draw students to commonly held NOS misconceptions can be highly effective highly contextualized activities (Clough, 2011). By using historical stories, working back and forth through the decontextualized to highly contextualized NOS continuum, student understanding of the NOS increases.

**Curricular Materials for Teaching the Nature of Science**

However, there are few classroom materials that are easily available for accurate highly contextualized settings that explicitly and reflectively address the NOS. These resources do not exist as textbook companies do not want to modify current text for fear of losing market share (Clough, 2011) and many secondary teachers (and post-secondary) claim that the have little available time to teach NOS, let alone the rest of their curriculum. This prompted the writing of an NSF grant to create thirty historical science stories for use at the post-secondary level. To
increase the efficacy of teachers and students teaching and learning of effective NOS concepts, the stories were specifically designed according to how people learn with the intent of being highly contextualized. To do this, Clough (2011), made sure the stories focused on science ideas that were already part of the curriculum, written in a way that allows autonomous use by the teacher, created for both past and present science ideas, included the words of scientists to show humanistic and authentic character, incorporated comments that explicitly and reflectively draw students attention to key NOS ideas, including questions that reflect on the NOS, and were connected to other science content in and out of the classroom.

Through an NSF grant-funded project (Clough, Olson, Stanley, Colbert, & Cervato, 2006), 30 historical short stories were written to be used in post-secondary introductory science classes. The long-term goal of the project was to have Post-secondary science teachers accurately and effectively convey the NOS to improve scientific literacy and attitudes towards science, scientists, and science education. By using the historical short stories, instructors could deliberately draw students’ attention to fundamental science ideas deeply entwined with NOS issues, therefore improving science content knowledge as well as confronting NOS misconceptions. Initial studies conducted on geology and biology students at the post-secondary level showed significant increases in NOS conceptions and a potential link to increased content understanding of biological evolution which led to the initial NSF grant proposal (Clough et al., 2006). Further research was undertaken by Reid-Smith (2013) to modify the historical short stories for use in thirteen secondary classrooms. Reid-Smith concluded that historical stories increased NOS understanding of secondary students, but under what conditions is still unclear.
Research Methodology

Purpose of Study

In this study, five different historical short stories with embedded questions were used in secondary chemistry classes at differing levels. The intent of the study was to determine what effect, if any, the use of historical and contemporary short stories about the development of scientific ideas has on secondary science students’ accurate understanding of the nature of science and to determine the students’ perceptions of the stories.

Research Questions

The study focused on the following research questions:

1. Does the use of historical science stories with explicit NOS statements and questions improve secondary science students’: (a) accurate understanding of fundamental NOS concepts made explicit in the story and (b) recollection of historical examples that logically support their NOS thinking?

2. What are secondary science students’ attitudes toward: (a) reading the short stories compared to a traditional textbook reading and (b) reading about scientists and how science ideas are developed?

Methodological Overview

The participants in the study were Chemistry and General Chemistry students at a Midwestern high school that requires one year of chemistry. Chemistry is taken by many college-bound (four-year institution) students and requires strong math skills (as the class covers quantum numbers, stoichiometry, and uses mathematical modeling); General Chemistry is taken.
by students who may be college bound (two-year institution or technical school), have struggled with math and may benefit from learning at a slower pace. The Chemistry course enrolls freshman through senior students (ages 14-18) while the General Chemistry course includes only juniors and seniors (ages 16-18).

For this study, a randomized control group pretest-posttest design was utilized (Isaac & Michael, 1971). The instructor taught three sections of Chemistry and three sections of General Chemistry. Two of the three sections – in both courses – were chosen as treatment, leaving the final section as the control group. The treatment groups utilized the modified historical short stories identified above in accord with the curriculum. During these units of study, students were asked to read the stories on their own (Chemistry) or in small groups within the class (General Chemistry). In-class activities followed over the next days with class discussions over the readings and embedded questions, in addition to instructor designed questions. The embedded questions and highlighted text boxes in the readings were used to explicitly address the NOS while learning about chemistry content knowledge.

The control groups used other stories/reading materials and in some cases, audio-visual materials, to cover the same content found in the treatment group stories. The instructor focused on asking discussion questions that focused solely on the content and did not explicitly address fundamental NOS ideas. A concerted effort was made to keep all other teaching identical between the treatment and control groups.

All students in the study were pre-assessed using two instruments: Views on Science and Scientific Inquiry (VOSSI) and Interest/Attitude Survey. The VOSSI survey featured six questions with Likert item responses and a written response section. The Interest/Attitude survey
contained 25 Likert item questions regarding attitudes towards reading and science class and two final questions (one Likert, one written response) regarding interest in a science-related career.

At the end of the semester, a post VOSSI and post Interest/Attitude survey was given to both control and treatment groups. Appropriate quantitative statistical tests were conducted to analyze and compare the pre and post-survey scores for control and treatment groups on VOSSI and Attitude/Interest surveys. Following the post surveys, participants from the treatment group were asked to be part of a short semi-structured interview process. Interested participants names were randomly selected and twenty-six participants were interviewed. The interviews lasted between 10 to 15 minutes and asked the participants to comment on specific fundamental NOS concepts that were addressed through the stories and on their interest level in reading the stories and science careers.
CHAPTER 2. LITERATURE REVIEW

Nature of Science in Science Education

The nature of science (NOS) combines various aspects of the social studies of science to create a view of the scientific community and how science functions. McComas, Clough and Almazroa (1998) describe the nature of science as “a fertile hybrid arena including the history, sociology, and philosophy of science combined with research from the cognitive sciences such as psychology into a rich description of what science is, how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors” (p. 511).

Examples of NOS concepts come from each context: historical – how scientific knowledge comes to be accepted, sociological – the effect of culture and society on science, psychological – interpretations of data can differ based upon prior knowledge and expectations, and philosophical – how do we know the truth of a proposition.

Science education reforms of the past 50 years stress the importance of NOS and have focused on students becoming scientifically literate (AAAS, 1993; NRC, 1996; NRC 2012), emphasize learning through inquiry (Sund & Trowbridge, 1967) not just learning science facts. McComas, Clough, and Almazroa (1998) state that accurately teaching NOS concepts lead to enhanced:

- understanding of science’s strength and limitations;
- interest in science and science classes;
- social decision making later in life;
- instructional delivery; and
- learning of science content.

Students who learn facts, hypothesis, and theories of science know the “what” of science but do not learn where this knowledge originates from, or the “how” of science (Duschl, 1994). Bruner
validates this, writing that “learning is…figuring out how to use what you already know in order to go beyond what you currently think” (p. 183). For this learning to occur, one needs to know something ‘structural’ about what they are learning; this alone is worth more than a thousand facts (1983). By viewing science through a historical, philosophical, and methodological lens, its structure can be unveiled. To understand science concepts, the origin of the information must be known, which can be developed by learning about the NOS.

**Importance of NOS in Science Education**

What is the importance of all citizens obtaining a structural knowledge of the fundamentals of science? Those that contribute to the liberal tradition of education believe that science taught through a NOS perspective, one that is informed by its history and philosophy, can promote understanding of the natural world, the appreciation of nature and science, and the awareness of ethical issues divulged by scientific knowledge and created by scientific practice (Matthews, 1994). Driver et al. (1996) provide five arguments for the inclusion of NOS as a goal of science education:

- a person’s understanding of the NOS is necessary if he/she is to make sense of the science and manage the technological objects and processes he/she encounters;
- to make sense of socio-scientific issues and participate in the democratic decision making process;
- to appreciate science as a major element that has shaped modern culture;
- to view the norms of the scientific community and their moral commitments; and
- to support learning of science and content.

An accurate understanding of NOS fundamentals is crucial for making sense of an ever-evolving world.
Current State of NOS Understanding in the United States

Unfortunately, the United States lacks a citizenship that understands the fundamental views of science. Surveys conducted by the National Science Board report that “64 percent of the American public effectively have no knowledge of how science works” (National Science Board, 1996). Pew Research findings indicate that a majority of the U.S. public believes that living things have evolved over time but only a third of them attribute this to “natural processes such as natural selection” (2009). Not only is the NOS important to learning in the field of biology, but also in physics, chemistry, earth science, and other science disciplines. Understanding the collisions between particles at the CERN Hadron Collider will not cause a massive black hole to form on earth, but may lead to unexpected discoveries/creations in the future, stem from learning about the NOS. Knowledge of how scientific ideas are generated, tested, peer reviewed as well as the use of models and data would help eliminate much political debate regarding global climate change. These misconceptions of science lead to poor decision making that give rise to societal issues or fail to solve societal issues. Yearly (1996) writes that policymakers use uncertainty and lack of scientific consensus to delay tackling environmental problems. Mitchell (2009) adds that appealing to uncertainty creates a climate where all scientific contributions run the risk of being dismissed. Another example of the low U.S. literacy is the public’s failure to see the importance of basic research in technological innovations which may have significant societal consequences when funding decisions are made in the future (Elmer-Dewitt, 1994). Neil deGrasse Tyson comments that important creations such as the MRI machine grew out of basic research and without basic research in physics, many health-related diagnostic tools would not exist (Laufenberg, 2014). The current status of scientific understanding in the United States is
sobering, and is a reflection of school sciences’ emphasis on factual recall and exclusion of the knowledge-generating process. To improve such statistics to reflect a scientifically literate society, science instruction must include critical context for understanding science.

**Teacher Conceptions of the NOS**

One reason for these statistics is poor NOS understandings by science educators. For the public’s misconceptions of science to improve, science teachers need a greater understanding of the NOS and how to accurately address it. Studies conducted on teacher NOS understanding have continually shown an uninformed view of NOS. Miller (1963) was one of the first to assess teacher NOS understanding and found that many science teachers, and consequently their students, failed to demonstrate an understanding of how science works. Schmidt (1967) replicated Miller’s work, reaching the same unfortunate conclusions. Work done by Elkana (1970) viewed teachers’ NOS conceptions as 20-30 years behind those of the philosophy of science. Cawthorn and Rowell (1978) found teachers held a naïve-realist position of science, and four years later (1982) many held an inductivist-empiricist outlook on science. DeBoer (1991), in a review of the history of science in education, found that teachers still held a positivist view, confirming Elkana’s work that teachers hold outdated conceptions of the philosophy of science. This trend still occurs today as science teachers often possess inaccurate or simplistic views of the NOS (Abd-El-Khalick & Lederman, 2000; Carey & Strauss, 1970; Lederman, 1992), and do not consider NOS issues important to teaching and learning (Bell et al., 1998; King, 1991; Lakin & Wellington, 1994).

Many teachers dismiss teaching NOS ideas which make little sense as teachers communicate the NOS to students regardless of whether it is done purposefully or accurately
McComas, Almazroa and Clough (1998) write that, “throughout these daily [classroom] experiences are explicit and implicit cues regarding how science works and the status of scientific knowledge” (p. 527). Not only are students learning misconceptions about the NOS, this practice also significantly impacts students’ attitudes towards science and science classes, making it more difficult to deeply understand science content (Clough & Olson, 2012). Teachers’ pedagogical decisions, therefore, have a very large effect on students’ science understandings as well as the enjoyment of science class.

Teacher decisions on construction of the course, materials to be used, instructional practices, labs and activities, and language used when talking to students all affect the way students perceive the context of science. Course construction is typically developed from state or local standards (many that include NOS references); however teachers have the autonomy, in many cases, to decide how information will be taught. Without planning for explicit NOS instruction, students will fail to develop accurate NOS understandings (Durkee, 1974; Tamir, 1972; Trent, 1965; Troxel, 1986; Abd-El-Khalik & Lederman, 2000). Kuhn (1970) echoes this sentiment when he wrote “more than any other single aspect of science, the pedagogic form has determined our image of the nature of science and of the role of discovery and invention in its advance” (p. 143). The course design and delivery, therefore, will shape what students learn about the NOS.

Pedagogical Decisions Regarding the NOS

In the United States, science textbooks are frequently used as a means of instruction (Weiss, 1993; Lapointe et al., 1989). This is harmful, as Postman (1995) warns textbooks are only concerned with presenting facts, while giving no clue as to how they were “discovered” and
presenting knowledge as a commodity to be acquired, not to be understood. In textbooks, the NOS is usually relegated to a short unit in the first chapter and inaccurately depicted throughout the rest of the chapters. Therefore, the use or disuse of text has consequences on the students NOS perceptions. Clough and Olson point to a multitude of research that shows science textbooks, common lab activities, and most audio-visual materials downplay or ignore altogether human influences in research, sanitizing the work that led to the scientific idea, therefore portraying science as a rhetoric of conclusions (Cawthorn & Rowell, 1978; Clough 2011; Jacoby & Spargo, 1989; Leite, 2002; Munby, 1976; Duschl, 1990; Rudge, 2000). Clough and Olson (2012) also add that teachers, students, and the general public’s misconceptions are reinforced by science textbooks, thereby creating a powerful self-supporting network that will continue as a vicious cycle. Without careful insight and planning, students will develop inaccurate NOS conceptions, which rarely lead to scientific literacy.

The teachers’ language use also affects students’ conceptions of science. Schwab (1964) observed science teaching as being an “unmitigated rhetoric of conclusions in which current and temporal constructions of scientific knowledge are conveyed as empirical, literal and irrevocable truths” (p.24). If teachers do not understand the NOS well, their language to students will convey an inaccurate view of the NOS. The teacher’s role in accurately depicting the NOS is crucial if we are to create a science-literate public and reverse student misconceptions. It has been well documented that students continue to maintain the same misconceptions into adulthood regarding scientists, how science operates, and the construction of scientific knowledge (Clough, 1995; Durant, Evans, Thomas, 1989; Millar & Wynne, 1988; Miller, 1983, 1987; NAEP, 1989, National Science Board, 2002; Rowell & Cawthorn, 1982; Rubba, Horner, & Smith, 1981; Ryan & Aikenhead, 1992; Ziman, 1991).
A teacher who is well-versed in the NOS can have a large effect on students’ understanding of the NOS as well as the science course. By teaching the NOS concurrently with science content, students can develop a dynamic view of the framework of science. This is best viewed through the work of Songer and Linn (1991) who studied the difference in students with a dynamic and static view of science. Students’ who held a dynamic view saw science knowledge as tentative and best learned by understanding what ideas mean and how they are related, as opposed to the static view that science is a large conglomeration of facts. These students also integrated understanding of the concept being taught better than those who held a static view. Students also viewed science as a potential worthwhile career when exposed to accurate conceptions of NOS. At the university level, Tobias (1990) found that students were uninterested in science courses because they were devoid of historical, philosophical and sociological foundations of science. The incorporation of NOS helps to humanize the subject, making it a more approachable career choice. NOS instruction also helps students link to content. McComas, Almazroa and Clough (1998) state that without understanding what law and theory mean in the context of science, the content is difficult to understand. Accurately conceptualizing scientific theory and law relates to understanding how science operates and is imperative for evaluating the strengths and limitations of science, as well as the value of different types of science knowledge. When students deeply understand scientific laws and theories, they understand that evolution is not “just a theory,” and could interpret the theory of evolution as the mechanism that accounts for the diversity of life on Earth. Understanding the basis of a scientific law, an invariable relationship seen in nature, would help students better understand Boyle’s law, the interaction of pressure and volume, or the law of periodicity, relationships between elements on the periodic table.
NOS Objectives in Secondary Science Education

A consensus view of NOS objectives suitable for use in secondary settings has been around for more than 20 years. McComas (2008) gives the following abbreviated list of tenets as being appropriate for use at the K-12 level:

- Science produces, demands, and relies on empirical evidence.
- There is no one step-wise scientific method by which all science is done, Experiments are not the only route to knowledge.
- Scientific knowledge is tentative, durable and self-correcting.
- Laws and theories are related but distinct kinds of scientific knowledge.
- Science has a creative component.
- Science has a subjective element. In other words, ideas and observations in science are “theory-laden”.
- There are historical, cultural and social influences on the practice and direction of science.
- Science and technology impact each other, but they are not the same.
- Science and its methods cannot answer all questions.

However, NOS concepts should be presented to students not as a list of facts to memorize but as questions that force students to investigate and reflect upon their understanding. NOS tenets, promoted by many science education researchers (e.g., Osborne et al., 2003, Lederman and Lederman, 2004, McComas, 2008) can easily be something to be transmitted rather than investigated in a science classroom (Clough, 2007). To avoid this problem, Allchin recommends a “Whole Science” approach. By looking at the credibility of a scientific claim, in the classroom or the newspaper, an informed citizen will be able to interact with experts, recognize relevant evidence as well as that which is bogus, understand the limits and foundations of scientific claims and negotiate through scientific uncertainty (Allchin, 2011). This approach shifts the focus from the tenet to the interpretive analysis of the NOS questions by examining the multiple
dimensions that shape scientific knowledge. To create a well-educated student, capable of navigating these questions, the NOS need be presented as questions rather than tenets, engaging the students to confront their naïve views of science and grapple with the complex realm of scientific knowledge creation.

**Effective NOS Instruction**

The significant misconceptions held by students and teachers embody the justification for inclusion of NOS in science courses, as well as science teacher preparation programs. Having an understanding of what NOS represents is not enough, as teachers need to recognize what effective NOS instruction looks like in the classroom. Effective NOS instruction needs to be explicit and reflective in nature, use conceptual change as a driving force, draw from a spectrum of decontextualized to contextualized settings, and utilize the seamless connection of the NOS and science content found in history of science examples.

Many science courses are created to utilize inquiry activities/labs that place students in the shoes of the scientist. A common misconception among science teachers is that students will be able to make sense of implicit messages received via these inquiry lab activities (Lederman, 1992; Abd-El-Khalick & Lederman, 2000; Moss et al., 2001; Khishfe & Abd-El-Khalick, 2002). Research shows that NOS instruction is most effective when it features an explicit and reflective character (Adb-El-Khalik et al., 1998; Abd-El-Khalik & Lederman, 2000). Explicit teaching requires forethought and planning to draw students’ attention to important NOS issues. Like all other learning, students interpret experiences based on the prior framework of knowledge; in this case, one that is filled with many inaccuracies. Without rewriting their NOS conceptions to align with accepted understandings, students will continue to ignore accurate NOS messages. To be
reflective, the teacher needs to make pedagogical decisions to help students make connections between the class experiences and the NOS issues. By helping students see these connections, accurate NOS ideas begin to be established. Teachers must deliberately focus students’ attention on NOS ideas for them to understand what is meant by NOS, let alone begin to make sense of its conceptions. Khishfe and Adb-El-Khalik (2002) articulate that by raising questions and creating situations, students are forced to consider the NOS in labs, readings, and other science experiences.

Even with explicit and reflective settings, students will hold onto deeply held NOS misconceptions. As Clough (2006) notes, years of science schooling and out of school science experiences (both implicit and explicit) that are usually inaccurate and simplistic, create a deeply held framework of misconceptions. This expansive framework acts to block out accurate NOS messages in authentic inquiry activities. Therefore, teachers must work towards creating an experience that causes the student to become dissatisfied with their NOS conceptions through a conceptual change model.

Appleton’s (1997) model of conceptual change discusses three potential pathways students can take when confronted with a scenario that challenges their understanding of phenomena. The first pathway is a when a student thinks they understand the conception and disengages with the lesson – prematurely exiting from the encounter. This is when a student decides the new idea fits perfectly with an existing idea, even though it does not fit (Clough, 2006). Therefore, this pathway does not lead to conceptual change and may strengthen the previous misconceptions or cause the student to dismiss the new information altogether. The second pathway holds that the student finds an approximate fit with the encounter where they decide to accept the fit (and exit prematurely), or work to accumulate more knowledge to make
sense out of why it doesn’t totally fit. The third and most desirable pathway finds the student acknowledging an incomplete fit, which leads to a search for additional information to resolve the incongruence. Science instructors need to expose students to scenarios that force them to the third pathway and help those who get stuck in either of the other available pathways.

Because students hold onto misconceptions of the NOS so strongly, again because of years of experience, teachers need to create conceptual change scenarios to force the students to abandon their conceptions for ones that are more accurate. For this to be successful, teachers need to understand potential pathways that students may take when interpreting a created situation. Creating the context is difficult but planning explicit lessons to confront students’ NOS notions that involve questioning, drawing students’ attention to features of the encounter they may have missed, and using students’ ideas in discussion are important in persuading students to reexamine their ideas (Clough, 2006). The use of explicit and reflective pedagogical decisions therefore becomes a crucial component of designing an effective conceptual change event.

To create scenarios that are explicit and reflective and create conceptual change, activities that address the NOS need to be explored. These activities live on a continuum that ranges from decontextualized to highly contextualized settings. To begin to unpack the NOS, students must have a base of knowledge to build upon. Clough (2006) acknowledges the use of black boxes, puzzle solving activities, and discrepant events, when used in the absence of science content, create decontextualized NOS instruction. Decontextualized activities directly illustrate important ideas about the NOS in an explicit and reflective manner; this creates a base of knowledge that will be used to introduce complex NOS issues that students will later explore in contextualized settings. Many of these types of activities can be used in accord to create conceptual change scenarios (Pintrich et al., 1993). Once students are exposed to NOS ideas and
have a fundamental understanding of the premise, they can be exposed to more highly contextualized settings.

Moderately contextualized settings appear as lab activities where the students are acting like scientists. By having students reflect upon the process of science within their own lab experiences, instructors hope that students will begin to see NOS in their science practice. Clough and Olson (2001) note that these settings can create a dual mindset of NOS conceptions; one that depicts school science and the other depicts how real science works. They add that learners have the ability to hold onto two incongruent perspectives without conflict, as noted in the research of Resnick (1987), Galili and Bar (1992), Mortimer (1995) and Tyson et al. (1997). It is important to note that students may view these activities as being not how real science works, keeping their misconceptions alive and well. Teachers do resist using decontextualized activities because they appear as an add-on that takes time away from content instruction (Abd-El-Khalick et al., 1998; Lakin & Wellington, 1994; Clough & Olson, 2001). Students can also dismiss these activities as not being like real science. These activities have importance though as they play a small role in getting students to reexamine their conceptions (Clough, 2006) and continue to build students NOS ideas.

The far end of the continuum holds explicit and reflective settings known as highly contextualized NOS activities. In this instruction, students are exposed to real science via scientists or historical and contemporary examples of science practice. Here, science content and NOS ideas are tightly connected, forcing students attention to important NOS issues that are “entangled in science content and its development” (Clough, 2006). By teaching in these settings, learning of content and NOS appear seamless, reducing the dual mindset of school science versus authentic science. Clough (2006) argues that highly contextualizing the NOS
requires integrating historical and contemporary science examples that connect fundamental ideas to commonly taught subject matter. The use of the continuum, from decontextualized to highly contextualized, and back and forth, is crucial to building accurate NOS conceptions in students. Teachers must explicitly plan for activities that build towards the use of highly contextualized instruction.

Through the use of historical short stories, a supplement to draw students’ attention to scientists’ authentic practice, students can gain a strong understanding of the NOS in a highly contextualized setting. An adequate understanding of the NOS, therefore, is central to increased scientific literacy (Klopfer, 1969; NSTA, 1982). By viewing the history of scientific advancements, many NOS questions can be unraveled and investigated. Matthews (1994) provides the following list as reasons for including a historical component when teaching science:

1. History promotes the better comprehension of scientific concepts and methods
2. Historical approaches connect the development of individual thinking with the development of scientific ideas
3. History of science is intrinsically worthwhile. Important episodes in the history of science and culture-the scientific revolution, Darwinism, the discovery of penicillin and so on—should be familiar to all students
4. History is necessary to understanding the nature of science
5. History counteracts the scientism and dogmatism that are commonly found in science texts and classes
6. History, by examining the life and times of individual scientists, humanizes the subject matter of science, making it less abstract and more engaging for students.
7. History allows connections to be made within topics and disciplines of science, as well as with other academic disciplines; history displays the integrative and interdependent nature of human achievements.

Through a historical approach, students are exposed to the development of ideas, the pitfalls scientists worked through, and how society influenced and was impacted by the scientific ideas. These examples within the history of science are evidence that the NOS should be included in a descriptive approach – that attends to what science is really like, instead of a normative approach
– what science should be like. A study done by Clough, Herman, and Smith (2010) found that post-secondary students’ interest in science and science careers increased after reading several historical short stories addressing how scientific knowledge was developed and came to be accepted. These stories can be used in highly contextualized settings to push students to explicitly and reflectively make sense of NOS conceptions.

**Current State of NOS Instruction**

Current research findings indicate that a minimal amount of accurate and effective NOS teaching and learning is taking place. Clough and Olson (2012) found that even with a wide variety of efforts aimed at encouraging teachers to devote explicit attention to the NOS, the efforts have had little effect. This sentiment may derive from teachers being unconvinced of the importance in emphasizing the NOS as a cognitive objective and not wanting to give up instructional time for “add-on” materials that distract from the content (Abd-El-Khalik, Bell, Lederman, 1998; Lederman, 1998). Teachers are not the only issue though in keeping NOS out of classroom instruction. Lakin and Wellington (1994) found that NOS instruction appears to be contrary to “expectations held of science and science teaching in schools, not only by teachers and pupils but also those perceived as being held by parents and society.” Because all of these stakeholders have “experienced” school science devoid of explicit NOS instruction, it is deemed as unnecessary and time wasting. Because many teachers did not experience accurate and explicit NOS instruction as students, and were not exposed to research findings on the NOS, many teachers do not consider it as an important component of science education (Abd-El-Khalick et al., 1998; King, 1991). If this trend continues, the vicious cycle described above will continue its course churning out more science illiterate citizens.
Due to legislation over the past ten years (e.g., No Child Left Behind Act, 2001), NOS instruction has continued to be an afterthought in science education. No Child Left Behind (NCLB) forced many teachers to adapt a “teaching to the test” agenda, therefore reducing time for NOS. David Labaree (1997) speculated that an overreliance on testing causes students only to care about what will be on the test, and NCLB seems to have transferred this mantra from students to teachers with the attitude: “Whatever is not on the test is not worth knowing, and whatever is on the test need be learned only in the superficial manner that is required to achieve a passing grade” (p. 46). Due to NCLB, teachers have felt great pressure to focus their energies towards solely preparing students to perform well on standardized tests.

Just recently, science education reform in the U.S. took another potentially backwards step in regards to the NOS, by creating the Next Generation Science Standards (NGSS), which have been adopted by 12 states as of August 2014 (Heiten, 2014). The NGSS approaches the issues of explaining both the natural world and what constitutes the formation of “adequate, evidence-based scientific explanations” by engaging students in scientific and engineering practices (NRC, 2013, Appendix H). The NGSS developers believe that students will implicitly learn about the formation of explanations (NOS) by engaging in activities the way a scientist or engineer would. The NGSS also created a NOS matrix with the basic understandings about the NOS:

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

The matrix creates a list of tenets for students and teachers to memorize, not a list of questions for students to ponder while making sense of NOS in highly contextualized settings. The idea is that the eight understandings of the NOS and the intersection of the understandings with science and engineering practices, disciplinary core ideas, and crosscutting concepts will form students’ accurate NOS conceptions (NRC, 2013, Appendix H). The NGSS also places the NOS in the context of science practices, which is problematic as students are taught what scientists do, but not why they do it. As Matthews (1994, p. 37) asserted,

“All science curricula contain views about the nature of science: images of science that influence what is included in the curriculum, how material is taught and how curriculum is assessed. The image of science held by curriculum framers sets the tone of the curriculum, and the image of science held by teachers’ influences how the curriculum is taught and assessed. When spelled out, these images of science become statements about the nature of science, or about the epistemology of science.”

The NGSS will create a vision of science and scientists for students. Unfortunately the lack of explicit NOS content in the standards will continue to drive the vicious cycle that already exists.

**Reason for this Study**

As the literature review alludes, teachers do not accurately teach the NOS for multiple reasons. However, teaching accurate conceptions of NOS is found in nearly all current science education reforms and holds significant importance in the school science experience. It is known that teachers do not teach the NOS because there are not materials available for them to use, and many lack an understanding of what is meant by the NOS. Teachers also do not think that enough time exists in the school year to cover the NOS as well as science content. If teachers
had a way to cover the NOS while teaching content with materials that were highly contextualized, students would be able to begin to deconstruct their inaccurate conceptions of NOS and replace them with accurate ones. As Matthews (1994) puts it, “meaningful discussions of these questions (what is the nature of science?) requires sophisticated thinking, and a good stock of basic information about particular parts of the history of science and philosophy of science” (p. 48). The creation of thirty historical short stories that feature embedded NOS statements and NOS questions wrap NOS in a highly contextualized way. These stories can be used to overtly draw students’ attention to NOS concepts while teaching science content, therefore not using up additional time that many teachers feel is nonexistent. By using the history of science – the stories themselves, and the philosophy of science – the embedded questions and text, students can take part in meaningful discussions that form an accurate view of the NOS. The history of science articles can be used to support secondary teachers in accurately and explicitly teaching the NOS.
CHAPTER 3. RESEARCH METHODOLOGY

Study Purpose

This study set forth to determine the impact of historical short stories on high school students’ NOS conceptions and to identify their attitudes towards reading such stories. The following research questions were investigated:

1. Does the use of historical science stories with explicit NOS statements and questions improve secondary science students’: (a) accurate understanding of fundamental NOS concepts made explicit in the story and (b) recollection of historical examples that logically support their NOS thinking?

2. What are secondary science students’ attitudes toward: (a) reading the short stories compared to a traditional textbook reading, and (b) reading about scientists and how science ideas are developed?

Study Context

The study reported occurred in three sections of General Chemistry and three sections of Chemistry taught at a suburban high school located in the Midwestern United States. These students were a subset of a larger study conducted by Reid-Smith (2013). The student population at this high school is 91% Caucasian with 23% of students receiving free or reduced lunch. The school operates on an eight-period schedule with classes meeting for 45-minute periods. The school offers three levels of chemistry: General Chemistry, Chemistry, and Advanced Placement (AP) Chemistry to its students.
General Chemistry is a lower level course designed for junior and senior students who struggle with math and are unlikely to pursue a traditional four-year post-secondary college option. The course covers the fundamental aspects of chemistry at a slower pace with less emphasis on mathematical modeling. Most students who register for General Chemistry do not have the academic standing of those who register for Chemistry. Chemistry is a more advanced course taken primarily by freshman and sophomores (also available to juniors and seniors) interested in taking more advanced science coursework and pursuing traditional post-secondary schooling. For this reason, many students will take this course early in their freshman year to open up their schedule for more advanced courses in their later years. While the Chemistry and General Chemistry courses are not required for high school graduation, all students must complete three years of science credit. Thus, most students at this school register for one of the two chemistry courses.

Thirteen sections of Chemistry and three sections of General Chemistry were offered at the time of the study. The researcher taught the three sections of Chemistry and three sections of General Chemistry in which the study took place. The students in the researcher’s sections were introduced to the study at the beginning of the second semester. The informed consent form appearing in Appendix A was provided to the students. The study and its intent were described, and students were informed that participation was entirely voluntary with no impact on their grade whether or not they participated. Students and parents were provided with contact information for all researchers involved in the study and encouraged to ask questions about the study or participation in it. Students were provided two weeks to return the consent form. To be included in the study, both student and parent/guardian signatures were required.
Of the 48 students enrolled in the three sections of General Chemistry, 37 agreed to take part in the study. Of the 59 students enrolled in the three sections of Chemistry, 47 agreed to be part of the study. The total sample size was 84 out of 107 possible students.

At the time of the study, the researcher teaching the two courses was completing his fifth year as a high school science teacher. The teacher possessed a B.S. in biology with a minor in educational computing and held state endorsements to teach chemistry, biology and general science. The teacher/researcher has previously taught high school biology, environmental biology, chemistry, general chemistry and anatomy courses. At the time of the study he had completed most all coursework for an M.S. degree in education that included a nature of science and science education course, application of learning theories specific to science education, advanced science pedagogy, and natural and physical science courses. The researcher is passionate about increasing students’ knowledge of the history of science, the nature of science and student interest in science and science careers.

Study Methodology

This study employed a mixed methods research approach utilizing randomized control group pretest-posttest design (Isaac & Michael, 1971) to answer the research questions. A mixed methods approach was chosen as both qualitative and quantitative data collection were deemed most beneficial to answering each research question. The randomized control group design selected class periods at random for treatment and control groups. To do so, a coin was flipped and two sections of each class were selected as the treatment group. The treatment groups for General Chemistry consisted of 24 participants divided into two classes and 13 participants in the Control group (one class). The treatment groups for Chemistry included 29 participants divided
into two classes and 18 participants in the control group (one class). Both treatment and control groups were pretested at the start of the second semester and post-tested at the end of the semester. Conditions were, to the extent possible, kept the same with the exception for exposing the treatment group to historical short stories with explicit attention given to NOS concepts. Data was collected with surveys featuring Likert sub-item options, both open-ended questions and restricted categorical responses and semi-structured interviews.

To determine participants’ NOS conceptions as well as their use of historical examples in defense of those conceptions, the *Views on Science and Scientific Inquiry* Questionnaires (VOSSI – in Appendix B), (described later in this chapter) was given as a pre-posttest. Participants from the treatment groups were randomly selected and twenty-six were interviewed after completing the posttest. The semi-structured interviews were conducted to verify participants’ conceptions with those indicated on the Likert sub-items and in the written response and employ a deeper investigation into participants’ NOS conceptions.

To answer the second research question, a second survey, the *Interest/Attitude Survey* (Appendix C) was given pre-posttest to both treatment and control groups for General Chemistry and Chemistry participants. This survey featured categorical responses, Likert sub-item answers, and open-ended questions referring to the participants’ interest in attitudes towards the story delivery method and content. Interviews were also conducted to verify participants’ survey responses and allow for a deeper analysis of participant conceptions.

**Treatment vs Control Groups**

The Chemistry treatment and control groups were taught following the same curriculum and content for the given units of study, as were the General Chemistry treatment and control
groups. The Chemistry course curriculum consisted of periodicity, bonding, chemical reactions, and stoichiometry while the General Chemistry curriculum consisted of chemical reactions, gas laws, and food chemistry. The same teacher taught all Chemistry and General Chemistry treatment and control classes and, to the extent possible, kept factors related to each course the same.

The Chemistry and General Chemistry treatment group students received historical science stories that overtly drew their attention to NOS ideas that would otherwise be implicit in the stories. These stories were chosen as they aligned with science content dictated by the curriculum. The NOS ideas addressed by the treatment stories in both Chemistry and General Chemistry treatment groups included: social and cultural issues on science, imagination and creativity in science, social interaction among scientific researchers, development and acceptance of science ideas, establishment of scientific knowledge, and scientific laws compared to theories. The treatment stories included text boxes that highlighted NOS concepts along with embedded questions that forced students to think deeply about NOS ideas. NOS instruction in the treatment sections was limited to discussion of the readings and the embedded questions.

Control group students received instruction aligned with science content as dictated by the curriculum. In the place of the treatment stories, control groups read other types of science stories or watched videos that displayed content similar to the stories read in the treatment group. These control group experiences were devoid of textboxes and embedded questions that would overtly draw students’ attention to NOS ideas.

The treatment stories originated from a prior NSF project directed at the post-secondary introductory science level (Clough, 2006). These stories, which are freely available at www.storybehindthescience.org, were modified for use at the secondary school level by Reid-
Smith (2013). The modifications included: shortening the textual length of the story, reducing the complexity of vocabulary in the stories, embedding more NOS and content specific questions throughout the stories, and the insertion of visual aids, including photographs of scientists involved in the development of science ideas, photographs and diagrams of equipment used by scientists in the stories, and drawings and diagrams to help students understand the abstract ideas described in the stories. The additional NOS and content questions helped to divide up the text, keeping students engaged while reading, and help them identify key NOS and content ideas within the story.

Chemistry Treatment and Control

In the Chemistry treatment group, three stories were implemented: A Puzzle with Many Pieces: Development of the Periodic Table, Conservation of Mass: The interplay of creativity and collaboration between scientific laws and theories, and the Building Ideas: The Origin of Modern Atomic Theory (see Appendices D-F). Table 1 notes the NOS ideas overtly addressed in each story.

The control group for Chemistry completed three different readings that covered the same information: periodic table, conservation of mass, and a shortened summary of atomic history (see Appendices I-K). The control materials were chosen for similar content to minimize differences between control and treatment groups and came from various high school level chemistry texts and were part of the prior school year curricular materials.
General Chemistry Treatment and Control

General Chemistry units of study during this semester consisted of chemical reactions, gas laws, and food chemistry. The historical science stories used in the General Chemistry treatment group included Conservation of Mass: The interplay of creativity and collaboration between scientific laws and theories, Early Developments in the History of Thermometry and A Matter of Degrees: the Early History of Heat (see Appendices E, G-H). Table 2 notes the NOS ideas overtly addressed in each story.

Table 1. Chemistry Treatment Group Stories and NOS Ideas Overtly Addressed

<table>
<thead>
<tr>
<th>Stories</th>
<th>NOS ideas overtly addressed</th>
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| Development of the Periodic Table | • Imagination and creativity in science  
|                                  | • Social interaction among researchers  
|                                  | • Development and acceptance of science ideas  
|                                  | • Establishment of scientific knowledge  
|                                  | • Scientific laws compared to theories                                                    |
| Conservation of Mass             | • Imagination and creativity in science  
|                                  | • Social interaction among researchers  
|                                  | • Development and acceptance of science ideas  
|                                  | • Establishment of scientific knowledge  
|                                  | • Social and cultural influences on science  
|                                  | • Scientific laws compared to theories                                                    |
| Development of the Atomic Model  | • Imagination and creativity in science  
|                                  | • Social interaction among researchers  
|                                  | • Development and acceptance of science ideas  
|                                  | • Establishment of scientific knowledge  
|                                  | • Social and cultural influences on science  

Table 2. General Chemistry Treatment Group Stories and NOS Ideas Overtly Addressed

<table>
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<tr>
<th>Stories</th>
<th>NOS ideas overtly addressed</th>
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<tbody>
<tr>
<td>Conservation of Mass</td>
<td>• Imagination and creativity in science</td>
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<td></td>
<td>• Social interaction among researchers</td>
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<td>• Scientific laws compared to theories</td>
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<td>Developments in Thermometry</td>
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<td>• Establishment of scientific knowledge</td>
</tr>
<tr>
<td></td>
<td>• Social and cultural influences on science</td>
</tr>
<tr>
<td>Early History of Heat</td>
<td>• Imagination and creativity in science</td>
</tr>
<tr>
<td></td>
<td>• Social interaction among researchers</td>
</tr>
<tr>
<td></td>
<td>• Development and acceptance of science ideas</td>
</tr>
<tr>
<td></td>
<td>• Establishment of scientific knowledge</td>
</tr>
<tr>
<td></td>
<td>• Social and cultural influences on science</td>
</tr>
<tr>
<td></td>
<td>• Scientific laws compared to theories</td>
</tr>
</tbody>
</table>

The control group for General Chemistry completed one reading covering the periodic table (same as Chemistry - Appendix I) and a PBS program, NOVA: Absolute Zero, addressing the development of thermometry and the development and acceptance of the theory of heat. These materials were used to minimize differences between control and treatment groups and came from a high school level chemistry text and the PBS website.

Pedagogical Implementation Practices

In both the Chemistry and General Chemistry sections in which this study took place, the instructor created a classroom culture that promoted discussion without fear of judgment or ridicule from students or teacher. By structuring frequent small group discussions, group
problem solving and whole class discussions throughout first semester, students were taught how to value others’ opinions, allow all ideas to be heard, and proper argumentation when they disagreed with other students’ ideas. The teacher modeled appropriate behaviors with wait time, scaffolding of participant questions to desired outcomes, and accepting all participant ideas in the context given by the participant. This encouraged students to participate and feel comfortable sharing their ideas in small groups and with the entire class during the research semester. Both participant course evaluations and an external observer (Smith, 2013) characterized the instructor as having a positive and friendly attitude with students and promoting active participation and engagement.

Chemistry

The stories were implemented near the start of each unit as an introduction and to raise questions. With the exception of the Conservation of Mass story (read in class when the instructor was absent), instruction for each story in the Chemistry class involved having students, as homework, read and answer the embedded questions over a two day span. Subsequently, two 45 minute class periods were devoted to discussing the assigned story and embedded questions. Students were asked to discuss their answers to the embedded questions that were assigned as homework and come to a consensus answer with their partner(s) (1-2 additional students). This process usually lasted 10-15 minutes, and the instructor walked throughout the classroom to probe each group and ask questions to determine understanding or help guide struggling students. The remaining class time focused on whole class discussion of the content and embedded questions. To encourage student engagement, the instructor gave participation points for answering questions from the teacher, asking questions of peers, or making relevant
comments or questions to be used in the discussion. Throughout the discussion, the instructor asked probing, elaboration, and clarification questions to assist students in deeply reflecting on the NOS ideas in the stories. Students were required to participate at least three times during the discussions. Most students took advantage of these points, with a select few opting to turn in their questions to be graded after the discussion (this method was used to grade students who missed the in class discussion or did not gain all of their points).

The Chemistry control group read text related to the science content, with two readings that gave some historical information of the material, but mainly focused on content. However, none of the readings overtly drew students’ attention to the nature of science. The history of the periodic table reading, from Modern Chemistry (Davis et al., 2002) textbook (Appendix I), rather than the Mendeleev historical short story, was read prior to a Mendeleev card sorting activity, the same activity used in the treatment group. Students’ read the reading in class and answered questions based on the organization of the periodic table. The development of the atomic model historical short story was utilized by the treatment group at the end of the school year to review for the final exam. In place of that historical short story, the control group read excerpts from Chemistry (Wilbraham, 2008) textbook (Appendix K), covering the different atomic models through time.

While that reading did not feature embedded NOS questions, the instructor did ask students questions aimed at the models and the scientists responsible for their creation. This discussion closely resembled the content covered in the treatment group, which focused on who the scientists were, their contribution to the model of the atom, but stopped short of discussing the relevant NOS concepts presented. The periodic table and atomic model readings slightly convey that science is a creative endeavor (use of the word create/created), the time required for
development and acceptance of science ideas (a timeline of atomic models), and the atomic model also conveys the tentativeness of established scientific knowledge (the timeline of models), but the instructor did not ask questions related to these NOS concepts. The readings also reinforced, again implicitly, several common NOS misconceptions. The textbook readings are shortened and leave out much of the development of ideas, including the creativity of thinking and uncertainty and disagreements regarding the meaning of data. For example, the atomic model reading states, “The Bohr model gave results in agreement with the Hydrogen experiment” implies that data “tells” scientists the answer and removes the need for creativity in concluding what to make of data.

The final reading, *Travels with C* (Appendix J), described the journey of the element carbon through various chemicals, from the Modern Chemistry (Davis et al., 2002) textbook. It was used to help students understand how atoms are transferred in ecosystems and not created or destroyed. In both the treatment and control groups, the respective stories were followed by a building block stoichiometry lab.

**General Chemistry**

Student homework completion in General Chemistry is typically low, and students often struggle with or do not complete assigned readings, therefore stories were completed in class. Treatment stories were read in class, at times by the instructor, other times by the student (with vocabulary sheets included). In some cases where small portions of a reading could easily be digested, students were assigned those portions as homework (typically when only a small portion of the reading was left). Because the General Chemistry sections in this study are the only sections of that course offered in the school, remaining on pace with other sections was not
an issue. Thus, more time was devoted to addressing the embedded questions in the treatment stories. Either individually or in small groups, students were assigned specific questions from the readings. If completed individually, students were then assigned to work with others to create a consensus answer. Similar to the Chemistry course, students were required to engage in the discussion a minimum of three times to gain participation points in the large class discussion. Questions were asked to draw students’ attention to the NOS ideas in the stories, promote deeper reflection about their own answers, as a request for evidence to support answers, or to make connections to other experiences or content. As in the Chemistry discussions, these experiences lasted over two to three class periods.

The General Chemistry control group used the conservation of mass materials in the same manner as the Chemistry control sections. General Chemistry did not have access to textbook readings that delved into the development of thermometry and heat, causing the researcher to employ a video called “NOVA: Absolute Zero” (PBS, 2008). Within the video, similar historical content was covered over the development of thermometers and standardized scales, as well as the battle between theories of heat: caloric versus kinetic energy transfer. Students were asked questions pertaining to the science ideas while the video played and then additional questions were covered in greater detail in a discussion afterward. These questions did not focus on the NOS, rather asked the students to ponder “What might be the importance of having standardized scales of measurement for scientific work?” and “What problems might occur during scientific work if there were no standard scale of temperature?”

Because the control materials used to cover temperature and heat discuss the work of scientists through a historical lens, the NOS was implicitly addressed through a highly contextualized activity. The “Absolute Zero” video implicitly and accurately conveys the NOS
concepts of social and cultural influence on science, imagination and creativity in scientific investigations, and time for development and acceptance of science ideas.

Assessment Instruments

Two pencil and paper assessment instruments were used to collect participant data to answer the research questions. These included the *Views on Science and Scientific Inquiry* (VOSSI) questionnaire to ascertain participants’ views regarding particular NOS issues, and the *Interest/Attitude Surveys I and II* to ascertain participants’ interest and attitudes toward the treatment stories. Semi-structured interviews with an interview protocol (Appendix L) were also used with approximately 53 percent of study participants to assist in determining the validity of the VOSSI, and more deeply understanding participants’ responses on the paper and pencil assessment instruments.

**Views on Science and Scientific Inquiry Questionnaires**

The VOSSI questionnaire was used to measure participant understanding of NOS constructs covered in the readings utilized in both Chemistry and General Chemistry classes. The VOSSI is based on the structure of the *Student Understanding of Science and Scientific Inquiry* (SUSSI) questionnaire (Liang et al., 2006; 2008). The SUSSI questionnaire assesses student understanding of six NOS constructs with four Likert sub-items followed by an open-response question (See figure 1). The combination of Likert sub-items with an open-response question provides a valuable tool for assessing understanding of NOS constructs both qualitatively and quantitatively. Qualitative responses can be used to verify validity of the quantitative Likert sub-items and afford richer information about students’ thinking regarding each NOS construct.
(Liang et al., 2008), and they also may be used to determine the extent that students draw from the treatment stories as evidence for their post-treatment views. The VOSSI utilizes items assessing understanding of six NOS constructs from the original SUSSI questionnaire, on which previous validity and reliability testing has been conducted. An additional six items were developed by a group of four science education researchers, utilizing the same structure as SUSSI items, to assess NOS constructs not assessed by the SUSSI items (Clough, Herman, & Smith, 2010; Herman, Clough, & Olson, 2011). The full VOSSI instrument used in this study appears in Appendix B.

An initial analysis of internal reliability was calculated using Cronbach's Alpha values. Cronbach's Alphas were used to determine the internal consistency between the Likert-item responses that comprised each NOS construct on the pre-VOSSI and post-VOSSI instruments. Cronbach's alphas ranged from 0.366 to 0.875 for the VOSSI instrument. Ideally Cronbach’s alpha values should be above .70 to identify confidence that the items in a scale are measuring the same underlying construct and can be combined into a single scale (Pearson, 2010). Cronbach’s alpha values are sensitive to the number of items in a scale; scales that feature less than ten items frequently produce Cronbach alpha’s below 0.70 (Pearson, 2010). Because the VOSSI constructs consisted of less than ten scale items and had been previously field tested, the instrument was deemed reliable.
At the beginning of the spring semester in January, prior to the start of the study, all students’ understanding of the NOS was assessed using the VOSSI. In late May, following the last science unit of the semester, the VOSSI was again administered. Approximately sixteen weeks separated the pre and post VOSSI assessment. A total of six constructs were included on the VOSSI assessment which came from the twelve created by Liang (2008), Clough, Herman, & Smith (2010) and Herman, Clough, & Olson (2011).

**Table 3.** NOS constructs used in student VOSSI surveys

<table>
<thead>
<tr>
<th>Social and Cultural Influences on Science</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Imagination and Creativity in Science</td>
<td></td>
</tr>
<tr>
<td>Social Interaction among Scientific Researchers</td>
<td></td>
</tr>
<tr>
<td>Time for Development and Acceptance of Science Ideas</td>
<td></td>
</tr>
<tr>
<td>Tentativeness of Scientific Knowledge</td>
<td></td>
</tr>
<tr>
<td>Scientific Laws Compared to Theories</td>
<td></td>
</tr>
</tbody>
</table>

An effort was made to ensure that selected VOSSI items were aligned with NOS ideas targeted in the treatment stories. For example, both the Chemistry and General Chemistry treatment groups used the story *Conservation of Mass: The interplay of creativity and*
collaboration between scientific laws and theories. This story included text boxes stating “Note how the prevailing idea influences how experimenters interpret their work.” This text box draws students’ attention to chemist Joseph Black using the accepted Aristotelian idea that matter could not be created nor destroyed in guiding his work. Later in the story a question box appears asking the student to identify “How does this example illustrate that scientists are influenced by the predominant ideas of the culture in which they live?” Students are asked to draw from the story referring to Black, as well as other scientists Priestly and Stahl and link their work to cultural influences as described in the story. These types of text boxes and questions were included to overtly draw students’ attention to, and reflect on, the NOS ideas that society and culture do affect how science is conducted and accepted (VOSSI item 1C), and scientists use knowledge created by other scientists to guide their work (VOSSI item 3A).

Each VOSSI item also included a writing prompt immediately below the four Likert sub-items. The writing prompt was included to determine the credibility of responses to the four Likert sub-items, provide a means to investigate the students’ depth of understanding of each construct, and determine whether students in their post-assessment would reference the stories in what they wrote.

**Interest and Attitude Surveys**

The Interest and Attitude surveys employed were the same used by Smith (2010) in a similar study. Smith found that student comments during her study raised the issue whether students’ interest in the stories was related to their attitudes towards reading in general, conceptions of effective science learning and attribution of academic success.
All students completed the *Interest and Attitude Survey 1* (Appendix C) prior to implementing the stories. The *Interest and Attitude Survey 1* includes three multi-item indices of Likert sub-items to measure students’ attitudes towards readings, conceptions of an effective science learning environment, and attributions of academic successes and failures. The survey consists of three sections of Likert scale questions: a set of 7-items to assess students’ attitude towards readings, a set of 10-items to assess students’ perceptions of an effective learning environment and the alignment of their views with reform-based teaching practices, and a set of 8-items to assess whether students attribute their academic success to factors within their control (e.g., effort) or factors outside their control (e.g., luck, fixed intelligence, teachers). Initially, the researcher thought this data would be useful however it was later deemed unnecessary for this particular study. Students’ responses to the questions on *Interest and Attitude Survey 1* were not used by the researcher to answer the given questions in the study.

At the end of the study, all students completed *Interest and Attitude Survey 2*. This survey was utilized to understand students’ attitudes toward and interest in the stories and to determine other factors that may have correlated with students’ interest in the stories. Students in the treatment groups took *Chemistry Interest and Attitude Survey 2* (Appendix C), while students in the control groups completed *Interest and Attitude Survey 2 – Post Control* (Appendix C). The *Chemistry Interest and Attitude Survey 2* included three multi-item indices measuring students’ reading attitude, perception of an effective science learning environment, and attributions of academic success. Additional Likert questions were included to assess students’ interest in the stories, interest in the stories compare to typical science class readings, preference for similar stories to replace typical class readings, perceived importance of understanding the NOS for high school science education, and perception of how the stories promoted understanding the NOS.
The control groups completed *Interest and Attitude Survey 2 – Post Control* which was identical to the *Chemistry Interest and Attitude Survey 2*, but lacked additional questions regarding what students liked and disliked about the stories.

**Semi-structured Interviews**

After data were collected from the aforementioned instruments, semi-structured interviews were conducted with a randomly selected sample of participant volunteers. Thirty-two participants interested in completing interviews submitted their names, and because time did not permit all to be interviewed, twenty-six were randomly selected to take part in an interview. Interviews were conducted over a span of three weeks, with each interview lasting approximately ten minutes in length. Eight volunteered from the General Chemistry group, the remaining eighteen from Chemistry. To determine the credibility of participants’ Likert-item responses, each participant’s written response was analyzed for congruency with their Likert responses. Each Likert response was cross-checked with the written response for congruent NOS conception. The interviews further assisted the research by providing a means to investigate the participants’ depth of understanding of each NOS construct, whether participants would make reference to the stories, and was also used to gain further insight into participants’ responses to the *Interest and Attitudes Survey II* questions. The interview afforded the researcher a deeper understanding of what the participants wrote in survey responses by asking for an explanation of their answers. The interview questions can be found in Appendix L.
Data Analysis

Research Question 1

Following the implementation of the historical short story treatment, control treatment groups VOSSI responses underwent statistical analysis to determine if significant differences existed between overall NOS understanding between the two groups. Participant responses to the six NOS construct Likert sub-items on the pre and post VOSSI were given numerical values, with a score of five representing the most informed view of NOS and one to represent the least informed view. Each NOS construct contained four questions that participants answered on the 1-5 Likert scale. The Likert scores were then added up (after reverse coding for negatively worded statements) to create a score ranging from four to twenty on each of the six NOS constructs. The higher the score, the more informed view the participant had regarding the given NOS construct.

To address the first research question, participants’ pre and post data was entered into SPSS version 20. Multiple Analysis of Covariance (MANCOVA) tests for each control treatment group were performed on both General Chemistry and Chemistry groups. This statistical analysis compared treatment and control participants’ overall NOS understanding as measured on the VOSSI post assessments. VOSSI pre-assessment scores were included as a covariate to account for any pre-existing differences between control and treatment group participants. Analysis of Covariance (ANCOVA) was completed to determine the significance of differences between Control and Treatment participants’ performance on individual NOS components (Tabachnick & Fidell, 2013).
Research Question 2

The interest and attitude survey results were used to answer the second research question. SPSS was used to calculate descriptive and frequency statistics for Interest and Attitude Survey 2 to determine correlation between participants’ interest in the stories, preference for the stories versus typical class readings, preference for similar stories to replace typical class readings, perceived importance of NOS goal for HS science education, and perception of how the stories promoted the NOS goal. Remaining data from the survey was omitted from this study. Interview data was used to then analyze the responses given on the Interest and Attitudes Survey II. Coding practices used by Reid-Smith (2013) were adopted as participants in this study were a subset of Reid-Smith’s larger study. Reid-Smith utilized Dedoose (2012) web application for analyzing qualitative and mixed methods data to code open response items regarding participants’ likes and dislikes in reference to the historical short stories. Common themes were then created from participants responses through reiterative rounds of open/initial and focus coding (Charmaz, 2006; Saldana, 2009). Codes generated by Reid-Smith (2013) were used to analyze participant responses to generate focused categories specific to this study responses.

Assumptions and Limitations

Several assumptions and limitations exist in this study. First, outside the treatment variable, the treatment and control groups are presumed to be, for all practical purposes, equivalent. As noted earlier, effort was made to approach this conjecture, but it cannot be assured. Each class was randomly assigned as either control or treatment; however the distribution of special education and gifted students in each class, as well as students retaking the
course was random as well. Students are placed into classes by a computer program that sorts students based on their course selection and available time slots for each course. Therefore students’ pre-VOSSI scores may vary widely and to address this concern, MANCOVA analyses used pre-implementation scores as a covariate.

Second, the school’s mostly homogenous population may limit the applicability of the study’s results to more diverse settings. Schools around the United States may not have such low diversity; therefore the study may not be applicable. Third, the study also focused on just one science discipline which may limit its application to other science courses.

Third, the researcher/instructor had previously taken a course addressing the nature of science and its implications for science education. Backhus & Thompson (2006) report that, based on the results of their survey, “at most perhaps 6% of pre-service teachers will have taken such a [NOS] course as a requirement” (p. 74). Thus, the instructor of this course can hardly be said to be typical of science teachers nationwide.

Fourth, the instructor is presumed to have not unintentionally drawn control group students’ attention to NOS ideas. Because the instructor previously completed a Nature of Science and Science Education course and typically does make effort to draw students’ attention to and reflect on NOS ideas, he may have inadvertently done so in the control groups. The day-to-day instruction was not video or audio recorded, and thus this issue cannot be ruled out.

Finally, during the fall semester immediately preceding the study, the instructor did overtly teach the NOS. Students were exposed to both contextualized and decontextualized NOS activities throughout the first semester. Because the study took place in the second semester, NOS understanding developed in first semester could have influenced students in both the
treatment and control groups, and thus diminishes the impact of the treatment stories and/or create a ceiling effect in regards to students’ pre VOSSI results.
CHAPTER 4. RESULTS

Introduction

The purpose of this study was to determine the impact of historical science stories containing overt NOS prompts on high school students’ NOS understanding and attitudes toward the stories. This chapter presents the results for the two research questions set forth in this study:

1) Does the use of historical science stories with explicit NOS statements and questions improve secondary science students’ (a) accurate understanding of fundamental NOS concepts made explicit in the story and (b) recollection of historical examples that logically support their NOS thinking?

2) What secondary science students’ attitudes are toward: (a) reading the short stories compared to a traditional textbook reading and (b) reading about scientists and how science ideas are developed?

Reliability of the VOSSI Instrument

An initial analysis of internal reliability was calculated to determine consistency between Likert-items that comprised each NOS construct on the pre-VOSSI and post-VOSSI instruments. All VOSSI items are internally consistent with the exception of Law/Theory. Table 4 shows the internal consistency for each independent NOS construct.

<table>
<thead>
<tr>
<th>VOSSI Item</th>
<th>N</th>
<th>Cronbach’s α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social and Cultural Influences on Science</td>
<td>79</td>
<td>.720</td>
</tr>
<tr>
<td>Imagination and Creativity</td>
<td>80</td>
<td>.871</td>
</tr>
<tr>
<td>Social Interactions Among Scientists</td>
<td>80</td>
<td>.734</td>
</tr>
<tr>
<td>Time to Develop and Accept Ideas</td>
<td>80</td>
<td>.875</td>
</tr>
<tr>
<td>Tentativeness of Scientific Knowledge</td>
<td>79</td>
<td>.607</td>
</tr>
<tr>
<td>Scientific Law and Theory</td>
<td>79</td>
<td>.366</td>
</tr>
</tbody>
</table>

Research Question 1a

Before performing statistical analysis on control treatment survey results, the validity of study participants’ Likert responses were assessed by comparing a sample of participants’
written responses and interview responses to their Likert responses. Of the twenty-six participants whose Likert responses were compared with their written responses, the congruency is as follows: social/cultural influence – 92 percent, imagination/creativity – 96 percent, social interaction – 100 percent, time – 100 percent, tentativeness – 96 percent and law/theory – 96 percent. Thus, study participants’ Likert responses were deemed as a valid indication of their NOS views. Congruency of VOSSI items can be found in table 5.

Table 5. Congruency of written responses to NOS Likert responses

<table>
<thead>
<tr>
<th>VOSSI Item</th>
<th>Congruent</th>
<th>Not Congruent</th>
<th>Indecipherable</th>
<th>No written response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social/Cultural Influence</td>
<td>19/26 (73%)</td>
<td>2/26 (8%)</td>
<td>4/26 (15%)</td>
<td>0/26 (0%)</td>
</tr>
<tr>
<td>Imagination/Creativity</td>
<td>24/26 (92%)</td>
<td>1/26 (4%)</td>
<td>1/26 (4%)</td>
<td>0/26 (0%)</td>
</tr>
<tr>
<td>Social Interaction</td>
<td>22/26 (85%)</td>
<td>0/26 (0%)</td>
<td>4/26 (15%)</td>
<td>0/26 (0%)</td>
</tr>
<tr>
<td>Time</td>
<td>25/26 (96%)</td>
<td>0/26 (0%)</td>
<td>1/26 (4%)</td>
<td>0/26 (0%)</td>
</tr>
<tr>
<td>Tentativeness</td>
<td>21/26 (81%)</td>
<td>1/26 (4%)</td>
<td>3/26 (12%)</td>
<td>1/26 (4%)</td>
</tr>
<tr>
<td>Law/Theory</td>
<td>25/26 (96%)</td>
<td>1/26 (4%)</td>
<td>0/26 (0%)</td>
<td>0/26 (0%)</td>
</tr>
</tbody>
</table>

To address the first research question, a Multiple Analysis of Covariance (MANCOVA) test was performed to determine if significant differences existed between control and treatment participants’ overall NOS conceptions following the implementation of historical short stories. Analysis of Covariance (ANCOVA) tests were then conducted to determine the significance of differences between control and treatment groups’ performance on individual VOSSI items. Table 6 provides the pre and post means and standard deviations for the six VOSSI items for the control treatment groups for General Chemistry.
Table 6. General Chemistry VOSSI items – pre and post means and standard deviations

<table>
<thead>
<tr>
<th>NOS Component b</th>
<th>Control Pre (N=11)a</th>
<th>Control Post (N=11)a</th>
<th>Treatment Pre (N=22)a</th>
<th>Treatment Post (N=22)a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Social Cultural Influences</td>
<td>11.64</td>
<td>1.57</td>
<td>12.55</td>
<td>2.73</td>
</tr>
<tr>
<td>Imagination and Creativity</td>
<td>10.73</td>
<td>3.23</td>
<td>9.72</td>
<td>4.61</td>
</tr>
<tr>
<td>Social Interactions</td>
<td>13.64</td>
<td>1.63</td>
<td>14.00</td>
<td>1.95</td>
</tr>
<tr>
<td>Time</td>
<td>13.73</td>
<td>2.83</td>
<td>14.09</td>
<td>3.33</td>
</tr>
<tr>
<td>Tentativeness</td>
<td>14.55</td>
<td>1.86</td>
<td>14.73</td>
<td>2.05</td>
</tr>
<tr>
<td>Theory/Law</td>
<td>10.09</td>
<td>1.70</td>
<td>9.82</td>
<td>1.40</td>
</tr>
</tbody>
</table>

a. Two Treatment Participants and two Control Participants are not included due to missing data points.
b. Possible scores for each component range from a minimum of 4 to a maximum of 20.

Results of the initial MANCOVA analysis of the General Chemistry treatment group show no significant difference in regards to increased NOS understanding than the control group (F= 1.412, p= 0.239, Wilks’ Lambda = 0.541, eta squared= 0.459). Although MANCOVA results indicated no significant differences between control-treatment groups in General Chemistry, ANCOVA analysis conducted on the six VOSSI items did reveal significance on one NOS construct. The univariate analysis of participants’ VOSSI scores as separate dependent variables showed a significant difference in understanding for one component: Imagination and Creativity (F=7.599, p=0.010, partial eta squared 0.197). The remaining five components: Social/Cultural Influence (F=3.724, p=0.63, partial eta .107), Social Interactions (F=0.129, p=0.722, partial eta squared 0.089), Time (F=1.336, p=.257, partial eta squared 0.041), Tentativeness (F=0.617, p=0.438, partial eta squared 0.020) and Law/Theory (F=3.427, p=0.074, partial eta squared 0.100) indicate no significant differences between groups. ANCOVA analyses can be found in Table 7.
Table 7. Univariate analyses of VOSSI items for General Chemistry

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>F</th>
<th>Sig</th>
<th>Partial Eta Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social Cultural Influence</td>
<td>3.724</td>
<td>0.63</td>
<td>0.107</td>
</tr>
<tr>
<td>Imagination and Creativity</td>
<td>7.599*</td>
<td>0.010</td>
<td>0.197</td>
</tr>
<tr>
<td>Social Interactions</td>
<td>0.129</td>
<td>0.722</td>
<td>0.089</td>
</tr>
<tr>
<td>Time</td>
<td>1.336</td>
<td>0.257</td>
<td>0.041</td>
</tr>
<tr>
<td>Tentativeness</td>
<td>0.617</td>
<td>0.438</td>
<td>0.020</td>
</tr>
<tr>
<td>Law Theory</td>
<td>3.427</td>
<td>0.074</td>
<td>0.100</td>
</tr>
</tbody>
</table>

*significant at p < 0.01

The same statistical tests were performed on data for the Chemistry groups. Table 8 provides the pre and post means and standard deviations for the six VOSSI items for the control treatment groups for Chemistry.

Table 8. Chemistry VOSSI items – pre and post means and standard deviations

<table>
<thead>
<tr>
<th>NOS Component</th>
<th>Control Pre (N=17) a</th>
<th>Control Post (N=17) a</th>
<th>Treatment Pre (N=27) a</th>
<th>Treatment Post (N=27) a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Social Cultural Influences</td>
<td>13.12</td>
<td>3.06</td>
<td>13.47</td>
<td>2.94</td>
</tr>
<tr>
<td>Imagination and Creativity</td>
<td>11.94</td>
<td>4.74</td>
<td>11.00</td>
<td>3.95</td>
</tr>
<tr>
<td>Social Interactions</td>
<td>14.06</td>
<td>3.05</td>
<td>13.88</td>
<td>2.69</td>
</tr>
<tr>
<td>Time</td>
<td>16.12</td>
<td>2.37</td>
<td>16.53</td>
<td>2.70</td>
</tr>
<tr>
<td>Tentativeness</td>
<td>15.65</td>
<td>2.12</td>
<td>15.24</td>
<td>2.59</td>
</tr>
<tr>
<td>Theory/Law</td>
<td>10.24</td>
<td>1.68</td>
<td>9.94</td>
<td>2.25</td>
</tr>
</tbody>
</table>

a. Two treatment participant and one control participant are not included due to missing data points.

b. Possible scores for each component range from a minimum of 4 to a maximum of 20.

Results of the initial MANCOVA analysis of Chemistry participants show a significant difference in regards to increased overall NOS understanding of treatment in comparison to control participants (F= 7.292, p< 0.000, Wilks’ Lambda = 0.415, eta squared 0.585). Univariate
analyses of Chemistry participants’ VOSSI scores for each of the six VOSSI NOS items as dependent variables are shown in Table 9.

**Table 9.** Univariate analyses of VOSSI items for Chemistry

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>F (1,42)</th>
<th>Sig</th>
<th>Partial Eta Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social Cultural Influence</td>
<td>10.647**</td>
<td>0.002</td>
<td>0.202</td>
</tr>
<tr>
<td>Imagination and Creativity</td>
<td>19.634**</td>
<td>0.000</td>
<td>0.319</td>
</tr>
<tr>
<td>Social Interactions</td>
<td>0.220</td>
<td>0.641</td>
<td>0.005</td>
</tr>
<tr>
<td>Time</td>
<td>0.049</td>
<td>0.827</td>
<td>0.001</td>
</tr>
<tr>
<td>Tentativeness</td>
<td>0.259</td>
<td>0.613</td>
<td>0.006</td>
</tr>
<tr>
<td>Law/Theory</td>
<td>5.393*</td>
<td>0.025</td>
<td>0.114</td>
</tr>
</tbody>
</table>

*significant at p < 0.005 **significant at p < 0.01

The ANCOVA analysis of Chemistry participants’ scores show significant differences in three of the six VOSSI items. Social/Cultural Influence (F=10.647, p=0.002, partial eta squared 0.202), Imagination and Creativity (F=19.634, p<0.000, partial eta squared 0.319), and Law/Theory (F=5.393, p=0.025, partial eta squared 0.114) components all showed significant differences between control and treatment groups. Results for Social Interactions (F=0.220, p=0.641, partial eta squared= 0.005), Time (F=0.049, p=0.827, partial eta squared= 0.001) and Tentativeness (F=0.259, p=0.613, partial eta squared 0.006) components indicated no significant differences between groups.

**Research Question 1b**

Research question 1b sought to determine if participants, in written VOSSI responses and/or in their utterances during the semi-structured interviews, referenced the historical stories in a way that logically supported their NOS thinking. Table 10 summarizes how many General Chemistry participants referenced a story: (1) in their written response, (2) in their verbal response, (3) in both their written and verbal response, and (4) in either their written or verbal response. Table 11 summarizes the same questions for Chemistry. Two VOSSI written survey
responses, “time for development of science ideas” and “scientific laws and theories” were unintentionally omitted from the interview.

**Table 10.** General Chemistry Treatment participant frequency of references to stories

<table>
<thead>
<tr>
<th>NOS Component</th>
<th>Written Response</th>
<th>Verbal Response</th>
<th>Both Written and Verbal</th>
<th>Either Written or Verbal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social/Cultural Influence</td>
<td>1/8</td>
<td>0/8</td>
<td>0/8</td>
<td>1/8</td>
</tr>
<tr>
<td>Imagination/Creativity</td>
<td>2/8</td>
<td>5/8</td>
<td>2/8</td>
<td>7/8</td>
</tr>
<tr>
<td>Time</td>
<td>3/8</td>
<td>Not assessed</td>
<td>Not assessed</td>
<td>Not assessed</td>
</tr>
<tr>
<td>Tentativeness</td>
<td>1/8</td>
<td>2/8</td>
<td>1/8</td>
<td>2/8</td>
</tr>
<tr>
<td>Law/Theory</td>
<td>0/8</td>
<td>Not assessed</td>
<td>Not assessed</td>
<td>Not assessed</td>
</tr>
</tbody>
</table>

Participants in the General Chemistry treatment group referenced the stories to support their NOS thinking regarding Imagination/Creativity (VOSSI item 2) at 88 percent when answering by written or verbal response. Social interaction among scientists (VOSSI item 3) was the second highest percentage using either written or verbal response at 75 percent.

Social/cultural influence on science (VOSSI item 1) and tentativeness of scientific knowledge (VOSSI item 5) had the lowest percentage of written or verbal responses at 12.5 percent and 25 percent respectively. Both Time for development of scientific ideas (VOSSI item 4) and scientific law/theory (VOSSI item 6) items were not assessed in the interview protocol therefore they cannot be analyzed for total response. Verbal responses increased the likelihood of a story reference in all VOSSI items reviewed in the interview protocol with the exception of social/cultural influence (VOSSI item 1). Almost all of the written responses to VOSSI items 2, 3, and 5 come from participants who also referenced stories in the interviews.
<table>
<thead>
<tr>
<th>NOS Component</th>
<th>Written Response</th>
<th>Verbal Response</th>
<th>Both Written and Verbal</th>
<th>Either Written or Verbal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social/Cultural Influence</td>
<td>3/18</td>
<td>8/18</td>
<td>3/18</td>
<td>8/18</td>
</tr>
<tr>
<td>Imagination/Creativity</td>
<td>5/18</td>
<td>14/18</td>
<td>4/18</td>
<td>15/18</td>
</tr>
<tr>
<td>Social Interaction</td>
<td>7/18</td>
<td>11/18</td>
<td>7/18</td>
<td>11/18</td>
</tr>
<tr>
<td>Time</td>
<td>7/18</td>
<td>Not assessed</td>
<td>Not assessed</td>
<td>Not assessed</td>
</tr>
<tr>
<td>Tentativeness</td>
<td>12/18</td>
<td>11/18</td>
<td>10/18</td>
<td>12/18</td>
</tr>
<tr>
<td>Law/Theory</td>
<td>0/18</td>
<td>Not assessed</td>
<td>Not assessed</td>
<td>Not assessed</td>
</tr>
</tbody>
</table>

Participants in the Chemistry treatment group referenced the stories to support their NOS thinking regarding Imagination/Creativity (VOSSI item 2) at 83 percent when answering by either written or verbal response. Tentativeness of scientific knowledge (VOSSI item 5) had the second highest percentage at 67 percent referencing the story either by written or verbal response. Social interaction among scientists (VOSSI item 3) had 61 percent reference rate by either response type as well. Social/cultural influence (VOSSI item 1) was referenced only 44 percent of the time by either written or verbal response type. Both time for development of scientific ideas (VOSSI item 4) and scientific law/theory (VOSSI item 6) constructs were not assessed in the interview protocol therefore they cannot be analyzed for total response. Verbal responses increased the likelihood of a story reference in all VOSSI items assessed during the interview. Verbal responses increase the overall response score in all VOSSI items with the exception of tentativeness, where almost all written responses from a participant also corresponded with a verbal response. Almost all of the written responses to VOSSI items 1, 2, 3, and 5 come from participants who also referenced stories in the interviews. Examples of student responses to written and verbal questions are included below:

“Scientist(s) I believe use their imagination and creativity everywhere. They have to use it to create an idea, hypothesis, experiment, and understand everything. Dalton used his imagination and creativity to make his assumptions, and drawings of atoms and molecules.”
“Society and culture could affect scientific research because based on the believes or equipment in your society, you might not be able or do the same research as someone else. Also you could be affected by other scientists in your society, use parts of their research to fuel yours. Like Dalton use(d) many different ideas from scientists to complete his theory.”

“Science is building off of others, building off of previous knowledge. All knowledge comes from previous data. Like with the discovery of an atom. One guy found that there were electrons, another found the other particles.”

“To an extent I think culture does effect the way a scientist sees things and the way he conducts different experiments. Because everybody has different beliefs and a scientist is no different.”

“Question asked: To what degree do you think that scientists work with other scientists when doing research? I think they do most of the time it makes their job a lot easier and they can get different points of view of an experiment if they work together

Follow up question: Can you think of an example where social interaction was taking place between scientific researchers? I think that scientists were discovering the atom and the different particles inside they came together to see what types of stuff that they had discovered like some scientist discovered negative particles charges positive charges and neutral particles of the atom”

“Question: How do you think scientists use or do not use imagination and creativity in scientific investigations? I think going back to the last question they do use their imaginations and creativity when they’re coming up with ideas because maybe they’ll have to find a new way to solve the problem or new way to test like coming up with new equipment or new ideas of how to solve the problems so they would have to have some level of creativity

Follow up question: can you think of a specific example? Trying to remember his name he was I think his name was it wasn't Priestly it was Lavoisier I believe it was him that was creating new equipment and people can disagreeing with them because he was coming up with this new equipment that they were really familiar with and the use using his creativity to solve problems in a different way that had already been done.”

Research Question 2

Following the implementation of all the historical stories, participants in the treatment group completed a second survey “Interests and Attitudes 2” (Appendix C), to determine their impressions of the readings. Participants were asked what they liked and disliked about the readings, if the readings increased their interest of science, how interesting they found the
readings in comparison to textbook readings, the percentage of time the historical stories should be used in the classroom, should learning about how science works and how science ideas are formed be a goal of science education, and if the stories helped them reach this goal.

**General Chemistry Participants’ Interest in the Stories**

Table 12 summarizes the results of survey questions pertaining to the readings for General Chemistry and Table 13 summarizes participant attitudes toward reading. Interest ratings for the stories were completed on a five-point scale from (1) extremely uninteresting to (5) extremely interesting. 50 percent rated the readings as somewhat interesting or extremely interesting, while 33.3 percent of the participants rated them as extremely uninteresting/somewhat uninteresting. However even with a polarized group, 75 percent of the participants rated the stories as somewhat more interesting/much more interesting than science textbook or other typical class readings; only 12.5 percent of participants found them somewhat less interesting. Participants also thought that stories similar to the readings should be used in place of other in class readings texts, such as the textbook. 66.6 percent of the participants desired 75 or 100 percent of readings to be replaced, while 16.7 percent wanted 50 percent replaced, and only 16.7 percent thought 0 to 25 percent should be replaced.

In addition to story specific questions, General Chemistry treatment participants were asked their impression of the act and benefit of reading. 54.2 percent of participants indicated they find reading enjoyable, while 29.1 percent disagreed with this statement, and 16.7 percent remained neutral. Participants were much less divided over reading being categorized as a difficult task. 75 percent of General Chemistry treatment participants reported the act of reading as not difficult. Participants did vary when asked if they find understanding what they read to be
difficult. 50 percent of participants disagreed that reading is difficult, while 25 percent agreed it is difficult and 25 percent remained neutral. Participants were split when asked if they find reading boring: 45.8 percent responding it is not boring, 29.2 percent agreeing that it is, and 25 percent stating neutral. 58.3 percent of participants also responded that reading is beneficial with 12.5 percent disagreeing, followed by 45.8 percent agreeing that reading helps them learn, and 20.8 percent stating it does not help them learn.

Question four on the survey asked participants to choose to what extent the readings portrayed science as more interesting than previously thought. Most of the participants reported that science was portrayed as being more interesting than they thought. 45.9 percent of participants found the stories portrayed science as somewhat more interesting/much more interesting, and 29.2 percent said it was no more or less interesting than they previously thought. Only a quarter of the participants felt that the readings portrayed science as much less/somewhat less interesting. Question five then asked participants about the stories’ impact on their interest in science content. None of the participants found the stories to greatly increase their interest, while 41.7 percent of participants found their interest level was somewhat increased. 37.5 percent found no impact on their interest level, followed by 20.8 percent of participants had decreased interest after reading the stories.
Table 12. Summary of General Chemistry responses to *Interest/Attitude Survey*<sup>2</sup>  
*Participant Interest in the stories*

<table>
<thead>
<tr>
<th>Question 1: Overall, how interesting did you find this group of readings?</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Participants (N=24)</td>
</tr>
<tr>
<td>Extremely uninteresting</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Question 4: To what extent did the readings portray doing science as more interesting than you previously thought?</td>
</tr>
<tr>
<td>% of Participants (N=24)</td>
</tr>
<tr>
<td>Much less interesting</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Question 5: To what extent did the readings increase your interest in the science content in the stories?</td>
</tr>
<tr>
<td>% of Participants (N=24)</td>
</tr>
<tr>
<td>Greatly decreased my interest</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Question 6: How interesting did you find these readings compared to readings from a science textbook or other typical class readings?</td>
</tr>
<tr>
<td>% of Participants (N=24)</td>
</tr>
<tr>
<td>Much less interesting</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Question 7: If stories similar to the readings used this semester were to replace class textbook readings (or other readings typically used in your science class), approximately what percentage of textbook readings would you like replaced?</td>
</tr>
<tr>
<td>% of Participants (N=24)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Table 13. Summary of General Chemistry responses to Interest/Attitude Survey 2
-Participant attitudes towards reading

<table>
<thead>
<tr>
<th>Question</th>
<th>Description</th>
<th>% of Participants (N=24)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>10A: I find reading enjoyable</td>
<td></td>
<td></td>
<td>Completely disagree</td>
<td>Somewhat disagree</td>
<td>Neutral</td>
<td>Somewhat agree</td>
<td>Completely agree</td>
</tr>
<tr>
<td></td>
<td>20.8</td>
<td>8.3</td>
<td>16.7</td>
<td>29.2</td>
<td>25.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10D: I find reading difficult</td>
<td></td>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
<td>Completely Agree</td>
</tr>
<tr>
<td></td>
<td>41.7</td>
<td>33.3</td>
<td>20.8</td>
<td>4.2</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10H: Reading is boring</td>
<td></td>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
<td>Completely Agree</td>
</tr>
<tr>
<td></td>
<td>20.8</td>
<td>25.0</td>
<td>25.0</td>
<td>16.7</td>
<td>12.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10K: Reading is beneficial to me.</td>
<td></td>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
<td>Completely Agree</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>8.3</td>
<td>29.2</td>
<td>37.5</td>
<td>20.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10R: I find understanding what I read difficult</td>
<td></td>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
<td>Completely Agree</td>
</tr>
<tr>
<td></td>
<td>20.8</td>
<td>29.2</td>
<td>25.0</td>
<td>25.0</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10V: Reading does not help me learn.</td>
<td></td>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
<td>Completely Agree</td>
</tr>
<tr>
<td></td>
<td>20.8</td>
<td>25.0</td>
<td>33.3</td>
<td>12.5</td>
<td>8.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
General Chemistry treatment participants’ perceptions of NOS goal: Development of science ideas

Table 14 summarizes the results of General Chemistry treatment group survey responses pertaining to participant perceptions of the NOS goal: Development of science ideas. Question eight asked participants to give their opinion on whether learning about how science works and how scientific ideas are developed and become accepted should be a goal in science education. 45.9 percent of participants chose this goal should be important/extremely important in high school science classes, followed by 41.7 percent agreeing that the goal should be somewhat important. Only 12.5 percent of participants felt that this should not be a goal or the goal should be of little importance to high school science classes. Question nine then asked participants if the stories helped them reach the goal stated in question eight. 75 percent of participants somewhat agree or completely agree that the stories helped them reach this goal, with only 16.7 percent remaining neutral. Only 8.4 percent of participants completely or somewhat disagreed with this statement. Even though participants found the stories helped them reach this goal, they did not want to be tested over it. 54.2 percent said they should not be tested over this goal, and only 12.5 percent agreed that they should be tested (Question 10U). When participants were asked if they want to learn about who developed science ideas (Question 10S) they stated they did not want to or did not really know if they wanted to. 41.6 percent of participants did not want to learn about who develops science ideas, while only 25 percent wanted to learn this information, and 33.3 percent stated they were neutral on the topic.
Table 14. Summary of General Chemistry participants responses to Interest/Attitude Survey 2: Perceptions of NOS goal: development of science ideas

<table>
<thead>
<tr>
<th>Question 8: Learning about how science works and how scientific ideas are developed and become accepted is a goal of science education. How important do you think this goal is for high school science classes?</th>
<th>% of Participants (N=24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. this goal should not be a goal of HS science classes</td>
<td>4.2</td>
</tr>
<tr>
<td>2. this goal should be of little importance</td>
<td>8.3</td>
</tr>
<tr>
<td>3. this goal should be somewhat important</td>
<td>41.7</td>
</tr>
<tr>
<td>4. this goal should be important</td>
<td>41.7</td>
</tr>
<tr>
<td>5. this goal should be extremely important in HS science classes</td>
<td>4.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 9: These stories helped me reach the goal of understanding how science works and how scientific ideas are developed and become accepted.</th>
<th>% of Participants (N=24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Completely Disagree</td>
<td>4.2</td>
</tr>
<tr>
<td>2. Somewhat Disagree</td>
<td>4.2</td>
</tr>
<tr>
<td>3. Neutral</td>
<td>16.7</td>
</tr>
<tr>
<td>4. Somewhat Agree</td>
<td>58.3</td>
</tr>
<tr>
<td>5. Completely Agree</td>
<td>16.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 10S: I want to learn about the people who developed the ideas we learn in science class</th>
<th>% of Participants (N=24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Completely Disagree</td>
<td>25.0</td>
</tr>
<tr>
<td>2. Somewhat Disagree</td>
<td>29.2</td>
</tr>
<tr>
<td>3. Neutral</td>
<td>33.3</td>
</tr>
<tr>
<td>4. Somewhat Agree</td>
<td>12.5</td>
</tr>
<tr>
<td>5. Completely Agree</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 10U: Participants should be tested on their understanding of not only science ideas, but also how scientists came to understand those ideas.</th>
<th>% of Participants (N=24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Completely Disagree</td>
<td>25.0</td>
</tr>
<tr>
<td>2. Somewhat Disagree</td>
<td>29.2</td>
</tr>
<tr>
<td>3. Neutral</td>
<td>33.3</td>
</tr>
<tr>
<td>4. Somewhat Agree</td>
<td>12.5</td>
</tr>
<tr>
<td>5. Completely Agree</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Chemistry Participants’ Interest in the Stories

Table 15 summarizes the results of survey questions pertaining to the readings for Chemistry; Table 16 summarizes the participant attitudes toward reading. Chemistry participants were split on their interest in the stories with 40.7 percent reporting the stories to be somewhat to
extremely interesting, and 40.7 percent deciding they were extremely to somewhat uninteresting. However, 46.4 percent of participants found that the stories portrayed science as being somewhat more to much more interesting than they previously thought and 50 percent agreed they did not portray science anymore or less interesting than they already thought. Chemistry participants were more reluctant to replace typical textbook readings in class with stories. 35.7 percent of participants chose 75 to 100 percent replacement, while 39.3 percent chose 50 percent replacement. 25 percent of participants did not want the stories replaced or only 25 percent replacement.

In addition to story-specific questions, Chemistry treatment participants were asked their impression of the act and benefit of reading. Chemistry treatment participants responded that reading is enjoyable and not difficult. 71.4 percent of participants stated they find reading enjoyable, 85.7 percent responded that they did not find reading difficult, and 70.6 percent said they understand what they read. Participants were more divided when asked if they find reading boring. 57.1 percent stated reading is not boring, while 25 percent stated that it is boring. Most participants found reading to be beneficial and help them learn. 78.5 percent stated that reading is beneficial, while 75 percent reported that reading does help them learn.

Survey question four asked participants to choose to what extent the readings portrayed science as being more interesting than previously thought. Chemistry participants were split between the readings portraying science as being more interesting and no change on their interest. 46.5 percent of the participants indicated somewhat more/much more interesting, with 50 percent selecting no more or less interesting. Question five then asked if the stories increased participant interest in science content. Most participants reported no impact was made on their
interest. 50 percent of participants reported no impact, while 35.7 percent mentioned an increase in interest, and 21.5 percent less interested.

**Table. 15** Summary of Chemistry Treatment participants responses to *Interest/Attitude Survey*2 - *Participant Interest in the stories*

<table>
<thead>
<tr>
<th>Question 1: Overall, how interesting did you find this group of readings?</th>
<th>% of Participants (N=27)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Extremely uninteresting</td>
<td>7.4</td>
</tr>
<tr>
<td>2 Somewhat uninteresting</td>
<td>33.3</td>
</tr>
<tr>
<td>3 Neutral</td>
<td>18.5</td>
</tr>
<tr>
<td>4 Somewhat interesting</td>
<td>25.9</td>
</tr>
<tr>
<td>5 Extremely interesting</td>
<td>14.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 4: To what extent did the readings portray doing science as more interesting than you previously thought?</th>
<th>% of Participants (N=28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Much less interesting</td>
<td>0.0</td>
</tr>
<tr>
<td>2 Somewhat less interesting</td>
<td>3.6</td>
</tr>
<tr>
<td>3 No more or less interesting</td>
<td>50.0</td>
</tr>
<tr>
<td>4 Somewhat more interesting</td>
<td>35.7</td>
</tr>
<tr>
<td>5 Much more interesting</td>
<td>10.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 5: To what extent did the readings increase your interest in the science content in the stories?</th>
<th>% of Participants (N=28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Greatly decreased my interest</td>
<td>3.6</td>
</tr>
<tr>
<td>2 Somewhat decreased my interest</td>
<td>10.7</td>
</tr>
<tr>
<td>3 No impact on my interest</td>
<td>50.0</td>
</tr>
<tr>
<td>4 Somewhat increased my interest</td>
<td>28.6</td>
</tr>
<tr>
<td>5 Greatly increased my interest</td>
<td>7.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 6: How interesting did you find these readings compared to readings from a science textbook or other typical class readings?</th>
<th>% of Participants (N=28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Much less interesting</td>
<td>3.6</td>
</tr>
<tr>
<td>2 Somewhat less interesting</td>
<td>17.9</td>
</tr>
<tr>
<td>3 Equally interesting/uninteresting</td>
<td>23.1</td>
</tr>
<tr>
<td>4 Somewhat more interesting</td>
<td>32.1</td>
</tr>
<tr>
<td>5 Much more interesting</td>
<td>14.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 7: If stories similar to the readings used this semester were to replace class textbook readings (or other readings typically used in your science class), approximately what percentage of textbook readings would you like replaced?</th>
<th>% of Participants (N=28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% (stories not replace any textbook readings)</td>
<td>10.7</td>
</tr>
<tr>
<td>25% (stories occasionally replace any textbook reading)</td>
<td>14.3</td>
</tr>
<tr>
<td>50% (stories replace about half textbook readings)</td>
<td>39.3</td>
</tr>
<tr>
<td>75% (readings replace most textbook readings)</td>
<td>14.3</td>
</tr>
<tr>
<td>100% (stories replace all textbook readings)</td>
<td>21.4</td>
</tr>
</tbody>
</table>
Table 16. Summary of Chemistry Treatment participants responses to Interest/Attitude Survey2 - Participant attitudes towards reading

<table>
<thead>
<tr>
<th>Question</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>10A: I find reading enjoyable</td>
<td>3.6</td>
<td>10.7</td>
<td>14.3</td>
<td>25.0</td>
<td>46.4</td>
</tr>
<tr>
<td>10D: I find reading difficult</td>
<td>60.7</td>
<td>25.0</td>
<td>10.7</td>
<td>3.6</td>
<td>0.0</td>
</tr>
<tr>
<td>10H: Reading is boring</td>
<td>35.7</td>
<td>21.4</td>
<td>17.9</td>
<td>25.0</td>
<td>0.0</td>
</tr>
<tr>
<td>10K: Reading is beneficial to me</td>
<td>0.0</td>
<td>0.0</td>
<td>21.4</td>
<td>32.1</td>
<td>46.4</td>
</tr>
<tr>
<td>10R: I find understanding what I read difficult</td>
<td>14.3</td>
<td>56.3</td>
<td>14.3</td>
<td>14.3</td>
<td>3.6</td>
</tr>
<tr>
<td>10V: Reading does not help me learn</td>
<td>42.9</td>
<td>32.1</td>
<td>14.3</td>
<td>10.7</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Chemistry treatment participants’ perceptions of NOS goal: development of science ideas

Table 17 summarizes the results of Chemistry treatment group survey responses pertaining to participant perceptions of NOS goal: development of science ideas. Question eight asked participants to give their opinion on whether learning about how science works and how scientific ideas are developed and become accepted should be a goal in science education. Chemistry participants overwhelmingly supported this goal as being important in secondary science classes. 67.9 percent of participants selected this goal should be or is extremely important, while 25 percent of participants said it is somewhat important. In question nine, participants responded in a similar fashion to question eight, stating that they agreed that the stories helped them reach this goal. 71.4 percent of participants somewhat or completely agreed that the stories helped them meet this goal while 21.4 percent were neutral. Only 7.1 percent of participants stated they somewhat disagreed with this statement. Even though participants responded highly of the NOS goal, they were split on whether or not they should be tested on the goal. 32.1 percent disagreed on Question 10U that they should be tested over this goal, 32.1 percent agreed, and 35.7 percent remained neutral. Participants were also split when asked if they wanted to learn about the people who developed science ideas. 35.7 percent did not want to learn about scientists, 32.1 percent did want to learn and the final 32.1 percent stayed neutral (Question 10S).
### Table 17. Summary of Chemistry participants responses to Interest/Attitude Survey2

**Perceptions of NOS goal: development of science ideas**

#### Question 8: Learning about how science works and how scientific ideas are developed and become accepted is a goal of science education. How important do you think this goal is for high school science classes?

<table>
<thead>
<tr>
<th>% of Participants (N=28)</th>
<th>1 this should not be a goal of HS science classes</th>
<th>2 this goal should be of little importance</th>
<th>3 this goal should be somewhat important</th>
<th>4 this goal should be important</th>
<th>5 this goal should be extremely important in HS science classes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.6</td>
<td>3.6</td>
<td>25.0</td>
<td>50.0</td>
<td>17.9</td>
</tr>
</tbody>
</table>

#### Question 9: These stories helped me reach the goal of understanding how science works and how scientific ideas are developed and become accepted.

<table>
<thead>
<tr>
<th>% of Participants (N=28)</th>
<th>1 Completely Disagree</th>
<th>2 Somewhat Disagree</th>
<th>3 Neutral</th>
<th>4 Somewhat Agree</th>
<th>5 Completely Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0</td>
<td>7.1</td>
<td>21.4</td>
<td>50.0</td>
<td>21.4</td>
</tr>
</tbody>
</table>

#### Question 10S: I want to learn about the people who developed the ideas we learn in science class

<table>
<thead>
<tr>
<th>% of Participants (N=28)</th>
<th>1 Completely Disagree</th>
<th>2 Somewhat Disagree</th>
<th>3 Neutral</th>
<th>4 Somewhat Agree</th>
<th>5 Completely Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10.7</td>
<td>25.0</td>
<td>32.1</td>
<td>25.0</td>
<td>7.1</td>
</tr>
</tbody>
</table>

#### Question 10U: Participants should be tested on their understanding of not only science ideas, but also how scientists came to understand those ideas.

<table>
<thead>
<tr>
<th>% of Participants (N=28)</th>
<th>1 Completely Disagree</th>
<th>2 Somewhat Disagree</th>
<th>3 Neutral</th>
<th>4 Somewhat Agree</th>
<th>5 Completely Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10.7</td>
<td>21.4</td>
<td>35.7</td>
<td>32.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### What Participants Liked and Disliked About the Short Stories

Participants in the General Chemistry and Chemistry treatment groups answered extended response questions on the *Interest and Attitudes 2 Survey* (Appendix C) in response to what they liked and disliked about the historical short stories. Participant responses were coded
following the open/initial coding and focus coding procedures (Charmaz, 2006; Saldana, 2009). Codes were not mutually exclusive to single participants as responses could refer to multiple codes for things they liked or disliked.

What Participants Liked About the Short Stories

Treatment participants responses were divided into eight categorical themes that appeared throughout participant survey responses: (1) Mentally engaging, (2) Informative, (3) History of science, (4) Reading structure, (5) Helped with Classwork, (6) Not difficult, (7) Enjoy Science, (8) Liked nothing. Table 18 represents both General Chemistry and Chemistry treatment participants’ responses.

General Chemistry treatment participants gravitated towards two major themes in what they liked about the stories. The first theme with the most responses was the history of science. Participants liked reading about the development of science ideas (13%), seeing scientists working as humans (13%) and the overall history of science (17%). The second theme was the structure in which the stories were discussed. Twenty-nine percent of participants noted they enjoyed the group discussions that took place after the readings were read in class. This was not related to the stories themselves, rather the implementation process chosen by the instructor. Few participants (8%) found the stories to be mentally engaging and interesting while a larger number (17%) found them informative. Twenty-one percent of participants responded negatively to the question and stated they did not like anything about the stories.

Chemistry Treatment participants’ responses indicated that they liked the stories because they were mentally engaging, informative, featured the history of science, and for the reading structure. Twenty percent of participants stated the stories were mentally engaging or interesting
with another 28 percent participants saying they were informative. The history of science (10%) also drew a large number of responses as participants liked seeing the development of ideas (21%), as well as reading about scientists in a humanistic light (10%). Chemistry participants appreciated the reading structure based on its organization (7%), the amount of detail covered in the stories (10%), and the group discussions that took place in class (14%). Ten percent of participants indicated the stories were not difficult, while seven percent of participants indicated they did not like anything about the stories.

**Table 18. Summary of what participants liked about the treatment stories**

<table>
<thead>
<tr>
<th>What Participants Liked</th>
<th>Percentage of General Chemistry Participants (N=24)</th>
<th>Percentage of Chemistry Participants (N=29)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mentally engaging</td>
<td>8%</td>
<td>3%</td>
</tr>
<tr>
<td>Interesting</td>
<td>8%</td>
<td>17%</td>
</tr>
<tr>
<td>Informative</td>
<td>17%</td>
<td>28%</td>
</tr>
<tr>
<td>History of science</td>
<td>17%</td>
<td>10%</td>
</tr>
<tr>
<td>Development of Ideas</td>
<td>13%</td>
<td>21%</td>
</tr>
<tr>
<td>Scientists as People</td>
<td>13%</td>
<td>10%</td>
</tr>
<tr>
<td>History in General</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>Reading Structure</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>Organization</td>
<td>4%</td>
<td>7%</td>
</tr>
<tr>
<td>Amount of Detail</td>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>Embedded Questions</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>Group Discussions</td>
<td>29%</td>
<td>14%</td>
</tr>
<tr>
<td>Helped with Classwork</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>Not Difficult</td>
<td>8%</td>
<td>10%</td>
</tr>
<tr>
<td>Enjoy Science</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>Liked Nothing</td>
<td>21%</td>
<td>7%</td>
</tr>
</tbody>
</table>

**What Participants Disliked About the Stories**

Treatment participants’ responses to the survey question regarding what they disliked about the stories was divided into nine categorical responses: (1) boring or uninteresting, (2) disliked the structure, (3) difficult to understand, (4) dislike reading, (5) not useful, (6) disliked
history of science, (7) dislike science, (8) disliked everything, and (9) disliked nothing. Table 19 represents both General Chemistry and Chemistry Treatment participants’ responses. Numbers do not add to 100 percent as participants often gave more than one response.

General Chemistry treatment participants responded that the stories were boring, they disliked the way they were structured, said they were difficult to understand and disliked reading in general. Twenty-five percent of participants responded that the stories were boring or uninteresting, while another 25 percent indicated they did not like stories in general. Participants did not like the structure of the stories based on length, stating it was too long (25%), they disliked the questions they had to answer (21%) and its overall organization (13%). 21 percent of participants also wrote that the stories were difficult to understand. Only 4 percent of participants responded to each of the following: disliked the history of science, disliked science, or disliked everything about the stories.

Chemistry treatment participants had similar responses to those of General Chemistry: the stories were boring, they disliked the structure, found the stories difficult to understand, but also indicated the stories were not useful. Forty-one percent of responses indicated the stories were boring or uninteresting to participants in the Chemistry treatment group. Participants also indicated the stories were too long (21%), they disliked the questions (17%) and stated the stories were repetitive (10%). 28 percent of participants indicated the stories were difficult to understand while 17 percent thought the stories were not useful to the chemistry course. Only 4 percent of participants responded they disliked nothing about the stories or requested greater detail to be included.
Table 19. Summary of what participants disliked about the treatment stories

<table>
<thead>
<tr>
<th>What Participants Disliked</th>
<th>Percentage of General Chemistry Participants (N=25)</th>
<th>Percentage of Chemistry Participants (N=29)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boring or Uninteresting</td>
<td>25%</td>
<td>41%</td>
</tr>
<tr>
<td>Disliked the structure</td>
<td>25%</td>
<td>21%</td>
</tr>
<tr>
<td>Too Long</td>
<td>21%</td>
<td>17%</td>
</tr>
<tr>
<td>Disliked Questions</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>Too Much Info</td>
<td>4%</td>
<td>10%</td>
</tr>
<tr>
<td>Repetitive</td>
<td>13%</td>
<td>0%</td>
</tr>
<tr>
<td>Organization</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>Want more detail</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difficult to Understand</td>
<td>21%</td>
<td>28%</td>
</tr>
<tr>
<td>Dislike Reading</td>
<td>25%</td>
<td>0%</td>
</tr>
<tr>
<td>Not Useful</td>
<td>0%</td>
<td>17%</td>
</tr>
<tr>
<td>Disliked History of Science</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>Dislike Science</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>Disliked Everything</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>Disliked Nothing</td>
<td>0%</td>
<td>3%</td>
</tr>
</tbody>
</table>

General Chemistry treatment participant interview responses to short stories

During the semi-structured interviews, participants were asked three questions pertaining to the stories: (1) explain what you liked about these readings (2) to what extent did you like or dislike these readings compared to readings from a science textbook or other typical class reading and (3) learning about how science works and how scientific ideas are developed and become accepted is a goal of science education. “How important do you think this goal is for high school science classes?” was a follow-up question used to clarify participant answers. Eight General Chemistry treatment participants were interviewed.
When asked to explain what they liked about the readings, General Chemistry participants responded with similar responses to the written surveys. Participants liked seeing how ideas were formed, readings materials that were not textbook-like, enjoyed the story format, and learning about how scientists came up with ideas and explained those ideas. They also reported that they liked the ensuing discussions that took place and having a different type of activity as opposed to note taking. When asked to what extent they liked the stories or a textbook reading more, all participants responded that they liked the stories much more than a traditional textbook reading. Participants selected the stories over traditional readings as they were more interesting to read and not as “wordy” as textbooks can be. When participants were prompted with the final question of the set, should learning about how science works and how scientific ideas are developed and accepted be a goal, reactions were mixed. Most participants stated the goal was important but could not articulate why it was important. One participant responded that achieving this goal helps participants to interpret science concepts in the future, while another participant stated that they were unsure if it was important as they could not remember all the scientists’ names and felt others would struggle with this as well.

Chemistry treatment participant interview responses to short stories

Eighteen Chemistry treatment participants answered the same questions as the General Chemistry participants listed above. Responses to the first question, “what did you like about the stories?” were similar to those listed on the written portion of the survey. Participants liked learning about the development of ideas, found the stories very informative, and liked reading in a story format. Participants also frequently commented that they liked the in-class discussions and felt like scientists debating the questions proposed in the readings. All eighteen participants
also reported liking the stories over traditional textbook readings. Many participants stated they liked the stories because they had a greater level of detail, were more interesting and liked the story format, commenting that it was very different from science reading materials they had experienced in past course work. The final question regarding understanding the development of science as goal for high school students was accepted by 16 of the 18 respondents. Two clear themes emerged from their interviews: the goal is important for those pursuing a science career and it is important for all students regardless of career choice. Many participants stated that it is important to understand what scientists do and how knowledge is formed if they are going to pursue a science-based career. Almost all participants also responded that it was important for students not following a science-based career path to understand the development of science ideas as it helps students understand the content and the context of science. A few participants reported that learning about this goal may also increase interest in science-based careers. A second group of participants, who did not mention a link to science-based careers, also echoed the idea that all students should have a general understanding of how science works and where ideas come from. The two participants who responded that this goal should not be included in high school science had similar reasons for its exclusion. One stated that it does not relate to students who are science career bound and those students do not find learning about the goal to be worthwhile. The second stated it is not important to know if one is going into medicine, but only important for those entering the field of history.
CHAPTER 5. DISCUSSION & CONCLUSIONS

Study Overview

This study investigated the impact of historical science stories containing multiple prompts that overtly draw readers’ attention to particular NOS concepts illustrated in the stories. Specifically, this study set out to determine:

1. Does the use of historical science stories with explicit NOS statements and questions improve secondary science students’:
   (a) accurate understanding of fundamental NOS concepts made explicit in the story, and
   (b) recollection of historical examples that logically support their NOS thinking?
2. What are secondary science students’ attitudes toward:
   (a) reading the short stories compared to a traditional textbook reading, and
   (b) reading about scientists and how science ideas are developed.

Research Question 1a: Impact of Stories on Participants’ NOS Understanding

Summary of Findings for Research Question 1a

- Following the intervention in the General Chemistry classes, no significant differences were found between the control and treatment groups’ overall NOS understanding.
- Following the intervention in the Chemistry classes, significant differences were found between control participants’ and treatment participants’ overall NOS understanding.
- In the General Chemistry classes, participants having read the short stories had a significantly better understanding of the NOS construct “Imagination and Creativity in Science”. No significant differences were observed in the remaining five NOS constructs: Social/Cultural Influences on Science, Social Interactions among Scientists, Time for Development and Acceptance of Science Ideas, Tentativeness of Science Ideas, and Scientific Laws and Theories.
- In the Chemistry treatment classes, compared to the control participants, participants, after having read the short stories, had a significantly better understanding of three of the six measured NOS constructs: Social/Cultural Influences on Science, Imagination and Creativity in Science and Scientific Laws and Theories. No significant differences were observed in the three remaining NOS constructs: Social Interactions among Scientists, Time for Development and Acceptance of Science Ideas, and Tentativeness of Science Ideas.
General Chemistry

Research question 1a related to the extent that participants’ accurate understanding of NOS concepts was impacted by the use of historical short stories utilized in the treatment group in two chemistry courses. Results of MANCOVA analyses indicate that General Chemistry participants’ overall NOS performance on the VOSSI (i.e., all six NOS constructs as a whole) did not change between the treatment and control pre-post assessments. ANCOVA analysis did reveal a significant difference between treatment and control groups for one of the six VOSSI items: Imagination and Creativity in Science. Treatment group scores improved by 16.2 percent (+3.23 points out of a maximum 20) while the control group decreased by 5 percent (-1.01 points out of a maximum 20).

The remaining five constructs in the General Chemistry sections did not show a significant difference between treatment and control groups. This lack of significance may be due to the control group materials or the instructor’s language during class discussions that inadvertently drew attention to these NOS constructs. The video clips used from “Absolute Zero” did feature scientists shaping and being shaped by culture/society, scientists working together and discussing results, and a timeline of events. A cursory view of the video makes clear that there was some overt portrayal of and perhaps narration that conveyed science in a collaborative manner, interaction between society and science, and time required in the development of science ideas. While the NOS ideas were not as overt as they were in the treatment stories, the video clips certainly were drawing the viewers’ attention to NOS ideas. Because the results of research question two has bearing on making sense of research question 1a this research question will be more extensively discussed later in this chapter after the discussion of research question two.
Chemistry

Results of MANCOVA analysis on the Chemistry groups did indicate a significant difference in overall NOS understanding of participants in the treatment and control sections. ANCOVA analysis revealed three of the six NOS constructs had significant differences when comparing individual NOS constructs between treatment and control groups. Treatment group scores increased for Social/Cultural Influences by +6.5% (+1.30 points of out of a maximum 20), the control group increased +1.8% (+0.35 points of out of a maximum 20); Imagination and Creativity treatment increased by 22% (+4.3 points of out of a maximum 20), control decreased -4.7% (-0.94 points of out of a maximum 20); and Theory/Law treatment increased +1.5% (+0.29 points of out of a maximum 20), control decreased -1.5% (-0.3 points of out of a maximum 20).

The remaining three VOSSI items did not show significance: Social Interactions among Scientists, Time for Development and Acceptance of Science Ideas, and Tentativeness of Science Ideas. The reason for a lack of significance may be due to in class activities, language used by the instructor during class activities, and carryover of NOS instruction from first semester. In both treatment and control groups, participants had to create a timeline to represent the development of the atomic model, starting with Greek philosophers and documenting the atoms development, ending with its current conception in the twentieth century. In addition to the activity, language used by the instructor may have inadvertently drawn participants’ attention to NOS ideas. It is also of interest that both control and treatment participants began with a more informed NOS conception on three of the six constructs: Social interactions (Control pre-score average= 14.06, Treatment pre-score average= 14.22), Time for development (Control pre-score average= 16.12, Treatment pre-score average= 15.63), and Tentativeness of Science ideas.
(Control pre-score average= 15.65, Treatment pre-score average= 15.52); total scores have a maximum value of 20 (accurate, informed view of the NOS construct). These higher initial scores may result from NOS instruction that took place in the first semester with the instructor. This may also have led to no significance between groups, as well as an increase in total NOS construct score. Because the results of research question two has bearing on making sense of research question 1a this research question will be discussed later in this chapter after the discussion of research question two.

Research Question 1b: Participants recollection of historical examples that logically support their NOS thinking

Summary of Findings for Research Question 1b
- In the General Chemistry and Chemistry classes, participants often referenced the science stories in their written responses for the six VOSSI items. The exception was their written response to Scientific Laws and Theories.
- In the General Chemistry and Chemistry classes, participants referenced stories more often in the interview than on the written expression portion of the VOSSI survey.

Participants in both General Chemistry and Chemistry referenced stories on written response of the VOSSI survey; however this produced very low reference totals. This is not surprising as participants were high school students who do not like to write and often struggle to communicate their ideas in a written format. This conclusion is supported by an increase in participant references to the stories that took place in the semi-structured interviews. Participants in both courses, on the writing prompt and interview, did not reference the stories when referring to the Scientific Laws/Theories construct.
Both General Chemistry and Chemistry participants increased the number of story references when verbalizing answers to the semi-structured interview questions. Participants were not asked specific questions on NOS constructs regarding “time for development of science ideas” or “scientific law/theory”. Speculation on these constructs is limited due to this oversight in methodology. Because the results of research question two has bearing on making sense of research question 1a this research question will be explored later on in this chapter after the discussion of research question 2.

Research Question 2: Participants’ Interest and Attitude Towards the Stories

Summary of Findings for Question 2 - General Chemistry

- 50 percent of participants found the stories at least somewhat interesting, with 32.7 percent somewhat uninteresting/extremely uninteresting
- 75 percent of participants rated the stories as more interesting than reading from a traditional science textbook. Additionally, 83 percent of participants indicated they would like similar stories to replace at least half of their typical class readings.
- 45.9 percent of participants reported that the stories portrayed doing science as more interesting than they thought, while 25 percent reported doing science was portrayed as less interesting than they thought.
- 41.7 percent of participants indicated the stories increased their interest in related science content while 20.8 percent indicated decreased interest in the content.
- An overwhelming number of participants (87.6%) agreed that how science works and science ideas are developed should be at least somewhat of an important goal in high school science classes while only 12.5 percent of participants reported it should not be a goal at all. Additionally, 75 percent of participants agreed that the stories at least somewhat helped them meet this goal.
- In written responses regarding what they liked about the stories, General Chemistry participants most frequently reported liking the development of science ideas (13%), seeing scientists working as humans (13%), and the history of science (17%). Few participants stated the stories were engaging and informative. They also reported liking the discussions (29%), which were not part of the reading, but how the readings were facilitated in class.
In written responses regarding what they disliked about the stories, participants responded that they found the stories boring (25%), and did not like the stories in general (25%). They stated they disliked the length (25%), the questions that were to be answered (21%), and found the stories difficult to understand (21%).

General Chemistry participants confirmed the survey results when responding to the interview questions.

**Discussion of Research Question 2 – General Chemistry**

Approximately forty percent of all participants (41.7%) reported the stories increased their interest in science content, while almost half (45.9%) reported the stories portrayed science as more interesting than they thought. Three-quarters (75%) of participants expressed increasing the use of story-like readings to replace at least some of traditional classroom readings. Even though participants may not have liked the stories, they would much rather read from a historical story than their science textbook. This is encouraging, as 75 percent of participants reported reading the stories at least somewhat helped them meet the NOS goal of understanding how science works and scientific ideas are developed, a goal that 87.6 percent of participants deemed as at least somewhat important to high school science classes.

On the surface, these results appear to be positive for the lower level science group. However, further analysis is needed to understand if the participants attribute this increase to liking the stories or the implementation method employed by the instructor. Perhaps participants did not overly care for the stories but liked the implementation style – group classroom discussion of the stories. Multiple participant comments help with this speculation:

“I did not like these readings, but the one thing I liked was it was a group effort, with the discussions.”

“I liked the readings when we came together as a group at the end and gave our thoughts and talked about it.”
“I liked that we discussed them as a group and read through them together because it helped me understand the readings better. It also helped me to ask questions and kept me wondering.”

“I liked that it wasn't just a lecture and how we got points for bringing ideas up in class.”

Prior to use of the stories, the participants had not experienced a discussion of the same magnitude in the course, nor did their prior secondary science courses in this school encourage such discussions. A number of participants indicated liking the discussion format (29%) on the written expression portion of Interest/Attitudes Survey 2, and stated it in the interview (25%) as well. Participants offered more negative than positive comments when addressing their likes and dislikes on the two writing prompts of the Interest/Attitude Survey II. Participants posted a total of thirty-six negative comments when asked what they disliked about the stories, in comparison to twenty-four positive comments on what they liked in the stories, minus references to liking the discussions as they were not part of the story itself. There were also five comments posted in the “what did you like about the stories?” writing prompt that were categorized as “liked nothing.”

Many participants indicated that they disliked the length of the reading (25%), the questions they had to answer (21%), and found the stories difficult to comprehend (21%). During the implementation process, the researcher noted that participants found the questions very challenging and would ask for assistance in making sense out of the question itself. Often, participants required additional scaffolding, via questioning, during the discussions to make progress towards an acceptable answer. These and other negative attitudes toward the stories may reflect participants’ general dislike of reading about science. That students, without assistance from the instructor, struggled to comprehend portions of the stories may reflect the need to improve the stories and/or the mental effort required to comprehend science ideas and
thinking. Wolpert (1992), Cromer (1993) and Matthews (1994) are just some writers who have pointed out the counter-intuitive nature of many science ideas and the unnatural mode of thinking that produces those ideas. Reading and understanding science text, no matter how well written, requires that students mentally engage with and wrestle to understand content at a level they perhaps do not expect or desire. If stories like those used in the treatment groups addressed the development of mathematical ideas or any other counter-intuitive and difficult subject, students would likely express a similar dislike of reading those stories. So the important issue may not be whether students liked reading the stories, but rather did they like reading them better than traditional textbook and whether intended cognitive objectives are achieved.

Summary of Findings for Question 2 - Chemistry

- Participants were equally split as 40.7 percent stated they found the stories interesting as well as uninteresting. However, 46.4 percent of participants found the stories portrayed science as more interesting than previously though; with 50 percent stating their interest remained unchanged.
- 75 percent of participants indicated they wanted the stories to at least somewhat replace the typical classroom reading materials.
- 50 percent of participants reported that the stories did not impact their interest in science content, with 35.7 percent reporting it increased their interest, and 21.5 percent decreased interest.
- An overwhelming number of participants (92.8%) agreed that how science works and science ideas are developed should be at least somewhat of an important goal in high school science classes, with only 3.6 percent stating it should not be a goal at all. Additionally, 71.4 percent responded that the readings at least somewhat helped them reach this goal.
- In the written responses regarding what participants liked about the stories they responded most that the stories were mentally engaging (20%) and informative (28%), they enjoyed seeing the development of ideas (21%) and seeing scientists in a humanistic light (10%).
- In the written responses regarding what participants disliked about the stories they responded most that the stories were boring or uninteresting (41%), they were too long
(21%), disliked the questions (17%), found the stories difficult to understand (28%), and did not think they were useful to learning chemistry (17%).

- Chemistry participants who were interviewed confirmed the responses to the stories as indicated from the survey data. Sixteen of eighteen participants also stated the NOS goal of understanding the development of science is very important for high school science classes.

Discussion of Research Question 2 – Chemistry

Participant interest was split between finding the stories interesting and uninteresting at 40.7 percent. A larger percentage of participants (46.4%) did find the stories increased their portrayal of science as more interesting, with a very small number (3.6%) of students stating the opposite was true. Participants only reported that 35.7 percent found an increased interest in science content, while 21.5 percent had a decrease in interest after reading the stories. 50 percent of students found no change in liking or disliking science content. Even with participants holding differing views of the stories, 75 percent want at least some portion of their traditional classroom readings swapped with story-like readings. Similar to the findings in General Chemistry, 92.8 percent of participants reported the importance of understanding how science works and scientific ideas develop as an important NOS goal for high school science classes. Chemistry participants also agreed with General Chemistry participants that the stories helped them at least somewhat reach this goal at 71.4 percent. Sixteen of the eighteen interview participants also concluded that this NOS goal is important.

Some participants found the stories mentally engaging/interesting (20%), informative (28%), seeing the development of science ideas (21%), and viewing scientists in a humanistic light (10%). Participants were more apt to comment on the story itself and less on the discussion than General Chemistry participants. Some Chemistry participants disliked the length (21%) of the stories, and the embedded questions (17%), while finding the stories difficult to understand
(28%) and not applicable to learning chemistry (17%). 41 percent of participants found the stories boring as well. That participants disliked answering the questions, and found the reading difficult and too lengthy is not surprising, as they had to complete these on their own outside of class time. This trend is similar to General Chemistry participants, even though General Chemistry participants answered the questions in class with partners and did not always have to read for themselves. These attitudes, as was noted for General Chemistry, may reflect participants’ general dislike of readings about science and a need to improve stories or the mental effort required to comprehend science ideas and thinking. The fact that motivated students also struggled with the stories and counter-intuitive science ideas gives additional credence to rethinking the design of the stories.

**Discussion of Research Question 1a - General Chemistry**

General Chemistry participants did not show a significant difference in NOS understanding after implementation of the stories between the treatment and control groups. The researcher cannot say with a high level of certainty that all participants read the stories and answered all of the embedded questions because the stories were read in class by the instructor, or read in partner pairs. Questions were answered in partner pairs and one partner doing all of the work is possible. Another possibility is that the treatment stories are not appropriate for students lacking motivation and/or having learning difficulties. The General Chemistry treatment group had 25 percent of participants with an Individualized Education Plan (IEP). Alternatively, perhaps far more time and scaffolding is needed when implementing the treatment stories. Participants were only exposed to three stories over the course of the semester, which may not have been enough exposure to impact participants’ NOS understanding. Stories were never
intended to be teacher proof, and as with any difficult, but worthwhile learning objective, the teacher’s role is crucial.

Lack of significance between treatment and control may be due to the absence of reading and answering the questions, as outlined above, but other factors are likely. When looking at participants responses to “liking” the stories, General Chemistry participants were split, but strongly preferred using the stories over the traditional textbook if they had the choice. Upon reviewing participants’ written responses on the Interest/Attitude Survey II and interview data, many participants stated they “liked” the discussion format that was held after the readings and questions were answered. The researcher speculates that participants liked the discussion, and not the story, but because the two were done simultaneously, participants thought of the two as being synonymous. Participants liked learning about the development of science ideas, as indicated by the written responses and interview, but also commented that they disliked the length of the stories, the questions they had to answer, and found the readings difficult.

Even though there was no significant difference between treatment and control groups when viewing all NOS constructs together, Creativity and Imagination in Science did show significance when analyzed independently. This may have been due to the frequency of creativity/imagination being mentioned in the stories. Upon reviewing the three stories that General Chemistry participants read (Development of Thermometry, Conservation of Mass, Early History of Heat), 37 total textboxes or questions were featured in the three stories. Creativity/Imagination was discussed 11 times (30%) throughout the stories. This was the highest of the six NOS constructs surveyed in the study. The remaining five constructs had much lower numbers: social/cultural influence (5), social interactions (7), Tentativeness (1), Time (1), Law/theory (6), and six that did not fit the given constructs or were related to content derived
questions such as “What do you know about heat and how it works? How might heat be different than temperature?” Imagination/Creativity may be easier to create a conceptual change, as the other constructs may be deeply ingrained as misconceptions. Social interactions, even though they are discussed in the story, many times related more to scientists building off others’ ideas, therefore strengthening the misconception that they work alone. In addition, all photos of scientists feature them by themselves. This may further strengthen misconceptions that scientists work alone.

As it was discussed earlier, participants in lower level courses may not respond well to this type of treatment, and it has to be modified in a way that is more accessible to their needs. Based on the interviews, participants are able to recall parts of the stories, but not enough to create conceptual change in relationship to the NOS goals being promoted.

**Discussion of Research Question 1a - Chemistry**

The researcher can say with a high level of certainty that almost all participants read the stories and answered all of the embedded questions. Participants were required to show their embedded question answers to the instructor before the story discussion began in class, verifying that almost all participants had completed the questions, which required reading the entire story for accurate comprehension. Although the Chemistry treatment group showed a significant increase in NOS understanding than the control participants after the implementation of the stories, significant differences were only found for three of the six NOS constructs. Of the three constructs, significant gains were only found in Social/Cultural Influences on Science and Imagination and Creativity in Science, while Scientific Law and Theories showed a minimal change in understanding. This difference may be explained by the stories chosen to be
implemented in Chemistry. The stories implemented (Atomic Model Development, Conservation of Mass, and Development of the Periodic Table) heavily featured text boxes and embedded questions regarding Imagination and Creativity. A total 19 of 49 (39%) text boxes or questions in the three Chemistry stories revolved around Imagination and Creativity in Science. In addition to the text, many of the pictures displayed related to “creations or inventions” used in experimentation or creative ways to interpret results. The large amount of emphasis via textboxes and questions, coupled with images that exemplified creativity, may have added to the significant increase in participant understanding of the VOSSI item.

The Social/Cultural influence construct appeared in 8 of the 49 (16%) textboxes or questions, the second highest of the remaining constructs. Law/Theory construct had a total of 6 (12%) text boxes/questions, however, participant data showed minimal growth in understanding this construct. This is of little surprise as Theory and Law are often wrongly taught in elementary and middle school grades. Couple this with the use of law and theory in everyday language and the misconceptions become engrained in participants’ minds. Even though two stories, Heat and Conservation of Mass, placed a high amount of emphasis on reversing the misconception – textboxes that detailed the differences between scientific law and theory – participants still held onto their prior conceptions. One example, shown below, may have had an opposite effect on participants who do not understand the meaning of a scientific theory. In the Periodic Table story a text box reads:

Again, note how scientific laws and theories are different, yet related kinds of claims about the natural world. Also not that Mendeleev’s Period law had to be corrected when chemical theory put forward the existence of protons that more accurately explained
chemical periodicity. These chemical theories are now well-established, yet remain theories. All scientific theories, no matter how well established, remain theories. The last line, stating that theories remain theories, may back up a participant’s conception that theories are just ideas people have, and not the explanation of relationships seen in scientific laws. If a participant conceptualizes the word theory to mean an idea or guess, it is understandable that they would still think that law is held in higher regard than theory, as it is in everyday language. It is not surprising that six prompts in two stories did not make a change in participants’ understanding of these deeply ingrained misconceptions. Another language issue that needs to be addressed (p. 40) refers to a story relating scientists as “experimenters”. This language may lead students to infer that science is completed by experimentation only, another misconception of the NOS.

The remaining constructs did not show significant differences between control and treatment groups. Social Interactions tallied 6 (12%) total text boxes/questions; however, many of these prompts related to scientists building or working from one another’s ideas and rarely highlighted true social interactions among scientists. The prompts frequently conferred that rarely scientists worked alone. However, every picture featured in the three stories further backed the misconception that scientists work in isolation. Both Tentativeness and Time were rarely featured in the textboxes and questions, three and two times respectively. It is reasonable to believe that the low number of prompts dealing with Time and Tentativeness may have led to lack of significant difference in the treatment groups. A final reason for a lack of significance is speculated to be from the influence of first-semester instruction. The instructor did teach explicitly NOS concepts during the first semester of the school year. This may have influenced
both Chemistry and General Chemistry participants, causing control and treatment group scores to be not significantly different from one another.

**Discussion of Research Question 1b**

It has been discussed that participants were able to cite story examples when explaining their NOS conceptions in the written responses, but had greater results verbalizing references during the interview. It is speculated that the level of interest in the story may have helped participants remember portions of what they read, as they found it interesting. Further detail was gained by reviewing participant responses to the *Interest/Attitude Survey II*. Participants in General Chemistry and Chemistry stated they liked learning about the development of science ideas and liked seeing the human side of science as well. Student comments made on the written prompt also shed light on this idea:

“Reading it in story form made it easier to remember things from it than just taking notes over it. I like to take notes, but I liked the stories better.” GC

“I liked hearing about how scientists came up with ideas and how unique they were.” GC

“I liked the history involved and learning about the dudes behind the ideas.” GC

“What I liked most was that I was able to gain some background knowledge on the ideas and what not. It wasn't just some more info being pounded into my head.” GC

“I suppose I liked these readings because talking about them helped me learn more about what was in our unit. The readings gave a lot of history and information that helped me understand concepts better.” GC

“I enjoyed learning about how scientists come up with their ideas and how they work on them. Also on how scientists have worked together over time to come up with their current ideas that we have now.” C

“It was interesting finding out how science actually started and how we got here today.” C
Conclusion and Recommendation for Further Study

The results of this study suggest that the use of historical short stories was more successful with higher level Chemistry participants in comparison to lower level General Chemistry participants. However, that at least one NOS concept had a significant increase with both groups in Imagination and Creativity, a NOS idea often overtly addressed in the treatment stories, is worth noting. Redesigning the stories to include more text boxes and questions aimed at the remaining NOS constructs may help increase treatment scores as well. Additionally, adding pictures of scientists collaborating together may help increase participants’ understanding of social interactions between scientists. This study was limited by its size and scope, therefore increased sample size, length of intervention, and frequency of treatment stories should be addressed in future studies.

The lack of significant difference between participants in the General Chemistry treatment and control groups leaves several questions to be answered. What modifications need to be made to accommodate for lower level participants? Did the use of a highly contextualized video that implicitly discussed NOS conceptions impact the results? Questions on the Interest and Attitude survey should be modified to extract greater detail of information by changing: “reading is boring” to “I find science readings to be boring” and “I find understanding what I read difficult” to “I find most science readings are difficult to understand”. Participants reported that reading is “not boring” and indicated it as an “easy” task; however, many indicated they disliked reading the science stories. The issue may very well be with the difficulty of understanding the counter-intuitive nature of scientific thinking and science ideas, and the concomitant mental effort demanded. These and other changes to the Interest and Attitude
Survey questions and interview protocol may help more accurately identify what the underlying issue is with students’ attitudes toward the science stories.

Future studies should be completed during the first semester or over an entire year of school. First-semester studies would limit control participants from explicit and reflective NOS instruction that may take place with informed instructors. Semester long studies are limited in the number of stories that can be utilized; therefore a yearlong study may yield greater information into the effect of the stories on treatment participants’ NOS views.
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Herman, B.C., Clough, M.P., & Olson, J.K. (2011). Inservice teachers’ NOS teaching practices and factors from their preservice program that account for those practices. Paper presented at the Association for Science Teacher Education (ASTE) National Conference, Minneapolis, MN.


Munby 1976


APPENDIX A.1

INFORMED CONSENT DOCUMENT

Title of Study: Short Stories as Nature of Science Instruction in Secondary Science

Investigators: Jennifer A. R. Smith, M.S.
               Garrett Hall, B.S.
               Michael P. Clough, Ph.D.

FOR PARENTS:
This document describes a study your child is being asked to take part in. Please read through this document and sign it if you agree to allow your child to participate.

FOR STUDENTS:
This is a research study. Please take your time in deciding if you would like to participate. Please feel free to ask questions at any time.

INTRODUCTION
Understanding the nature of science (what science is and how it works) is an acknowledged goal of an effective science education. You are being invited to participate in this study because you are a student in a science course where emphasis is placed on understanding the nature of science. The purpose of this study is to determine how instruction that includes the use of historical science short stories in a secondary science course influences students’ understanding of the nature of science.

DESCRIPTION OF PROCEDURES
During the 2011-2012 school year, your science teacher will have you complete a nature of science questionnaire and an attitude survey as classroom activities to help inform their teaching decisions. Participation in this study means that your scores on a nature of science questionnaire and the interest/attitude survey may be used for data analysis in our research. The content of the course will in no way be altered by this study; all homework, quizzes, tests, lectures, laboratory activities and other classroom activities, including the questionnaire, are designed to meet pre-determined learning objectives for the course.

RISKS
No foreseeable risks exist for participation in the study.

BENEFITS
If you decide to participate in this study there may be no direct benefit to you. It is hoped that the historical science short stories will improve students’ understanding of the nature of science, and that the information gained in this study will benefit society by improving future secondary school science instruction regarding the nature of science.

COSTS AND COMPENSATION
You will not have any costs from participating in this study. You will not be compensated for participation in this research.
CONFIDENTIALITY
Records identifying participants will be kept confidential to the extent allowed by applicable laws and regulations. Records will not be made publicly available. However, federal government regulatory agencies, auditing departments of Iowa State University, and the ISU Institutional Review Board (a committee that reviews and approves research studies with human subjects) may inspect and/or copy your records for quality assurances and analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken: All information collected from teachers will be identified with pseudonyms to protect the identity of participating teachers, students, and schools. Once pre and post surveys are correlated, students’ names will be cut off of the surveys and replaced with a number. Only researchers involved with this study will have access to the data collected. All data will be kept in password protected computer files and/or locked file cabinets. If the results are published, your identity will remain confidential.

VOLUNTARY PARTICIPATION
Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences. Your science course grade and class participation will in no way be affected by your decision to participate or not to participate in this study.

QUESTIONS OR CONCERNS
We openly invite your questions and concerns. Please feel free to contact us at the numbers listed below if you have questions at any time.

Jennifer Smith, Iowa State University, Ames, IA (515) 250-5845
Dr. Michael Clough, Iowa State University, Ames, IA (515) 294-1430
Garrett Hall, Southeast Polk Senior High, Pleasant Hill, IA (515) 967-6631 ext 2389

Iowa State University, Ames, IA

If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, 1138 Pearson Hall, Iowa State University, Ames, Iowa 50011.

***************************************************************************
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PARTICIPANT SIGNATURE

Your signature indicates that you voluntarily agree to participate (or not) in this study, that the study has been explained to you, that you have been given the time to read the document
and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Please mark one box below and then sign:

☐ I agree to participate in this study. My survey data may be used for research purposes.

☐ I do not agree to participate in this study. Do not use my survey data for research purposes.

If you do not agree to participate, what is your reason? __________________________________________

________________________________________

________________________________________

Participant’s Name (printed) __________________________

________________

(Participant’s Signature)  (Date)

________________

(Signature of Parent/Guardian or Legally Authorized Representative)  (Date)
APPENDIX A.2

INFORMED CONSENT DOCUMENT

Title of Study: Impact of Historical Science Short Stories on Students’ Attitudes and NOS Understanding

Investigators: Garrett Hall, B.S.
             Jennifer A. R. Smith, M.S.
             Michael P. Clough, Ph.D.

FOR PARENTS:
This document describes a study your child is being asked to take part in. Please read through this document and sign it if you agree to allow your child to participate.

FOR STUDENTS:
This is a research study. Please take your time in deciding if you would like to participate. Please feel free to ask questions at any time.

INTRODUCTION: Understanding the nature of science (what science is and how it works) is an acknowledged goal of an effective science education. You are being invited to participate in this study because you are a student in a science course where emphasis is placed on understanding the nature of science and science short stories were used as class activities. The purpose of this study is to determine how instruction that includes the use of historical science short stories in a secondary science course influences students’ understanding of the nature of science.

DESCRIPTION OF PROCEDURES: During the 2011-2012 school year, your science teacher had you complete a nature of science questionnaire and an attitude survey as classroom activities to help inform their teaching decisions. Participation in this study means that your scores on a nature of science questionnaire and the interest/attitude survey may be used for data analysis in our research. Your teacher would like to interview you and discuss your responses to the surveys you filled out in class. The interview will consist of questions based around your experiences with the stories and your responses to the survey items. This is strictly voluntary and you can opt out of the interview at any time. The interview will last approximately 30 minutes and will be conducted before or after school. Your teacher is extremely interested in using these stories and your opinions of the stories. To ensure accuracy, interviews will be audio-recorded. Recordings will not contain student names and will be erased after they are transcribed to a written format.

RISKS: No foreseeable risks exist for participation in the study.

BENEFITS: If you decide to participate in this study there may be no direct benefit to you. It is hoped that the historical science short stories will improve students’ understanding of the nature of science, and that the information gained in this study will benefit society by improving future secondary school science instruction regarding the nature of science.
COSTS AND COMPENSATION: You will not have any costs from participating in this study. You will not be compensated for participation in this research.

CONFIDENTIALITY: Records identifying participants will be kept confidential to the extent allowed by applicable laws and regulations. Records will not be made publicly available. However, federal government regulatory agencies, auditing departments of Iowa State University, and the ISU Institutional Review Board (a committee that reviews and approves research studies with human subjects) may inspect and/or copy your records for quality assurances and analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken: All information collected will be identified with pseudonyms to protect the identity of participating teachers, students, and schools. Once pre and post surveys are correlated, students’ names will be cut off of the surveys and replaced with a number. Audio recordings of interviews will not contain student names and will be erased once they are transcribed to a written form. All recordings will be erased no later than September 1, 2012. Only researchers involved with this study will have access to the data collected. All data will be kept in password protected computer files and/or locked file cabinets. If the results are published, a pseudonym will be used and your identity will remain confidential.

VOLUNTARY PARTICIPATION: Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences. Your science course grade and class participation will in no way be affected by your decision to participate or not to participate in an interview for this study.

QUESTIONS OR CONCERNS: We openly invite your questions and concerns. Please feel free to contact us at the numbers listed below if you have questions at any time.

Garrett Hall, Southeast Polk Senior High, Pleasant Hill, IA (515) 967-6631 ext 2389
Jennifer Smith, Iowa State University, Ames, IS (515) 250-5845
Dr. Michael Clough, Iowa State University, Ames, IA (515) 294-1430

If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, 1138 Pearson Hall, Iowa State University, Ames, Iowa 50011.

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PARTICIPANT SIGNATURE
Your signature indicates that you voluntarily agree to participate (or not) in this study, that the study has been explained to you, that you have been given the time to read the document and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

I agree to participate in this study. If I am chosen to participate in an interview, my data may be used for research purposes.

Participant’s Name (printed) ________________________________

____________________________________________________

(Participant’s Signature) (Date)

____________________________________________________

(Signature of Parent/Guardian or Legally Authorized Representative) (Date)
APPENDIX B.1

Views on Science and Scientific Inquiry – For Chemistry Classes (Pre)

Please read EACH statement carefully, and then indicate the degree to which you agree or disagree with EACH statement by circling the appropriate choice to the right of each statement.

SD = Strongly Disagree
D = Disagree More Than Agree
U = Uncertain or Not Sure
A = Agree More Than Disagree
SA = Strongly Agree

1. Social and Cultural Influences on Science:

<table>
<thead>
<tr>
<th></th>
<th>Scientific research is not influenced by society and culture because scientists are trained to conduct pure, unbiased studies.</th>
<th>SD</th>
<th>D</th>
<th>U</th>
<th>A</th>
<th>SA</th>
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<tr>
<td>A.</td>
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<tr>
<td>B.</td>
<td>Cultural values and expectations influence what science is conducted and accepted.</td>
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<tr>
<td>C.</td>
<td>Cultural values and expectations influence how science is conducted and accepted.</td>
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<tr>
<td>D.</td>
<td>All cultures conduct scientific research the same way because science is universal and independent of society and culture.</td>
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</table>

Explain how society and culture affect OR do not affect scientific research, and provide examples to support your answer.
2. Imagination and Creativity in Scientific investigations:

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</thead>
<tbody>
<tr>
<td>A.</td>
<td>Scientists use their imagination and creativity when they collect data.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>B.</td>
<td>Scientists use their imagination and creativity when they analyze and interpret data.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>C.</td>
<td>Scientists do not use their imagination and creativity because these conflict with their logical reasoning.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
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<tr>
<td>D.</td>
<td>Scientists do not use their imagination and creativity because these can interfere with the need to be unbiased.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
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</table>

Explain why scientists use OR do not use imagination and creativity, and provide examples to support your answer.

3. Social Interaction among Scientific Researchers:

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<tbody>
<tr>
<td>A.</td>
<td>Scientists usually work collaboratively with other scientists when conducting research.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
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<tr>
<td>B.</td>
<td>Scientists usually work with other scientists, but only to share results.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>C.</td>
<td>Scientists usually work alone when conducting research.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>D.</td>
<td>Scientific knowledge usually emerges from discussions and social interactions among scientists.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
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</table>

Explain to what degree scientists work with other scientists when doing research, and provide examples to support your answer.
4. Development and Acceptance of Science Ideas:

<p>| | |</p>
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<tbody>
<tr>
<td>A.</td>
<td>Credible scientific ideas are <em>usually</em> generated in a matter of days, weeks or months.</td>
</tr>
<tr>
<td>B.</td>
<td>Scientific ideas <em>usually</em> come to be accepted by the scientific community in a matter of days, weeks or months.</td>
</tr>
<tr>
<td>C.</td>
<td>Credible scientific ideas are <em>usually</em> generated over a period of years to decades.</td>
</tr>
<tr>
<td>D.</td>
<td>Scientific ideas <em>usually</em> come to be accepted by the scientific community over a period of years to decades.</td>
</tr>
</tbody>
</table>

Explain how much time is *usually* required for credible scientific ideas to be generated, and then accepted by the scientific community, and *provide examples to support your answer.*

5. Scientific Knowledge:

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>A.</td>
<td>Well supported and established scientific knowledge is subject to on-going testing and revision.</td>
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<td>Well supported and established scientific knowledge may be completely replaced by new ideas in light of new evidence.</td>
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<td>C.</td>
<td>Well supported and established scientific knowledge may be changed because scientists reinterpret existing evidence.</td>
</tr>
<tr>
<td>D.</td>
<td>Well supported and established scientific knowledge based on accurate research will not change.</td>
</tr>
</tbody>
</table>

Explain why you think well supported and established scientific knowledge changes OR does not change over time, and *provide examples to support your answer.*
10. Scientific Laws Compared to Theories:

<table>
<thead>
<tr>
<th></th>
<th>Scientific theories exist in the natural world and are uncovered through scientific investigations.</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>B.</td>
<td>Unlike theories, scientific laws are not subject to change.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td>C.</td>
<td>Scientific laws are theories that have been proven.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td>D.</td>
<td>Scientific theories explain scientific laws.</td>
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</tbody>
</table>

Explain what scientific theories and laws are and how they are different, and provide examples to support your answer.

Please explain any problems you had answering the survey questions above. This may include wording you did not understand, answer choices that didn’t make sense to you, or questions you didn’t know how to answer. Your comments below will help us prepare better questions for future students if needed. Your honest feedback is much appreciated.
APPENDIX B.2

Views on Science and Scientific Inquiry – For Chemistry Classes (POST)

Please read EACH statement carefully, and then indicate the degree to which you agree or disagree with EACH statement by circling the appropriate choice to the right of each statement.

SD  =  Strongly Disagree  
D   =  Disagree More Than Agree  
U   =  Uncertain or Not Sure  
A   =  Agree More Than Disagree  
SA  =  Strongly Agree

1. Social and Cultural Influences on Science:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>SD</th>
<th>D</th>
<th>U</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Scientific research is not influenced by society and culture because scientists are trained to conduct pure, unbiased studies.</td>
<td></td>
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<tr>
<td>B.</td>
<td>Cultural values and expectations influence what science is conducted and accepted.</td>
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<tr>
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<td>Cultural values and expectations influence how science is conducted and accepted.</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>D.</td>
<td>All cultures conduct scientific research the same way because science is universal and independent of society and culture.</td>
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</table>

Explain how society and culture affect OR do not affect scientific research, and provide examples to support your answer.
2. Imagination and Creativity in Scientific investigations:

<p>| | | | | |</p>
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<tbody>
<tr>
<td>A.</td>
<td>Scientists use their imagination and creativity when they collect data.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>B.</td>
<td>Scientists do not use their imagination and creativity because these conflict with their logical reasoning.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>C.</td>
<td>Scientists do not use their imagination and creativity because these can interfere with the need to be unbiased.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
</tbody>
</table>

Explain why scientists use OR do not use imagination and creativity, and provide examples to support your answer.

3. Social Interaction among Scientific Researchers:

<p>| | | | | |</p>
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</thead>
<tbody>
<tr>
<td>A.</td>
<td>Scientists usually work collaboratively with other scientists when conducting research.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>B.</td>
<td>Scientists usually work with other scientists, but only to share results.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>C.</td>
<td>Scientists usually work alone when conducting research.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>D.</td>
<td>Scientific knowledge usually emerges from discussions and social interactions among scientists.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
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</table>

Explain to what degree scientists work with other scientists when doing research, and provide examples to support your answer.
4. Development and Acceptance of Science Ideas:

<table>
<thead>
<tr>
<th></th>
<th>Credible scientific ideas are usually generated in a matter of days, weeks or months.</th>
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<th>D</th>
<th>U</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Scientific ideas usually come to be accepted by the scientific community in a matter of days, weeks or months.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
<tr>
<td>B</td>
<td>Credible scientific ideas are usually generated over a period of years to decades.</td>
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<td>U</td>
<td>A</td>
<td>SA</td>
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<tr>
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<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
</tbody>
</table>

Explain how much time is usually required for credible scientific ideas to be generated, and accepted by the scientific community, and provide examples to support your answer.

5. Scientific Knowledge:

<table>
<thead>
<tr>
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<th>Well supported and established scientific knowledge is subject to on-going testing and revision.</th>
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Explain why you think well supported and established scientific knowledge changes OR does not change over time, and provide examples to support your answer.
10. Scientific Laws Compared to Theories:

A. Scientific theories exist in the natural world and are uncovered through scientific investigations.  SD  D  U  A  SA

B. Unlike theories, scientific laws are not subject to change.       SD  D  U  A  SA

C. Scientific laws are theories that have been proven.          SD  D  U  A  SA

D. Scientific theories explain scientific laws.             SD  D  U  A  SA

Explain what scientific theories and laws are and how they are different, and provide examples to support your answer.
APPENDIX C.1

Interest/Attitude Survey Part I

Your honest feedback on this survey would be very helpful and much appreciated. This information will be used to understand you as a learner and your interest and attitudes towards class activities utilized in this course.

Please carefully read and answer each survey questions below. Be sure all your answers are clearly marked or written. Your answers to these survey questions should reflect your own honest opinions. There are no right or wrong answers.

1. Please mark an X in ONLY ONE BOX to indicate for which course you are completing this survey.
   - Biology
   - Chemistry

2. Please read statements A - Y below. Mark an X in ONLY ONE BOX to indicate your level of agreement with each statement.

   A. I find reading enjoyable.
      - Completely Disagree
      - Somewhat Disagree
      - Neutral
      - Somewhat Agree
      - Completely Agree

   B. Developing my own experiments in science class is a waste of time.
      - Completely Disagree
      - Somewhat Disagree
      - Neutral
      - Somewhat Agree
      - Completely Agree

   C. If I do poorly on a test, it is likely because I didn’t work hard enough to prepare.
      - Completely Disagree
      - Somewhat Disagree
      - Neutral
      - Somewhat Agree
      - Completely Agree

   D. I find reading difficult.
      - Completely Disagree
      - Somewhat Disagree
      - Neutral
      - Somewhat Agree
      - Completely Agree

   E. I learn better when we do a hands-on activity before a teacher explains a science idea.
      - Completely Disagree
      - Somewhat Disagree
      - Neutral
      - Somewhat Agree
      - Completely Agree

   F. Successful students understand things in class quickly.
      - Completely Disagree
      - Somewhat Disagree
      - Neutral
      - Somewhat Agree
      - Completely Agree

   G. When learning science, I want to understand how scientists developed science ideas.
      - Completely Disagree
      - Somewhat Disagree
      - Neutral
      - Somewhat Agree
      - Completely Agree
### H. Reading is boring.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### I. When learning science, I only want to be told what facts I need to know for the tests.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### J. The really smart students don’t have to work hard to do well in school.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### K. Reading is beneficial to me.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### L. When learning science, I want to understand how to use the information we learn about.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### M. If I do poorly on a test, it is likely the ideas were just too hard for me.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### N. I enjoy reading outside of class-work and assignments.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### O. When learning new information, relating it to experiences outside of class helps me.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### P. Students who are “average” in school will remain “average” for the rest of their lives.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### Q. Coming up with my own ways to solve problems in science class is a waste of time.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### R. I find understanding what I read difficult.

| | | | | | |
|---|---|---|---|---|
| Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree |

### S. I want to learn about the people who developed the ideas we learn in science class.

| | | | | | |
|---|---|---|---|---|
| | | | | |
T. If I do well on a test, most likely I was just lucky.

Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree

U. Students should be tested on their understanding of not only science ideas, but also how scientists came to understand those ideas.

Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree

V. Reading does not help me learn.

Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree

W. The harder I work at preparing for a test, the more likely I am going to do well.

Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree

X. I learn science best by memorizing information.

Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree

Y. If I do poorly on a test, it is likely the teacher did not teach well.

Completely Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Completely Agree

3. To what degree are you interested in a science-related career?
Mark an X in ONLY ONE BOX to indicate your level of interest.

- I have absolutely no interest at all in a science-related career.
- I have very little interest in a science-related career.
- I am completely undecided about my interest in a science-related career.
- I am considering a science or science-related career.
- I am absolutely sure I want to pursue a science-related career.

4. Please explain why you are or are not interested in a science-related career in the space below.
5. Please explain any problems you had answering the survey questions above. This may include wording you did not understand, answer choices that didn’t make sense to you, or questions you didn’t know how to answer. Your comments below will help us prepare better questions for future students if needed. Your honest feedback is much appreciated.
APPENDIX C.2

Interest/Attitude Survey Part 2 (Chemistry Version)

This semester your class activities included several readings regarding scientists and how science ideas came to be accepted. Your honest feedback regarding these experiences would be very helpful and much appreciated.

Please carefully read and answer each survey questions below. Be sure all your answers are clearly marked.

6. The readings your teacher utilized this semester may have included:
   • A reading about matter
   • A reading about the conservation of Mass
   • A reading about development of our understanding of atomic structure
   • A reading about the development of periodic table
   • A reading about the development of a temperature scale
   • A reading about our understanding of heat
   • A reading about entropy

   Overall, how interesting did you find this group of readings?
   Mark an X in ONLY ONE BOX.
   □ extremely uninteresting  □ somewhat uninteresting  □ neutral  □ somewhat interesting  □ extremely interesting

7. Please explain what you liked about these readings:

8. Please explain what you did not like about these readings:
9. To what extent did the readings portray doing science as more interesting than you previously thought? Mark an X in ONLY ONE BOX.

- [ ] Much less interesting
- [ ] Somewhat less interesting
- [ ] No more or less interesting
- [ ] Somewhat more interesting
- [ ] Much more interesting

10. To what extent did the readings increase your interest in the science content in the stories? Mark an X in ONLY ONE BOX.

- [ ] Greatly decreased my interest
- [ ] Somewhat decreased my interest
- [ ] No impact on my interest
- [ ] Somewhat increased my interest
- [ ] Greatly increased my interest

11. How interesting did you find these readings compared to readings from a science textbook or other typical class readings? Mark an X in ONLY ONE BOX.

- [ ] much less interesting
- [ ] somewhat less interesting
- [ ] equally interesting/uninteresting
- [ ] somewhat more interesting
- [ ] much more interesting

12. If stories similar to the readings used this semester were to replace class textbook readings (or other readings typically used in your science class), approximately what percentage of textbook readings would you like replaced? Mark an X in ONLY ONE BOX.

- [ ] 0% (I would prefer this type of readings not replace any textbook readings.)
- [ ] 25% (I would prefer this type of reading only occasionally replace textbook readings.)
- [ ] 50% (I would prefer this type of reading replace about half the textbook readings.)
- [ ] 75% (I would prefer this type of reading replace most of the textbook readings.)
- [ ] 100% (I would prefer this type of reading replace all textbook readings for the course.)

13. Learning about how science works and how scientific ideas are developed and become accepted is a goal of science education. How important do you think this goal is for high school science classes? Mark an X in ONLY ONE BOX.
This should not be a goal of HS science classes.
This goal should be of little importance in HS science classes.
This goal should be somewhat important in HS science classes.
This goal should be important in HS science classes.
This goal should be extremely important in HS science classes.

14. Mark an X in ONLY ONE BOX to indicate your level of agreement with the following statement:

These stories helped me reach the goal of understanding how science works and how scientific ideas are developed and become accepted.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

15. Please read statements A - Y below. Mark an X in ONLY ONE BOX to indicate your level of agreement with each statement.

A. I find reading enjoyable.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

B. Developing my own experiments in science class is a waste of time.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

C. If I do poorly on a test, it is likely because I didn’t work hard enough to prepare.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

D. I find reading difficult.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

E. I learn better when we do a hands-on activity before a teacher explains a science idea.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

F. Successful students understand things in class quickly.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

G. When learning science, I want to understand how scientists developed science ideas.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

H. Reading is boring.
I. When learning science, I only want to be told what facts I need to know for the tests.

J. The really smart students don’t have to work hard to do well in school.

K. Reading is beneficial to me.

L. When learning science, I want to understand how to use the information we learn about.

M. If I do poorly on a test, it is likely the ideas were just too hard for me.

N. I enjoy reading outside of class-work and assignments.

O. When learning new information, relating it to experiences outside of class helps me.

P. Students who are “average” in school will remain “average” for the rest of their lives.

Q. Coming up with my own ways to solve problems in science class is a waste of time.

R. I find understanding what I read difficult.

S. I want to learn about the people who developed the ideas we learn in science class.

T. If I do well on a test, most likely I was just lucky.
U. Students should be tested on their understanding of not only science ideas, but also how scientists came to understand those ideas.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

V. Reading does not help me learn.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

W. The harder I work at preparing for a test, the more likely I am going to do well.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

X. I learn science best by memorizing information.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

Y. If I do poorly on a test, it is likely the teacher did not teach well.

- [ ] Completely Disagree
- [ ] Somewhat Disagree
- [ ] Neutral
- [ ] Somewhat Agree
- [ ] Completely Agree

16. To what degree are you interested in a science-related career?
Mark an X in ONLY ONE BOX to indicate your level of interest.

- [ ] I have absolutely no interest at all in a science-related career.
- [ ] I have very little interest in a science-related career.
- [ ] I am completely undecided about my interest in a science-related career.
- [ ] I am considering a science or science-related career.
- [ ] I am absolutely sure I want to pursue a science-related career.

17. Please explain why you are or are not interested in a science-related career in the space below.
18. Please explain any problems you had answering the survey questions above. This may include wording you did not understand, answer choices that didn’t make sense to you, or questions you didn’t know how to answer. Your comments below will help us prepare better questions for future students if needed. Your honest feedback is much appreciated.
# Interest/Attitude Survey Part 2

Please carefully read and answer each survey questions below. Be sure all your answers are clearly marked.

1. Please read statements A – Y below. Mark an X in **ONLY ONE BOX** to indicate your level of agreement with each statement.

<p>| | | | |</p>
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<td>If I do poorly on a test, it is likely because I didn’t work hard enough to prepare.</td>
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<td>I find reading difficult.</td>
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</tr>
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<td></td>
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<td>I learn better when we do a hands–on activity before a teacher explains a science idea.</td>
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<td>H.</td>
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<td>J</td>
<td><strong>The really smart students don’t have to work hard to do well in school.</strong></td>
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<td>K</td>
<td><strong>Reading is beneficial to me.</strong></td>
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<td></td>
<td>Completely Disagree</td>
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<td>L</td>
<td><strong>When learning science, I want to understand how to use the information we learn about.</strong></td>
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<td></td>
<td>Completely Disagree</td>
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<td>M</td>
<td><strong>If I do poorly on a test, it is likely the ideas were just too hard for me.</strong></td>
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<td></td>
<td>Completely Disagree</td>
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<td>N</td>
<td><strong>I enjoy reading outside of class-work and assignments.</strong></td>
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<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
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<td>O</td>
<td><strong>When learning new information, relating it to experiences outside of class helps me.</strong></td>
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<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
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<td>P</td>
<td><strong>Students who are “average” in school will remain “average” for the rest of their lives.</strong></td>
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<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
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<tr>
<td>Q</td>
<td><strong>Coming up with my own ways to solve problems in science class is a waste of time.</strong></td>
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<tr>
<td></td>
<td>Completely Disagree</td>
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<td>R</td>
<td><strong>I find understanding what I read difficult.</strong></td>
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<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
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</table>
S. I want to learn about the people who developed the ideas we learn in science class.

- Completely Disagree
- Somewhat Disagree
- Neutral
- Somewhat Agree
- Completely Agree

T. If I do well on a test, most likely I was just lucky.

- Completely Disagree
- Somewhat Disagree
- Neutral
- Somewhat Agree
- Completely Agree

U. Students should be tested on their understanding of not only science ideas, but also how scientists came to understand those ideas.

- Completely Disagree
- Somewhat Disagree
- Neutral
- Somewhat Agree
- Completely Agree

V. Reading does not help me learn.

- Completely Disagree
- Somewhat Disagree
- Neutral
- Somewhat Agree
- Completely Agree

W. The harder I work at preparing for a test, the more likely I am going to do well.

- Completely Disagree
- Somewhat Disagree
- Neutral
- Somewhat Agree
- Completely Agree

X. I learn science best by memorizing information.

- Completely Disagree
- Somewhat Disagree
- Neutral
- Somewhat Agree
- Completely Agree

Y. If I do poorly on a test, it is likely the teacher did not teach well.

- Completely Disagree
- Somewhat Disagree
- Neutral
- Somewhat Agree
- Completely Agree

2. Learning about how science works and how scientific ideas are developed and become accepted is a goal of science education. How important do you think this goal is for high school science classes? Mark an X in ONLY ONE BOX.

- This should not be a goal of HS science classes.
- This goal should be of little importance in HS science classes.
This goal should be somewhat important in HS science classes.
This goal should be important in HS science classes.
This goal should be extremely important in HS science classes.

3. To what degree are you interested in a science-related career?
Mark an X in ONLY ONE BOX to indicate your level of interest.

☐ I have absolutely no interest at all in a science-related career.
☐ I have very little interest in a science-related career.
☐ I am completely undecided about my interest in a science-related career.
☐ I am considering a science or science-related career.
☐ I am absolutely sure I want to pursue a science-related career.

4. Please explain why you are or are not interested in a science-related career in the space below.

5. Please explain any problems you had answering the survey questions above. This may include wording you did not understand, answer choices that didn’t make sense to you, or questions you didn’t know how to answer. Your comments below will help us prepare better questions for future students if needed. Your honest feedback is much appreciated.
APPENDIX D

A Puzzle with Many Pieces: Development of the Periodic Table

Pre-reading Questions:
Most everyone recognizes the periodic table of chemical elements. The table is commonly found on science classroom walls, in science textbooks, and sometimes on t-shirts and other everyday items. The periodic table has come to symbolize chemistry.

1. What might be the important value of the periodic table?
2. In what ways, if any, do you think creativity plays a role in scientific work?

For centuries humans have studied chemical substances, their properties, and how they react. However, the insight that resulted in early versions of the periodic table occurred only over the last 150 years. The development of the periodic table illustrates that patterns in nature are often not straightforward or obvious.

Note that doing science well requires significant collaboration with others. This challenges the image of the scientist toiling alone in a laboratory. Science is not the solitary undertaking that many people think.

In the early 1800s, chemists knew about the existence of elements, and often printed lists of the known elements alongside the most current measurements of their atomic weights. Chemists also knew that some elements had similar chemical properties. For example, chlorine, fluorine and bromine behaved similarly in chemical reactions, while sodium, potassium and lithium also had many similar properties.

However, no one had the insight that the chemical elements might be ordered in a way that could link their chemical and physical properties in a meaningful pattern. A major reason for this was that in the early 1800s, no standardized system of atomic weights existed. Some chemists thought that oxygen had an atomic weight of 8; some thought it had an atomic weight of 16. Similar arguments existed over the weight of hydrogen, carbon, and most metals. These disagreements resulted in a great deal of confusion about the formulas for chemical compounds. In the 1840s, over 100 published formulas for acetic acid (the compound we now know as CH₃COOH) existed. Because chemists did not agree on the atomic weights of the elements, the difficulty they experienced in creating an organizational scheme for chemical elements based on both their weight and their chemical properties is not surprising.

In 1860, 150 of the most prominent chemists in Europe gathered in Germany to discuss how they could make their atomic weights and chemical terminology more consistent. August Kekulé, a respected young German chemist, convened the conference in order to resolve some of the issues in chemistry that he thought were creating confusion and holding back the development of new chemical ideas. Chemists from almost every European country traveled to Germany in order to discuss how they might standardize their systems of atomic weights.

During the conference, an Italian chemist, named Stanislao Cannizzaro, brought up a long-forgotten idea developed by his fellow Italian Amedeo Avogadro in 1811. Avogadro had argued that equal volumes of gases at the same pressure and the same temperature would contain the same number of molecules. Cannizzaro argued that if chemists accepted Avogadro’s argument as the basis of a new system of atomic weights, they would be able to standardize the weights of elements and calm the confusion that had arisen. Cannizzaro’s suggestion met with widespread support.

Note that nearly a half-century passed before Avogadro’s contribution was identified as a possible solution to the problem of atomic weight standardization. How does this demonstrate that:

(a) creative insight is crucial in science, and
(b) that previous science ideas become useful in unanticipated ways?

The conference was important for establishing a process to standardize atomic weights. But it was also important for another reason: one of the chemists in attendance was a twenty-six-year-old Russian named Dmitrii Mendeleev.
Mendeleev (Figure 1) was impressed with Cannizzaro’s argument in favor of Avogadro’s system. When he returned to Russia in 1861, he was filled with excitement over the developments in chemistry he had seen at the conference.

Figure 1. Dmitrii Mendeleev in 1897

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Dmitrii Ivanovich Mendeleev was born in January 1834 the youngest of 17 children (only eight of whom survived to adulthood). Mendeleev’s father, Ivan, was a teacher at the local gymnasium (what we would now call a high school). After Mendeleev graduated from the local gymnasium in 1850, he enrolled at St. Petersburg’s Chief Pedagogical Institute, where his father had become educated as a teacher. Mendeleev studied at the Chief Pedagogical Institute until 1855, where many distinguished professors encouraged his interest in chemistry. After finishing his degree, Mendeleev briefly taught secondary school. He was unhappy there, and in 1859 he accepted a government scholarship to travel to Germany and pursue his interest in chemistry. In the nineteenth century, Germany was unquestionably the center of the chemical world. His studies in Germany also gave him the opportunity to travel to the nearby important chemical conference.

Mendeleev returned to St. Petersburg, and in 1867 he was hired as a professor of chemistry at St. Petersburg University. Mendeleev needed to choose a textbook for the large introductory chemistry class he taught. But Mendeleev was dissatisfied with the available texts. At that time, chemistry was a rapidly advancing field. Most of the available textbooks were translations of German textbooks, and by the time the translations were finished the original books were already out of date.

Mendeleev decided to write his own textbook in Russian, based on the latest chemical knowledge. He signed a contract with a Russian publisher promising a two-volume textbook entitled *Principles of Chemistry*. When Mendeleev sent Volume 1 to the publisher in January 1869, he realized he had a problem. At the time, there were 63 known elements. He had only discussed nine of them (hydrogen, carbon, nitrogen, oxygen, sodium, bromine, iodine, fluorine, and chlorine) in Volume 1. How could he possibly discuss all 54 remaining elements in Volume 2?

Mendeleev began considering how he could group the elements together to address them in the second volume of his textbook. He thought about elements that had similar reactive properties—such as sodium and potassium, and wrote the first two chapters on those elements. But Mendeleev was uncertain how to proceed from this point. He wanted to map out a strategy. However, despite working feverishly on his problem the entire weekend with little sleep, Mendeleev had not come up with any sort of pattern that might link groups of elements having similar properties.

That morning, over a cup of tea he turned his attention to mail that had recently arrived. On the back of one letter he eventually began listing several elements in the order of their atomic weights. But this order didn’t explain anything of importance. Mendel then began grouping elements with similar properties, but also noted their atomic weights. For instance, the halogens:

\[
F = 19 \quad Cl = 35 \quad Br = 80 \quad I = 127
\]

The oxygen group of elements:

\[
O = 16 \quad S = 32 \quad Se = 79 \quad Te = 128
\]

And the nitrogen group of elements:

\[
N = 14 \quad P = 41 \quad As = 75 \quad Sb = 122
\]

Within each group, no relationship appeared to exist between the atomic weights. But the writing on the back of the letter shows that Mendeleev then arranged the three groups as follows:

\[
F = 19 \quad Cl = 35 \quad Br = 80 \quad I = 127
\]

\[
O = 16 \quad S = 32 \quad Se = 79 \quad Te = 128
\]

\[
N = 14 \quad P = 41 \quad As = 75 \quad Sb = 122
\]
This task was not as straightforward as it may seem. Mendeleev had to make judgments regarding similarities and differences between elements, and group them in a manner that made sense to him. He then noticed that with the exception of P and Te, each element descended by atomic weight. This didn’t make any sense to Mendeleev, but he gambled that what was emerging to him was not simply coincidental. He continued trying to make sense of the pattern he had developed.

On 17 February 1869, Mendeleev first printed and circulated a table (Figure 2) that he entitled “An Attempt at a System of Elements, Based on Their Atomic Weight and Chemical Affinity.” Two weeks later Mendeleev published a paper titled “A Suggested System of the Elements” containing his periodic table (Figure 3).

At first, Mendeleev thought his system of organizing the elements was simply a useful teaching tool. But as he thought about and investigated the chemical properties of various elements in the table, he became convinced that his system was, in fact, a law of nature. In 1870, Mendeleev described the **law of periodicity** --- many of the physical and chemical properties of the elements tend to recur in a systematic manner with increasing atomic weight.

As you read the story of the development of the periodic table, note that scientific laws and theories are different forms of knowledge. Both make claims about the natural world. Scientific laws, like Mendeleev’s Periodic Law, state invariable relationships in nature. Scientific theories explain those relationships. Because they are different types of the knowledge, a theory never becomes a law and a law never becomes a theory.
Prior to Mendeleev’s announcement, others had also been working to make sense of the known elements. One notable success of Mendeleev’s system is that it accounted for partial patterns suggested previously by other chemists. However, even Mendeleev acknowledged that several anomalies appeared in his organizational structure. In some cases, atomic weights did not fit the ascending order in his table, but Mendeleev simply questioned the reliability of the previously determined values. In cases where no known elements appeared to fit his organizational scheme, Mendeleev left gaps in the table. His gaps boldly predicted that those elements did exist and would one day be isolated with properties fitting appropriately between the already known elements in his table.

Mendeleev’s claim that his periodic system was a law of the natural world was met with significant skepticism. Critics kept pointing to the many holes Mendeleev had left in his Table. However, Mendeleev saw the same holes as a strength of his Periodic Law because he could make predictions with it.

Scientific laws state invariable relationships in nature. In this case, Mendeleev’s Law of Periodicity describes the relationship between atomic weight and an element’s chemical and physical properties.

5. Why might a scientific law’s ability to make accurate predictions be considered a strength?

In 1871 Mendeleev predicted the existence of three previously unknown elements. He called these elements eka-boron, eka-aluminum, and eka-silicon. Eka-boron, he said, would be an element with an atomic weight of 44 with chemical properties like those of boron. Eka-aluminum would have an atomic weight of 68, and eka-silicon would have an atomic weight of 73.

In August 1875, a French chemist named Paul Émile Lecoq de Boisbaudran was analyzing a metal from a mine in the French Pyrenees, and noticed a line on its spectrum that did not correspond to any known element. Lecoq de Boisbaudran called this new element “gallium.” When news of the discovery of gallium spread through the chemical world, Mendeleev announced that his prediction had been confirmed—gallium was the element he had called “eka-aluminum.”

This was convincing evidence of Mendeleev’s claim that his periodic law could make scientific predictions. But, many chemists wondered whether eka-aluminum had simply been a lucky guess. What about the other two elements Mendeleev had predicted?

In 1879, a Swedish chemist named L.F. Nilsson isolated a rare earth metal that did not correspond to any known element. Nilsson named this new element “scandium.” Scandium’s atomic weight was measured to be 45, and it had many of the chemical properties Mendeleev had predicted for eka-boron. Another Swedish chemist, named Per Cleve, wrote an excited letter to Mendeleev announcing that Nilson had discovered eka-boron, further evidence in support of Mendeleev’s periodic law.

Mendeleev’s third predicted element, eka-silicon, was not discovered for another seven years. In February 1886, the German chemist Clemens Winkler, announced that he had discovered a new mineral in the German mines. He called this element “germanium,” and it had an atomic weight of 73. Winkler was astonished that another chemist had predicted germanium’s existence, and enthusiastically agreed that Mendeleev had indeed developed a scientific law capable of making striking predictions about the chemical elements.

Increasingly, scientists began to accept Mendeleev’s law, that many of the physical and chemical properties of the elements tend to recur in a systematic manner with increasing atomic weight. By 1886, the status of the periodic table, and Mendeleev’s own status as its discoverer, seemed stable. But in the 1890’s, there were many further developments in the understanding of the theory explaining the periodic table—many of which Mendeleev opposed.

In 1894, the Scottish chemist William Ramsay announced the discovery of a new element, “argon.” According to Ramsay, argon was a gas with an atomic weight of 40, placing it between chlorine and potassium. Argon was also inert—it did not react with other elements. Mendeleev was less than enthusiastic about Ramsay’s “argon.” He had not predicted the existence of an element between chlorine and potassium. Ramsay’s argument that argon was inert was also deeply troubling. To Mendeleev, who had based his periodic system around the careful study of the way elements reacted with one another, the idea of an inert element that did not react with anything seemed impossible.
In 1895, Ramsay (Figure 4) discovered another inert gas, helium, with an atomic weight of 4. Eventually, as Mendeleev studied the density and spectra of Ramsay’s new gases, he came to believe that Ramsay had been right. By 1903, in the seventh edition of the Principles, Mendeleev was praising Ramsay’s work as some of the most important recent chemical research, and had created a new place on his periodic table for the “argon group” of inert gases – now called the noble gases.

**Figure 4. William Ramsay in his lab**

Mendeleev was able to make room in his system for Ramsay’s noble gases. However, he was never able to come to terms with another major discovery of the 1890s: radioactivity. In 1896, the French physicist Henri Becquerel discovered that uranium (one of the elements on Mendeleev’s table) could spontaneously emit energy. Two years later, Pierre and Marie Curie discovered two more elements, radium and polonium, both of which were extremely rare, and both of which were also radioactive. The French physicists argued that radioactivity was the result of elements disintegrating.

Mendeleev thought the idea of an element disintegrating was patently absurd. Elements, in his view, were unchanging and indestructible. The idea that one element could turn into a different element sounded more like medieval alchemy than modern science. A visit to the Curies’ laboratory in 1902 did little to change his mind.

Mendeleev also rejected the theory, gaining strength among many chemists and physicists, that atoms might be composed of smaller particles. In 1897, English Physicist J.J. Thompson proposed that cathode rays were made up of particles that were 1000x smaller than a hydrogen atom. Thomson argued that these particles (which came to be called electrons) were the building blocks of atoms. This was yet another theory that seemed to go against everything Mendeleev knew about chemistry, elements, and mass. When he died in 1906, Mendeleev was still denying radioactivity and subatomic particles.

Despite Mendeleev’s thinking that radioactivity and subatomic theory undermined his entire system of chemistry, the new theories did not result in the abandonment of his periodic system of the elements. Instead, the periodic system evolved after his death to incorporate the new theory and an important correction was made to Mendeleev’s Periodic Law. That is, the systematic recurrence of physical and chemical properties is associated with increasing atomic number (i.e. the number of protons in the nucleus), not atomic weight. In 1911, the Dutch scientist Anton van den Broek used the new subatomic theories to re-order the periodic table according to the atomic numbers of the elements, rather than by atomic weight.

In 1914, the English chemist Henry Moseley was able to further demonstrate that each element in the periodic table had a characteristic atomic number, and was able to show that several “new elements” were in fact compounds. Moseley identified seven gaps in the new atomic number periodic table - elements 43, 61, 72, 75, 85, 87, and 91, all of which would be discovered by 1945. (Moseley did not live to see these discoveries; he died in World War I at the age of 26.)

Ernest Rutherford’s discovery of the proton in 1919 and James Chadwick’s discovery of the neutron in 1932 continued to deepen scientists’ understanding of the structure of the atom and why the chemical properties of the elements fall into a periodic pattern. Niels Bohr’s work on the structure of the atom further illuminated why elements in the same column have similar chemical properties: they have the same number of electrons in their outer electron shell.

Mendeleev would no doubt be quite surprised to sit in an introductory chemistry class today and hear that his periodic system of the elements can be explained by studying the subatomic particles that he insisted did not exist!
Mendeleev’s periodic table (Figure 2) doesn’t look much like the modern periodic table (Figure 5), but it uses a similar format. The elements are grouped in order of increasing atomic weight (we use atomic number now) in a way where elements with common properties appear together, in the same columns. You’ll see this type of chart in textbooks and schools all over the world, but it’s not the only way to group the elements.

Many different periodic tables have been developed. There are circular tables (Figure 6), helical tables (Figure 7), three-dimensional tables, and many more. However, all these tables are still periodic. The elements are categorized according to trends in their properties. Thus, while several different ways have been developed to represent the relationship among elements, the modified core of Mendeleev’s period law still pervades all of them.

Many people wrongly think experiments and a step-by-step scientific method are the only routes to good scientific knowledge.

6. How does Mendeleev’s work and important contribution to our understanding of the natural world illustrate that experiments and following a step-by-step scientific method are not the only way to scientific knowledge?
APPENDIX E

Conservation of Mass
The interplay of creativity and collaboration between scientific laws and theories.

Pre-reading Questions:
1. The conservation of mass is a well known and accepted scientific law. Scientists assume to be true when doing their work. Explain, in your own words, what you think the term “conservation of mass” means.
2. Many people think that good science ideas emerge from experimental evidence. What do you think and what are your reasons for your opinion?

But in the 16th century, a new chemical idea arose that cast doubt on the well accepted idea that mass is conserved in chemical reactions. The German chemist and physician Georg Ernst Stahl was seeking to explain why some materials burned, while others did not. Between 1718 and 1723 he developed and clarified the idea that a substance’s ability to burn depended on whether or not it contained phlogiston, the “essence of combustibility.” Stahl thought that phlogiston was a “subtle fluid” — something that could not be measured, but that nonetheless existed.

The idea that phlogiston could not be weighed or measured may appear silly to you. But at this time other things in nature, such as light and heat, were also classified as “subtle fluids”.

According to Stahl, when an object burned, its phlogiston was released into the surrounding air. When the object lost all of its phlogiston, or when the air had absorbed all the phlogiston it could, the burning stopped. Today we might write Stahl’s explanation for what happens when metal and wood are burned like this:

Metal → Metallic Ash + Phlogiston
Wood → Ash + Phlogiston

Thus materials that burned consisted of the resulting physical product and phlogiston. Stahl’s theory went a long way towards explaining why some objects changed when heated and others didn’t, and also explained why the same object might burn more brightly in one location than in another. But a problem arose with the explanation. The “metallic ash” resulting from the burning of some metals was greater than that of the original metal while the burning of wood and other organic material resulted in ash that weighed less than the original material. If the weights of reactants and products were to be balanced, that would mean phlogiston could have a positive or a negative weight.

This was a puzzling idea, but those supporting the phlogiston explanation did not want to discard such a useful theory because of this problem. Some chemists thought this problem was the result of their imprecise measuring.
equipment. These chemists thought that when they learned more about phlogiston and developed better balances, the problem would be resolved. However, others began to question whether mass was always conserved as had been thought since the time of Aristotle.

After Stahl, the most famous advocate of the phlogiston theory was the English experimenter Joseph Priestley (1733–1804). Priestley (Figure 1), like most other natural philosophers of his time, did not make his living through science. Instead, Priestley was a well-known Dissenting minister (English Christians who did not agree with the teachings of the Anglican Church were known as Dissenters.) and religious thinker who made his living as a preacher and also as a schoolmaster.

Throughout this story, notice how those working to understand the natural world are either pursuing their interest as a hobby outside their work, are wealthy, or have the financial support of a benefactor. The word “scholar” comes from the Latin word “scholae” which means “leisure time”. Today we hardly think of conducting scholarly work as “leisure”. However, historically, doing science and other forms of scholarship was associated with leisure time.

3. Why do you suppose that in the past, leisure time was associated with doing science and other forms of scholarship?

Priestley had been interested in chemistry from an early age, and as an adult, he came to believe that investigations into the natural world could reveal truths that would overthrow unjust or tyrannical religious and political authorities. His chemical work was therefore strongly linked to his Dissenting beliefs. In 1767, Priestley had published a treatise on the history of electricity that gained him admission to the Royal Society of London.

In 1773, Priestley found a patron, Lord Shelburne, who was interested in Priestley’s work and invited him to move to the Shelburne estate and pursue his research in chemistry there. During his time, Priestley pursued a series of studies on the chemistry of air. He isolated several different types of air with different properties, but the two most important were the substances Priestley called “fixed air” and “dephlogisticated air.” Fixed air was air that already contained a great deal of phlogiston. For example, if a piece of wood was burned under a sealed glass dome, when the burning was complete, the air inside the dome would be fixed air because phlogiston would be released into the air when the wood was burned. Priestley found that mice placed in domes filled with fixed air could not survive as long as mice placed in domes filled with regular air.

Figure 1. Joseph Priestley

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Priestley was therefore surprised to find that unlike mice, plants seemed to thrive in fixed air. In fact, if a mouse and a plant were placed in the same sealed dome, the mouse lived much longer than a mouse in a dome alone. Priestley concluded that plants were capable of removing phlogiston from the air. He called the improved air they left behind “dephlogisticated air.” Priestley saw these findings as confirming evidence for the phlogiston theory.

Notice that Priestley had to interpret the results of his tests. The data he collected did not tell Priestley what to think. Priestley compiled evidence from his tests and interpreted the evidence as support for the existence of the immeasurable substance phlogiston – an idea scientists no longer accept.

4. How does this example illustrate that scientists are influenced by the predominant ideas of the culture in which they live?

However, in France, another chemist was also studying different types of air, and coming to a conclusion entirely different from Priestley’s. Antoine Laurent de Lavoisier (1743-1794), like
Priestley, did not make his living through his scientific interests. In 1768, Lavoisier (Figure 2) had purchased shares in the Ferme générale, a private corporation of shareholders responsible for collecting taxes for the king. In 1771, Lavoisier married a young woman named Marie-Anne Paulze (1758-1836), the only daughter of a wealthy colleague at the Ferme générale. His wife's fortune and his own earnings as a shareholder in the Ferme made Lavoisier an extremely rich man, and Lavoisier used this money to pursue his interest in chemistry. On a typical day, Lavoisier would rise at five in the morning and work in his laboratory from six until nine, and then return to the laboratory in the evening after his work at the Ferme générale was complete. On Saturdays he would work with his assistants (including his wife, who drew many of the illustrations we have of Lavoisier's laboratory) all day on his latest scientific project.

Lavoisier's research was characterized by a determination to measure everything as precisely as possible. Unlike Priestley, who used simple experimental setups that anyone else could easily duplicate, Lavoisier put a great deal of his wealth into constructing sophisticated experimental equipment (Figure 3). He was especially interested in obtaining the best, most reliable balances he could in order to measure the weights of his reactants and products exactly. Lavoisier knew about and accepted the phlogiston theory. But the negative weight problem troubled him a great deal, and in 1772 he set out to investigate the combustion of sulfur in air and also phosphorous in air, measuring everything as precisely as possible, to determine why some burned objects gained weight. As is often the case with research, Lavoisier encountered many technical problems in his work and much conceptual confusion ensued.

Figure 2. Antoine Laurent de Lavoisier

Public Domain Image

Lavoisier slowly came to the conclusion that the phlogiston theory was not viable – some substances gained too much weight during combustion. The explanation that they were losing an unmeasurable substance, phlogiston, simply didn't make sense any longer to Lavoisier. Instead, in a paper he submitted to the Académie des Sciences in November of 1772, Lavoisier argued that when sulfur and phosphorous were burned, the increase in their weight was due to these compounds combining with air. Lavoisier reached this conclusion in part by studying lead calx (what we now call lead oxide, or PbO), a compound that gave off bubbles when dropped into water. He had begun to speculate that lead calx was lead combined with air, and when placed in water the air was given off. This sparked an original idea that the calcination of metals, the combustion of sulfur and the combustion of phosphorous likely all involved these substances combining with air.

Priestley, however, was suspicious of Lavoisier's elaborate experimental setup and unconvinced by his arguments and novel explanation. Priestley was not as troubled as Lavoisier by the weight gain during combustion and the "negative" weight of phlogiston, because Priestley was one of the chemists who thought the Aristotelian idea of conservation of mass might be wrong. Priestley pointed to examples such as heat and light – chemists could not weigh them, but clearly they existed. Priestley thought that it might be possible for immaterial substances like heat, light and phlogiston to undergo a transformation and acquire mass, and thought this sort of transformation better explained the mysterious weight gain during combustion.
5. Why might Lavoisier’s use of elaborate equipment and experimental setups have increased other scientists’ suspicion and distrust of his results and arguments?

Thus, Priestley never accepted Lavoisier’s ideas, and the two chemists never saw eye to eye on the question of combustion. Around that same time the existence of a substance we today call “oxygen gas” was independently isolated, first by the Swede Carl Wilhelm Scheele, and later by Priestley, although Priestley is given credit because he published his work in 1774, three years before Scheele. However, neither Priestley nor Scheele understood that the substance they had identified consisted solely of one element.

Soon after publishing his work, Priestley shared his accomplishment with Lavoisier. After several more years of studying combustion and the chemistry of air, Lavoisier argued that Priestley's dephlogisticated air was instead air that contained an element that he named “oxygen.” Lavoisier said that when a substance was burned, it combined with the oxygen in the air, resulting in the weight gain he had observed. Lavoisier was far more successful spreading his ideas. He began promoting his own system of chemistry, one that rejected phlogiston and employed a new chemical nomenclature that Lavoisier said was more rational than the old names.

6. Although Lavoisier is often credited with formulating the law of conservation of mass, many chemists and physicists had previously accepted and used the idea that matter would not spontaneously arise or vanish. What then was Lavoisier’s important contribution?

In 1783, Lavoisier published Les Réflexions sur le phlogistique, where he firmly denied the existence of phlogiston. For some time, Lavoisier’s claims were difficult for most in England and France to accept. Others who tried to recreate his laboratory equipment reported difficulties. Not until after Lavoisier’s 1785 work separating water into its component gases did many French chemists accept his ideas. In a 1789 paper on the chemistry of fermentation, Lavoisier explicitly stated the principle of the conservation of mass: the reactants in a chemical reaction had to have the same mass, and the same elements, as the products. This principle became an underlying assumption of the transformed science of chemistry that Lavoisier had helped create.

In England, however, phlogiston had undergone a “Renaissance” in the 1770s and 1780s, and was a central feature of chemistry. Thus, many chemists there regarded the existence of phlogiston as beyond dispute. Even Joseph Black who had always accepted that matter could not be created or destroyed was very slow to accept Lavoisier’s idea of oxygen’s involvement in burning. However, by 1900, in a letter to Lavoisier, Black wrote that he had been habituated 30 years to believe and teach the doctrine of Phlogiston... I felt much aversion to the new system... This aversion however proceeded from the powers of habit alone has gradually subsided... Your plan... is infinitely better supported than the former Doctrine.

The final years of Priestley and Lavoisier’s lives were marked by political unrest. During a series of riots in England in 1790 against Dissenters, Priestley’s home was burned to the ground and he barely escaped with his life. He and his wife moved to Pennsylvania, where Priestley died in 1804. Lavoisier was even less fortunate. In 1789, the same year Lavoisier published his paper stating the principle of the conservation of mass, the French overthrew their king and the country was plunged into a revolution. When the Committee of Public Safety came to power under the leadership of Maximilien Robespierre, they began ordering the executions of people they saw as supporters of the old regime. According to the Committee, Lavoisier’s participation in pre-Revolutionary tax collection made him an enemy of the Revolution, and he was executed in May 1794.

By 1900, both the laws of conservation of mass and conservation of energy were well-established. But in 1905, a young patent clerk in Switzerland would contribute a startling new suggestion: that mass and energy were interchangeable. The clerk’s name was Albert Einstein (1879-1955).
$E=mc^2$ is perhaps the most famous equation in the history of science. While almost everyone has heard of this equation, few realize the way it unites two fundamental principles of physics. As Einstein himself would put it in his 1916 book *Relativity*:

“Before the advent of relativity, physics recognized two conservation laws of fundamental importance, namely, the law of the conservation of energy and the law of the conservation of mass; these two fundamental laws appeared to be quite independent of each other. By means of the theory of relativity they have been united into one law.”

Note that although the conservation of mass and conservation of energy were scientifically accepted laws of nature, the laws had to be modified to account for Einstein’s scientific theory that unified these two scientific ideas, and later evidence that supported his theory’s prediction.

7. In what ways does this story illustrate that science is a creative endeavor?

8. In what ways does this story illustrate that scientific ideas are seldom the result of the work of an individual scientist, but rather the result of complex interactions between multiple scientists?
APPENDIX F

Building Ideas: The Origins of Modern Atomic Theory

Pre-reading Questions:
1. In what ways might scientists use creativity in their work?

Few people today have difficulty accepting the existence of atoms or the protons, neutrons, and electrons that constitute them. Yet, until the 1890s, both the existence of atoms and the possibility of subatomic structures remained subjects of heated debate. Atoms cannot be observed directly, even with the most powerful microscopes. Thus, scientists who wished to confirm the atomic hypothesis would need to base their conclusions upon indirect evidence obtained using a variety of new tools.

Origins of the Atomic View

The idea of the atom originally emerged from conversations among ancient Greek philosophers. Atomism came to be associated with the philosopher Democritus. He believed that the universe consisted of elementary particles of matter that were in constant motion. These particles might differ in terms of shape, size, and mass, but all of them were ultimately indivisible. Democritus once claimed, "... in reality, there are only atoms and the void."

The philosopher Aristotle disagreed. According to Aristotle, the atomist position was absurd. In particular, Aristotle questioned the belief in a void completely absent of matter through which atoms could travel. In Aristotle’s views of physics, objects required constant force to keep them moving in a straight line. In a void, there would be nothing pushing against the atoms, so they should not be able to move.

The debate between supporters of Aristotle’s physics and Democritus’ atoms persisted for centuries. During much of that time, the Aristotelian view was accepted. Eventually, a new group of scientists began to consider old questions during the Scientific Revolution.

The Debate Rages On

During the Scientific Revolution, the main supporter of the Aristotelian view was the French philosopher Rene Descartes. Descartes strongly denied the existence of atoms or the void. He believed that the universe was filled entirely with matter that could always be divided into even smaller portions.

Descartes faced opposition from two notable British scientists: Robert Boyle and Isaac Newton. Boyle, a member of the British aristocracy and an amateur chemist, supported a view in which matter consisted of fundamental particles capable of combining in different shapes. He backed up this position with two books of experiments investigating the behavior of atmospheric gases published in 1660 and 1691. Newton took an even sharper stand against Descartes. His work on gravity embraced the void and eliminated the need for contact to cause motion. In one of his books, Newton clearly stated his belief that "God in the beginning formed matter in solid, massy, hard, impenetrable, moveable particles...".

Yet, despite their support for an atomistic framework, Boyle and Newton’s particles remained confined to theoretical physics. The man credited with linking atoms to chemical composition was an admirer of Newton's named John Dalton (Figure 1). Dalton was a talented student, but his family’s Quaker background prevented enrollment at either Oxford or Cambridge. Fortunately, he obtained training in science and mathematics from a tutor who introduced Dalton to meteorology.

![Figure 1. John Dalton, 1895](Public Domain Image)

Dalton contributes to the conversation

Dalton's meteorological studies took place at the same time as a significant shift in the way we viewed the atmosphere. In 1789, the French scientist Antoine Lavoisier had broadened the definition of "element" to include any substance...
that could not be chemically separated into simpler components. Lavoisier went on to demonstrate that air was not an element, but a mixture of gases including oxygen, azote (later renamed nitrogen), and water vapor.

What Dalton wished to understand was what kept these various atmospheric gases from separating into layers based on their densities. Lavoisier had claimed that water vapor had loosely combined with the other gases in the air, which prevented the formation of distinct gas layers. However, Dalton's weather data suggested that air became saturated with different amounts of water vapor depending upon the temperature. He began to wonder why different gases had different solubility in water. This question led him to a completely new idea. He began considering how the weights of different types of matter compared to each other. What were the relative weights of the different types of matter? Before beginning, Dalton had to make several assumptions he could work from (Figure 2).

1. All atoms of a particular gas are identical. A chemical reaction occurs when atoms of different elements combine.

2. Law of Multiple Proportions:
   When two elements can combine in multiple ways, the ratio of the two compounds' weights occur in whole number ratios.

3. Rule of Simplicity:
   If two elements A and B form only one compound, the compound is binary (AB).
   \[
   A + B = AB
   \]
   If two elements A and B can combine to form more than one compound, one compound is binary (AB) and the other is ternary (A₂B₂ or AB₃).
   \[
   A + B = AB \quad \text{or} \quad A₂B₂
   \]

With these assumptions in place, Dalton could begin compiling a table comparing the weights of each atom. At the time, for example, water was the only known compound of hydrogen and oxygen, so according to the rule of simplicity, it must consist of one atom of each element (HO).

Using the measurement techniques perfected by Lavoisier, one could determine that water was 85% oxygen and 15% hydrogen by weight. Therefore a single atom of oxygen had to be approximately 5.66 times heavier than an atom of hydrogen. (85/15 ≈ 5.66)

By repeating this process with various compounds, Dalton was able to successfully compile a table listing the relative atomic weights of twenty-one different gases. He presented papers and lectures outlining his ideas at the Manchester Literary and Philosophical Society and at other places across Britain. In 1808, Dalton published a textbook presenting a series of circular symbols to represent atoms of different elements (Figure 3), and defended the existence of atoms as indivisible, spherical entities.

**Figure 2. Dalton's Assumptions**

**Figure 3. Dalton's Drawings of Atoms and Molecules**

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**Memo:**

1. Dalton, Newton and Lavoisier are working to better understand the natural world, but notice they are not only making observations and collecting evidence. They are making assumptions and creating ideas. Then coming up with creative ways to test those ideas.

2. Note that Dalton's work is influenced by the work of previous scientists and scientists of his time. How might past scientific work influence future scientific work in both positive and negative ways?
Initial reactions to Dalton’s atomic theory were mixed. Some people endorsed Dalton’s belief in the atom. Other scientists, including two of Britain’s foremost chemists, objected sharply to the idea of invisible particles. They acknowledged that Dalton’s research provided a useful tool, but preferred to use the term “equivalent weight” to refer to the amount of matter involved in a reaction rather than “atom”.

Additionally, chemists in different countries used different relative weight tables, each starting with a different standard for comparison. In Britain, chemists tended to use the tables of Dalton’s colleague Thomas Thomson that were based on the assumption that hydrogen had an atomic weight of 1. In contrast, scientists on the European Continent used a different table based on oxygen having an atomic weight of 100.

In 1860, a concerned group of chemists convened the world’s first international scientific conference in the German city of Karlsruhe. Their goal was to establish a standardized set of definitions, assumptions, and notation systems so that future scientists could communicate with each other more effectively. The majority of scientists at the conference recommended the use of atoms rather than equivalents. They also accepted Amadeo Avogadro’s hypothesis that under similar temperature and pressure conditions, equal volumes of different gases contained the same number of particles. This stance required one to acknowledge the possibility that, contrary to Dalton’s rule of simplicity, elements could exist in polyatomic form. From that point forward, the formula for hydrogen gas was H₂ rather than H, and water’s formula became H₂O.

Resistant to change

For the remainder of the 1800s, most chemists endorsed the atomist position set forth at Karlsruhe. Some remained uncertain as to whether the atom actually physically existed, but found it useful as an idea and tool. For example, organic chemist August Kekulé did not believe that atoms actually existed, but he still found the idea useful when doing his work. Others were more resistant to the atomist position, and some remained committed to the use of equivalent weights rather than atoms.

Despite the harsh criticisms from the anti-atomists, scientists continued to develop new techniques that might potentially shed light on mysteries of the atom. William Crookes, a British scientist, improved the cathode ray tube while working to better understand the structure of matter. This improvement would eventually help transform our understanding of the atom.

People often think of scientists as objective observers of the natural world, that scientists “discover” the truth. Yet, the idea of atoms was debated for thousands of years. While observation does play a significant role in science, clearly reputation, personality, prior experience, and even culture affect scientific progress.

3. Explain how various factors could cause scientists to be biased in their investigations?

Making sense of new observations

The cathode ray tube consisted of a glass cylinder with metal plates at either end. When an electric potential difference was applied to the two ends of the tube, a glowing greenish beam came from the negative electrode. Scientists were uncertain precisely what these “cathode rays” were. Some, like Crookes, thought they were charged particles being released, while others believed they were a form of electromagnetic wave. The study of these mysterious rays and the device producing them were researched across Europe during the 1890s. In 1895, French physicist Jean-Baptiste Perrin demonstrated that cathode rays carried negative charge and could be deflected using a magnetic field. J.J. Thomson (Figure 4), the head of the prestigious Cavendish Laboratory at Cambridge University, would expand on Perrin’s work, providing evidence for the existence of atoms and even smaller particles of matter.

Figure 4. J.J. Thomson, 1894

Public Domain Image
First, Thomson provided evidence that the rays carried the electric charge by using a magnet to bend the rays to an electrometer. As Thomson explained "this experiment shows that however we twist and deflect the cathode rays by magnetic forces, the negative electrification follows the same path as the rays..."

He next took a straight cathode ray tube and drilled a hole through its anode. He then focused the cathode ray beam to travel beyond the anode, striking the glass on the other side (Figure 5). In the space between the anode and the glass, he set up a pair of metal plates (labeled D and E in Figure 5) capable of generating an electric field perpendicular to the beam. When Thomson activated the field, he was able to change the direction of the beam. Thomson now had two means of altering the direction of his rays: electric fields and magnetic fields.

![Figure 5. Thomson's drawing of the Crookes cathode ray tube by which he observed the deflection of cathode rays by an electric field.](image)

In his final investigation, Thomson added a pair of coils capable of generating a magnetic field outside the tube. The electric and magnetic fields were arranged so that each would push the cathode rays in opposite directions, moving the spot on the glass wall up or down. By balancing the electric and magnetic fields against one another, Thomson was able to use their strengths to calculate the ratio between each particle's mass and electric charge. He repeated the process several times with a variety of gases, in each case obtaining the same ratio. When compared to the mass to charge ratio of the smallest previously known particle, a hydrogen ion (H⁺), he determined that the cathode ray particles were nearly 2,000 times lighter. Thomson reported these findings in an 1897.

Thomson had the first evidence for the existence of subatomic particles. Thus, he shattered the most important characteristic of the atom from Democritus to Dalton, its indivisibility. In his paper, he referred to it as a “carrier of electricity”, but it soon became known as an “electron”. Support of the electron's existence raised new questions about the structure of the "indivisible" atom.

Further support for the existence of atoms came in 1905 when a previously unknown Swiss patent clerk named Albert Einstein determined the physical size of atoms and molecules through a statistical analysis of Brownian motion - the seemingly random movement of particles suspended in a liquid. However, this new evidence left much unanswered about these particles. For example, electrons were negatively charged, but atoms were electrically neutral. Was there some sort of positive charge in the atom offsetting the charge of the electron? In addition, it soon became clear that unless there were thousands of electrons present in each atom, their total mass would remain insignificant compared to that of the atom as a whole. Where was the rest of the atom's mass hiding?

![Tip: Oftentimes, new evidence and understanding raises new questions about nature. Science is better viewed as a process of refining our ideas based on new evidence rather than a march toward certain truth. A great strength of the scientific endeavor is that even the most well accepted ideas are open to revision.]

4. Using examples from the story, what factors, other than new observations, might affect how/why science ideas change?

Thomson struggled to devise a model that would effectively explain the structure of the atom while taking into account the newly understood properties of the electron. Initially, he proposed a model incorporating thousands of electrons to account for the atom's weight, but dismissed this after interpretation of new data indicated that the number of electrons in an atom was roughly equal to half its atomic weight. By 1907, he had devised a new model where electrons were dispersed through a positively charged medium. Thomson's idea was later named the "plum pudding model," since the electrons were scattered throughout the positively charged atomic mass like raisins in the traditional English Christmas dessert (Figure 6).
Speculation regarding the structure of the atom extended well beyond Thomson's laboratory. Across the world, physicists were at work evaluating the "plum pudding model" and proposing alternative ideas. Jean Perrin, the French theorist, whose early work on cathode rays had inspired Thomson's experiments, proposed an atom that consisted of one or several strongly charged positive masses surrounded by many small negatively charged particles similar to small negative "planets." At nearly the same time, the Japanese physicist Hantaro Nagaoka proposed a similar "Saturnian" model, where electrons moved in central rings around a central positively charged sphere. Meanwhile, in Germany, Johannes Stark envisioned the atom as a surface consisting of spherical zones of positive energy with small point-like electrons nestled between them. Determining which of these ideas most accurately reflected reality would require creative insight and new investigation techniques.

**Struggling to make new observations**

The major challenge confronting scientists interested in atomic structure remained the same as in Dalton's time: atoms were simply too small to be observed directly. A young researcher at England's Cavendish laboratory developed a new way to investigate the structure of the atom. Ernest Rutherford (Figure 7) was born in New Zealand and had earned a research scholarship at The Cavendish Laboratory in 1895.

In 1897 Rutherford began focusing his research on a new type of radiation that had recently been discovered in France. Henri Becquerel, Marie Curie, and Pierre Curie had come across a new radiation from elements such as uranium. The nature of this new type of radiation was not fully understood. However, Rutherford eventually figured out that uranium actually emitted two different kinds of radiation. The first, which he called alpha radiation, was easily absorbed and had a positive electric charge. The second type, called beta radiation, was 100 times more penetrating and carried a negative charge.

Rutherford continued to investigate these two types of radiation and came to understand that alpha rays consisted of helium ions with a double positive charge, while beta radiation was made of particles identical to Thomson's electron. By 1907, he realized that the stream of particles emitted by radioactive materials could be used to test the various atomic models. By firing these particles at atoms, one might learn from observing how the particles behaved. Rutherford recruited Hans Geiger and Ernest Marsden, a pair of talented students, to assist in an investigation that would help us understand where electric charge was located in the atom.

Geiger and Marsden designed a means of focusing the alpha particles into a fine beam that could be directed at a thin metal foil mounted in front of a screen. Alpha particles fired at the foil would pass through the foil hitting the screen and causing a small flash. Rutherford believed one could obtain information about the structure of the atoms in the foil by keeping track of the position of the various flashes.

Rutherford assigned the task of observing the particles to Geiger and Marsden. The two men sat in a dark room using a movable, low-powered microscope to count the flashes of alpha particles. If the plum pudding model were correct, the trajectories of the alpha particles...
would be deflected only slightly after passing through the foil because charge and mass were uniformly distributed throughout the atom (Figure 8, top image). Initial observations appeared to support Thomson’s hypothesis. However, one day in 1909, Rutherford passed by Geiger and Marsden’s lab and suggested that they check if the foil was reflecting any of the particles backward. “I do not think he expected any such result,” Marsden recalled later, “but it was one of those ‘hunches’ that perhaps some effect might be observed.” A few weeks later, Marsden and Geiger had indeed discovered that 1 out of every 20,000 alpha particles deflected at an average angle of 90 degrees (Figure 8, bottom image).

**Figure 8. Rutherford’s Gold Foil Experiment**

The top image illustrates the expected results if the “plum pudding model” of the atom was accurate. The bottom image illustrates the observed results. Instead of simply passing through the atoms of the foil, some of the alpha particles were deflected off at an angle.

![Public Domain Image obtained from](http://en.wikipedia.org/wiki/File:Rutherford_gold_foil_experiment_results.svg)

In 1911, Rutherford published a report in which he outlined these alpha particle experiments and proposed a new atomic model explaining their results. Citing the earlier proposals of Perrin and Nagaoka, Rutherford argued that the atom consisted of a positively charged core (or *nucleus*) that contained the majority of the atom’s mass and was surrounded by a cloud of negative electrons (Figure 9). The large deflections observed by Geiger and Marsden occurred when a positively charged alpha particle collided with the positively charged nucleus of an atom. Since these collisions were relatively rare, the nucleus of the atom had to be considerably smaller than the complete atom. Rutherford’s model was, in many respects counterintuitive. It required one to accept that the majority of the atom’s volume consisted of empty space and that the positive charges in the nucleus did not repel one another.

**Figure 9. Rutherford’s Atomic Model**

![Public Domain Image obtained from](http://en.wikipedia.org/wiki/File:RutherfordAtomicModell.png)

Growing acceptance of Rutherford’s ideas by the scientific community did not, however, mean that his atomic model was considered complete. In a 1920 lecture before the Royal Society, he outlined many of these shortcomings. One flaw of his model was its inability to explain the mass of the nucleus. At the time, the only known subatomic particles were the negatively charged electrons and the positively charged components of the nucleus, which Rutherford named *protons*. Rutherford suggested the existence of a third fundamental particle, a sort of proton-electron composite, whose mass was equal to the proton but with no electrical charge. He referred to this hypothetical particle as a *neutron*.

At this point in his career, Rutherford had replaced his former teacher J.J. Thomson as head of the Cavendish Laboratory, and his responsibilities as director limited his time for research. By 1932, however, one of his researchers, James Chadwick, confirmed that a particle matching the description Rutherford had presented in 1920 was emitted when the element beryllium was bombarded with alpha particles.
The evidence for the neutron resolved earlier disagreements concerning atomic mass. Additionally, neutrons provided an explanation for the existence of isotopes (substances that share the same physical and chemical properties but possess different atomic masses).

By the time of Chadwick's work, the atom had undergone a radical transformation from the ideas first proposed by Democritus. Even Dalton would hardly recognize an atom that could be divided into three fundamental particles (electrons, protons, and neutrons). While ideas about structure of the atom have evolved over time, the desire to understand matter at its most basic level has remained a constant motivation. This search has driven scientists to collaborate internationally to establish a common vocabulary and standards of evidence. The quest prompted the creation of new research centers and forced investigators to develop innovative techniques. Above all, the quest to understand the atom unified the previously unrelated fields of physics and chemistry. Few scientific ideas before or since have proven quite as powerful or as versatile.

The road to our current understanding of the atom includes many players, many ideas, and spans thousands of years. Yet, many people envision scientific breakthroughs as “eureka” moments. While many of the scientists in this story may have felt “eureka” moments of exciting realizations, the overall story demonstrates how human understanding of the natural world moves forward in unpredictable ways.

5. Not only do scientists have to be creative in designing new experiments and tests, they also must create ideas that account for the data. Many people believe science is not creative and that too much creativity may lead to biased results. Use examples from this story to illustrate that science must be a creative process.

6. Describe how our ideas about the atom have changed over time and how each of the following individuals contributed to our current understanding:

Democritus
Dalton
Thomson
Rutherford
Chadwick
APPENDIX G

Pre-reading Questions:

1. What might be the importance of having standardized scales of measurement for scientific work?
2. What problems might occur during scientific work if there were no standard scale of temperature?

Early Developments in the History of Thermometry

The systematic study of heat can be traced to efforts of philosophers living in the Eastern Mediterranean beginning in the fourth century B.C.E., when Aristotle listed fire as one of the four fundamental constituents of the natural world. Aristotle, however, did not attempt to create a graded scale indicating the relative heat of a substance. It would take several centuries until the Roman physician Galen (C.E. 129-200) suggested the creation of a nine-point scale indicating deviations from normal body temperature. Galen’s medical ideas would remain popular until the late 1600s, but none of his followers used his scale to create an instrument for measuring temperature.

These ancient investigations provided the inspiration for the creation of the first modern thermometers in the early 17th century. Santorio Santorrio, a professor of medicine at the University of Padua, took an interest in Galenic medicine. The physicist Galileo Galilei was a colleague of Santorrio’s at Padua. Both Santorrio and Galilei created instruments to indicate changes in temperature (Figure 1). Santorrio and Galileo’s instruments had different scales, but operated on the same principle — the ability of heat to alter the pressure of the air inside a tube in comparison to pressure of the surrounding atmosphere.

Figure 1. A Galileo Thermoscope on the left

![Image from the 1832 Edinburgh Encyclopaedia](image-url)
However, after Galileo's student Evangelista Torricelli invented the barometer, scientists noted that air pressure changed depending upon one's altitude and the prevailing weather conditions. Therefore, the standardization of thermometric measurements would require a different instrument design.

Note how improved understanding of air pressure changed what scientists accepted as appropriate ways to measure temperature. Developments in one area of scientific understanding often affect understanding of other areas of science. Science is like a puzzle of the natural world. When one piece is altered, the other pieces might require altering or rearranging to create a more coherent picture.

The quest for an accurate thermometer gained a powerful new ally in 1657 when Duke Ferdinand II of Tuscany founded the Accademia del Cimento (Academy of Experiment) in Florence, dedicated to expanding the mathematical and experimental program advocated by Galileo. Duke Ferdinand took an active role in his Accademia and provided researchers with space to work in Florence's Pitti Palace. The Duke also developed an improvement upon previous open-air thermometer designs, calling upon the artisans in his family's workshop to construct a sealed thermometer, consisting of a closed glass tube with a bulb filled with alcohol. The expansion and contraction of the enclosed liquid was measured using a scale dividing the thermometer into fifty smaller subdivisions. The members of the Accademia hailed Duke Ferdinand's new instrument as a success, and they ordered the manufacturing of new ones of various shapes and sizes (Figure 2).

The Duke went so far as to hang ornate thermometers of all different shapes and colors in every room of his palace. He also arranged for the publication of an account of the Accademia's research into heat, including detailed instructions so that glassblowers elsewhere could create their own high-quality thermometers.

Although the Accademia's thermometers provided a template upon which other researchers could base their instruments, it soon became evident that even the most sophisticated Florentine thermometer possessed flaws.

3. The density of the alcohol used inside Florentine thermometers varied from batch to batch. Additionally, alcohol has a lower boiling point than water. Why might each of these be problematic for researchers using these new thermometers?

Figure 2. Florentine thermometers and a hygrometer

For example, the Accademia knew that the distillation of alcohol resulted in a liquid whose density varied from batch to batch. Thus, the readings on two identical thermometers may no longer match if the alcohol differed. In addition, alcohol evaporates at a lower temperature than water; this was an inconvenience for scientists investigating high temperature phenomena. Fortunately, both of these problems could be remedied by replacing alcohol with another substance, typically mercury or air.

Arguably, a more serious design flaw was the Accademia's method for determining the size of the degree divisions on its thermometers. The Accademia's calibration method consisted of finding the space between two fixed marks and dividing it into a number of equal parts. Unfortunately, the two reference points - "the most severe winter cold" and "the greatest summer heat" - were remarkably vague. If temperature measurements were to possess any value for investigators, the size of a degree had
to remain constant. This meant scientists would need to find phenomena which only occurred at a single specific temperature.

Prior to the British Royal Society commission’s decision to adopt the boiling point of water as a fixed point, a variety of alternatives were suggested. While a few, like Robert Hooke, believed they could simplify the process by using a single fixed point (like the temperature at which water froze or boiled) and measuring degrees based on the expansion or contraction of a chosen fluid, most continued to suggest using two fixed points. In 1701, for example, Isaac Newton endorsed using “the heat of the air in winter when the water begins to freeze” and “blood heat” (i.e. the temperature of a human body) as reference temperatures. Other proposals were even more bizarre. Joachim Dalencé suggested the temperature at which butter melted. Additionally, both Edmond Halley and French mathematician Philippe de La Hire suggested that air’s temperature in deep caves would provide a better low temperature point than the freezing point of water.

4. Note the many differing ideas about how to best create a standardized temperature scale. What does this illustrate about:
   (a) the subjectivity of science and
   (b) the inventive nature of science?

**Development of Modern Temperature Scales**

By the mid-1700s, this excess of possible reference points and thermometric scales had been reduced down to two. The first of these was created by the Polish-born instrument-maker Gabriel Daniel Fahrenheit (Figure 3). An orphan whose parents died from mushroom poisoning when he was fifteen, Fahrenheit’s relatives apprenticed him to a bookkeeper. His interest in science, particularly the construction of scientific instruments, led him to abandon his apprenticeship so that he could travel across Europe to perfect his skills.

In 1708, Fahrenheit arrived in Copenhagen, where he met with Danish astronomer Ole Roemer. Roemer had previously devised a sixty degree temperature scale where 0° was the temperature of a mixture of ice and salt and 60° was the boiling point of water. On this scale, 7.5° would be the melting point of ice and blood heat would be 22.5°. Fahrenheit liked aspects of Roemer’s scale, but found it “inconvenient and inelegant on account of the fractional numbers.” He shifted the melting point of ice up to 8° and the blood-heat mark to 24° before quadrupling his numbers so that the amount the mercury expanded between each degree in his thermometers agreed with those being used by Boyle and Newton. The net result was a scale where water’s freezing point was 32°, the temperature of the human body was 96°, and the boiling point of water corresponded to 212°.

**Figure 3. Gabriel Daniel Fahrenheit**

Scientists in Britain and the Netherlands quickly adopted Fahrenheit’s temperature scale. However, a different system eventually won out in France and the rest of Europe. As early as 1710, a Swedish scholar named Elvius had proposed the use of a centigrade system, where the values of 0° and 100° were assigned to the freezing and boiling points of water. This centigrade system is often associated with the name of another Swede, Anders Celsius (Figure 4).

**Figure 4. Anders Celsius**

Painting by Olof Arenius
Image Obtained from Uppsala University Astronomy webpage
The son and grandson of astronomers, Celsius had participated in expeditions intended to confirm the extent of the earth's curvature. During these expeditions, Celsius became frustrated with the instruments available to measure cold. He obtained a thermometer from St. Petersburg and etched a new scale on it, similar to Elvius' proposal, but with the boiling and freezing points reversed. In other words, 0° was the temperature at which water boiled and 100° was the temperature at which it froze. This reversal might reflect Celsius' interest in how cold, rather than how hot, objects were.

After Celsius' death, Martin Stroemer became his successor at the University of Uppsala. Stroemer simply reversed Celsius' numbers, creating the modern centigrade temperature scale. The Celsius system grew in popularity, especially after the widespread adoption of the metric system encouraged the use of decimal units. However, the Fahrenheit system had its own advantages (Figure 5). For example, the Fahrenheit scale has 180° (212° - 32°) between the boiling and freezing points of water, while the Celsius system has only 100° (100° - 0°). Therefore, one could obtain more precise temperature readings in Fahrenheit without resorting to fractional degrees.

Figure 5. Comparison of the Celsius and Fahrenheit temperature scales

Textbooks often mistakenly portray new scientific knowledge as being discovered instantaneously by an individual scientist. However, this story illustrates the extensive time often needed to develop new scientific ideas.

The Split Between Heat and Temperature

Although some doubt remained as to which scale was more appropriate or whether certain physical phenomena always occurred at a constant temperature, by the second half of the 1700s, the existence of standardized thermometric scales meant that observations of thermal phenomena were no longer entirely subjective. Scientists could now make increasingly meaningful comparisons of their experimental results, which might, perhaps, determine the ultimate nature of heat.

5. In what ways does the story of the quest for a standardized temperature scale illustrate that science is a creative endeavor?

6. Textbooks often portray science as a solitary endeavor in which individuals instantaneously discover new scientific knowledge. In what ways does this story illustrate that scientific ideas are seldom the result of the work of an individual scientist, but rather the result of complex interactions between multiple scientists?
APPENDIX H

A Matter of Degrees: The Early Science of Heat

Pre-reading Questions:
1. What are scientific theories and what role do they play in scientific work?
2. What do you know about heat and how it works? How might heat be different than temperature?

By the second half of the 1700s, the existence of standardized temperature scales meant that observations of thermal phenomena were no longer entirely subjective. Scientists still debated whether the Celsius scale or the Fahrenheit scale was more appropriate. Additionally, some scientists doubted whether certain physical phenomena (i.e., the boiling and freezing points of water) always occurred at a specific temperature. However, with the new temperature scales, scientists could now make increasingly meaningful comparisons of their experimental results. Perhaps such results might help determine the ultimate nature of heat.

At least until the middle of the 1800s, the question of what exactly a thermometer measures remained much debated. Up to that point, scientists across Europe remained divided as to how best to understand and explain heat. Was heat an invisible fluid, undetectable except for its tendency to warm up other substances? Or was heat a physical phenomenon associated with matter in motion?

Although today’s scientists accept a version of the second idea, the idea’s eventual success was not obvious nor immediate. In fact, both approaches provided scientists with a useful theoretical framework for interpreting heat-related phenomena, and each played an important role in the creation of the modern field of thermodynamics.

The Split Between Heat and Temperature

Until 1759, there was no distinction between the amount of heat contained in a substance and the number obtained by reading a thermometer submerged in the substance. That year, however, a Scottish scientist named Joseph Black (Figure 1) began a series of experiments which would significantly alter how chemists and physicists wrote, spoke, and thought about heat.

Black was a professor of medicine and chemistry at the University of Glasgow. He was a popular teacher, and most of what we know about his scientific research comes from transcripts of his academic lectures published after his death. Black wished to build off the work of two men who used mercury and water to explore heat -- Dutch physician Herman Boerhaave and a British Army officer named George Martine.

Boerhaave, a friend of Fahrenheit’s, was interested in how heat behaved in liquid mixtures. Boerhaave took two equal volumes of water at different temperatures and mixed them together. As might be expected, the resulting temperature of the mixture was exactly halfway between the two initial temperatures. For example, if the initial temperatures were 60°F and 80°F, the mixture's temperature was 70°F.

Boerhaave then altered his experiment by replacing one container of water with what an equal volume of mercury. Boerhaave assumed that the amount of heat required to increase the temperatures of two different substances would be proportional to their densities. Because the density of mercury is approximately 14 times greater than that of water, Boerhaave expected mercury to have a larger heating effect on the mixture than did the water. However, the results of Boerhaave’s experiment contradicted his hypothesis. When he mixed equal volumes of water and mercury, the mercury never produced more of a heating or cooling effect.

Boerhaave had been at a loss to explain the results of his experiment. However, Black was familiar with another experiment conducted several years later by the British Army officer George Martine. Martine had placed equal volumes of mercury and water at equal distances...
from a large fire and tracked the rate at which each substance's temperature increased. Before these experiments were made, scientists assumed the time needed for the mercury to heat or cool would be 14 times longer than for an equal volume of water. In fact, however, the mercury warmed about twice as fast as the water.

Black concluded that the results of Boerhaave's and Martine's experiments shared a common cause: mercury required less heat to produce a given temperature rise than an equal volume of water. Black realized that heat does not distribute itself among substances in proportion to their density or volume. Instead, heat distributes itself based on a different characteristic property of each substance, its **heat capacity**. Every substance had a different heat capacity, and therefore required a different amount of heat to raise its temperature the same amount.

By developing the idea of heat capacity, Black had taken a step toward distinguishing between the quantity of heat present in a substance and its temperature. He expanded upon this idea by studying heat's involvement in state changes like boiling or melting. Earlier scientists had observed that when water boiled, its temperature remains constant even though heat continued to be applied to the liquid. Black explained, "However long and violently we boil a liquid, we cannot make it in the least hotter than when it began to boil. The thermometer always points to the same degree, the vaporific point [e.g. boiling point] of that liquid."

Black reasoned that although it could not be detected using a thermometer, the extra heat added to the water during boiling was absorbed to convert the liquid into a vapor. Black's challenge was to somehow determine the amount of this otherwise invisible or, in Black's words, "latent" heat.

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**3. Textbooks and media often wrongly portray the development of scientific knowledge as occurring instantaneously by an individual scientist working alone. In what ways is this inaccurate view of science contradicted by the story so far?**

**Vibrations and Fluids: Two Competing Theories**

Black recognized that the concepts of heat capacity and latent heat would have significant consequences on the longstanding efforts of scientists to explain thermal phenomena. At the time, the European scientific community was divided into two major schools of thought. Each group claimed to possess a more comprehensive explanation of the cause of temperature changes, gas expansion, and state changes. On one side were scientists who believed that the ultimate cause of heat was matter in motion. On the other side were scientists who felt that heat consisted of invisible particles of heat capable of invading ordinary matter to raise its temperature.

Although Black had discovered that the quantity of heat contained in a substance could not be determined by simply reading a thermometer, he was still uncertain which of these two theories of heat best explained his experimental findings. He noted that "our knowledge of heat is not brought to that state of perfection that might enable us to propose with confidence a theory of heat or to assign an immediate cause for it." Yet, Black thought his discovery should be considered alongside each of these theoretical frameworks to see which one it fit most closely.
Many people wrongly believe that a scientific theory will become a law once it is supported by enough evidence.

As you continue to read the story about how our understanding of heat developed, note that scientific laws and theories are different forms of knowledge. Both make claims about the natural world; scientific laws state unchanging relationships in nature, while scientific theories explain those relationships. Because they are different types of the knowledge, a theory never becomes a law and a law never becomes a theory.

In this story, scientists are struggling to decide which scientific theory best explains heat.

The idea that heat consisted of motion, Black observed, was based mostly on several methods for producing heat. For example, heat could be generated through frictional contact. Examples of generating heat through friction include striking flint and steel together, and the traditional practice among blacksmiths of heating up metal by hammering it quickly on different sides. In every case, the increase in heat was associated with a mechanical force being applied to a substance.

While Black acknowledged the common-sense utility of considering heat as a kinetic process, his discovery that different substances possessed characteristic heat capacities seemed to disagree with the idea that heat was the motion of particles of matter. He thought, if that theory were true, denser substances, which contained more particles of matter, should possess higher specific heats. But as Black had conclusively demonstrated, such was not the case with mercury, whose specific heat was less than water even though its density was greater. "I do not see how this objection can be evaded," Black wrote.

One might assume that Black's rejection of the theory that heat was matter in motion corresponded with his wholehearted agreement of the alternative theory—heat consisted of an invisible substance capable of altering the properties of ordinary matter. In fact, his viewpoint was somewhat more complicated. Black was sure heat was something other than matter. However, he also noted that no experiment had demonstrated that the weight of a substance increased when it was heated.

Black and other scientists found it concerning that heat did not seem to add weight to a substance; if heat was ultimately an invisible form of matter, it could not be detected in the same fashion as normal matter. Some scientists tried to remove this concern by suggesting the matter of heat was so subtle that no quantity of it could have a measurable weight. Black did not find these claims completely satisfactory. Thus, he remained unconvinced about the ultimate nature of heat.

4. Summarize Black's concerns with each of the two theories of heat.

Black's public indecision about which theory best explained heat did not prevent other people from integrating his ideas into their own understanding. This work proved particularly intriguing to those who thought heat was an invisible form of matter that invaded normal matter. Most notable were French chemist Antoine-Laurent Lavoisier (Figure 2) and physicist Pierre-Simon Laplace (Figure 3). In their 1783 Memoir on Heat, these two men set forth the principles of a new approach towards the study of heat, which became known as the caloric theory.

Figure 2. Antoine Laurent de Lavoisier

Figure 3. Pierre-Simon Laplace
According to caloric theory, heat consisted of a subtle, weightless fluid called caloric which could not be created or destroyed. Caloric particles repelled one another but were attracted to particles of ordinary matter. The physical sensation of heat was the result of caloric flowing from a hotter body to a colder one. While the concentration of caloric in a substance could be detected using a thermometer, Lavoisier and Laplace suggested that it could also combine chemically with particles of matter. This combined caloric could not be detected with a thermometer and could only be observed in chemical reactions or physical state changes where heat was absorbed or released.

The idea that caloric could not be weighed or measured may appear silly to you. However, at this time, investigators also explained phenomena associated with light, electricity, and magnetism in terms of invisible fluids.

The caloric theory provided straightforward and powerful explanations for how heat behaved. The tendency of caloric particles to repel one another explained both why heat flowed from warm bodies to colder ones and why materials expanded when heated. The differing heat capacities of substances reflected a variability in the amount of caloric they could absorb. In addition, the assumption that caloric should be treated as a chemical element capable of forming compounds with ordinary matter, as Lavoisier would explicitly claim in 1789, provided a means of accounting for Black’s finding that a substance’s temperature remained fixed during state changes; additional caloric reacted with ice to form liquid water, for example, becoming “combined caloric” which did not cause a sensible change in heat. The caloric model even provided explanations for phenomena that Bacon and his supporters had cited as proof that heat was caused by motion. Hammering a piece of iron caused its temperature to increase, for example, not because its matter was vibrating faster but because caloric was being physically squeezed out of the metal like water from a sponge.

At a time when scientists explained phenomena associated with electricity and magnetism in terms of invisible fluids, it is unsurprising that the caloric theory found a large number of supporters. As one scientists wrote, even if the alternative kinetic theory were correct, the caloric theory was “by far the simplest way to account for the heat of bodies.”

5. Summarize the reasons why the caloric theory made so much sense to many 18th century scientists.

Rumford’s Response: Opposition to Caloric

Yet despite the caloric theory’s explanatory power, a few scientists refused to abandon the idea of heat as matter in motion. The most prominent of these holdouts was Benjamin Thompson, better known to his colleagues as Count Rumford (Figure 4). Rumford was born in Massachusetts, but fled to London after the American colonies declared independence from Britain. He acted as King George III’s undersecretary of state for the colonies and also gained fame as an inventor who designed improved fireplaces and kettles.

Figure 4. Benjamin Thompson, Count Rumford

Rumford became interested in caloric theory in connection to his military responsibilities. In 1792, he organized an experimental trial to determine how large a gunpowder explosion would be required to rupture one of the Bavarian army’s cannons. In a letter submitted to the Royal Society, he calculated that it would take 55,000 atmospheres worth of pressure to destroy a cannon’s barrel. He noted that this force depends on the elasticity of water vapor. Unlike Lavoisier, who “imagined that the force of fired gunpowder depends in great measure upon the expansive force of uncombined caloric,” Rumford warned that when discussing explosions, it was dangerous and unnecessary to consider the action of caloric, whose existence was not yet clearly demonstrated. Rumford spent the rest of his life fighting against the existence of caloric and in favor of the idea that heat and all of its effects could be explained solely by matter in motion.

The source of Rumford’s frustration with caloric was the tendency of its supporters to ignore the
inconvenient or contradictory aspects of their theory. If caloric were a material substance, it should possess all of the properties of ordinary matter including mass and volume. Yet when Rumford conducted a series of experiments tracking the weight of different liquids as they were repeatedly heated and cooled, he discovered no evidence of any change in their weight. He wrote, "I think we may safely conclude that ALL ATTEMPTS TO DISCOVERY ANY EFFECT OF HEAT UPON THE APPARENT WEIGHT OF BODIES WILL BE FRUITLESS." While supporters of caloric countered that heat was, along with electricity, magnetism, and light simply another example of an immeasurable fluid, Rumford felt that the results of another experiment would demolish their position.

The experiment in question centered around the origin of heat generated by friction. Supporters of caloric claimed that heat from friction was simply caloric squeezed out from the surface of two bodies. Lavoisier and Laplace had argued that caloric could neither be created nor destroyed. Rumford realized that if this was true, then with sufficient friction one could cause all of the caloric to be drained from a substance. He decided to test this conclusion.

Rumford utilized the same equipment used to drill holes into cannons. He was testing whether the heat generated in the drilling process was always the same, no matter how long the drilling continued. To accomplish this task, he took a piece of metal and shaped it into a cylinder. He then arranged for the metal cylinder to be fixed in place and surrounded with a small wooden box which could in turn be filled with water. He attaching a dulled bit to the normal drilling apparatus, inserted the bit into the water-filled box, and turned on the machinery. The horse-driven drill ground against the metal cylinder, generating heat in the surrounding water and eventually causing it to boil. Rumford measured the amount of time it took to heat the box of water several times and found that the supply of heat "appeared evidently to be inexhaustible." He concluded if heat could be supplied without limitation, then it could not possibly be a material substance. Thus, he thought heat must be MOTION and not an invisible form of matter.

Rumford’s theory of heat, involved the vibration of stationary atoms sending out invisible waves of heat. While it does involve the movement of molecules, this was still very different from the modern conception of heat caused by randomly moving molecules. Despite Rumford’s confidence, most advocates of caloric theory did not find his arguments persuasive. They noted that the three hours it took to boil water was not the same as eternity and that there was no proof that friction was an "inexhaustible" source of heat. Additionally, Rumford’s work suggested that heat could be created from nothing, destroying the principle of heat conservation which had been accepted for over a century.

The solution to the last of these problems, replacing "conservation of heat" with "conservation of energy," would only become evident thirty years after Rumford’s death. A key figure in this transition, James Joule, cited Rumford’s research as an inspiration. It would, however, be unfair to suggest that the caloric theory hindered the later development of thermodynamics.

Belief in caloric provided a logical theoretical explanation for the discrepancy between heat and temperature and inspired innovative experiments among both supporters and opponents. While our current understanding of heat more closely resembles Rumford’s idea of matter in motion, the presence of terms like "latent heat" and "heat capacity" in modern textbooks reveals the continued debt that thermodynamics owes to the caloric theorists.

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1. Again, note how scientific laws and theories are different, yet related kinds of claims about the natural world. These chemical theories are now well-established, yet remain theories. All scientific theories, no matter how well established, remain theories.

6. In what ways does this story illustrate that science requires creativity?

7. In what ways does this story illustrate that scientific ideas are seldom the result of the work of an individual scientist, but rather the result of complex interactions between multiple scientists?
Imagine the confusion among chemists during the middle of the nineteenth century. By 1860, more than 60 elements had been discovered. Chemists had to learn the properties of these elements as well as those of the many compounds that they formed—a difficult task. And to make matters worse, there was no method for accurately determining an element's atomic mass or the number of atoms of an element in a particular chemical compound. Different chemists used different atomic masses for the same elements, resulting in different compositions being proposed for the same compounds. This made it nearly impossible for one chemist to understand the results of another.

In September 1860, a group of chemists assembled at the First International Congress of Chemists in Karlsruhe, Germany, to settle the issue of atomic mass as well as some other matters that were making communication difficult. At the Congress, Italian chemist Stanislao Cannizzaro presented a convincing method for accurately measuring the relative masses of atoms. Cannizzaro's method enabled chemists to agree on standard values for atomic mass and initiated a search for relationships between atomic mass and other properties of the elements.

**Mendeleev and Chemical Periodicity**

When the Russian chemist Dmitri Mendeleev heard about the new atomic masses discussed at Karlsruhe, he decided to include the new values in a chemistry textbook that he was writing. In the book, Mendeleev hoped to organize the elements according to their properties. He went about this much as you might organize information for a research paper. He placed the name of each known element on a card, together with the atomic mass of the element and a list of its observed physical and chemical properties. He then arranged the cards according to various properties and looked for trends or patterns.

Mendeleev noticed that when the elements were arranged in order of increasing atomic mass, certain similarities in their chemical properties appeared at regular intervals. Such a repeating pattern is referred to as *periodic*. The second hand of a watch, for example, passes over any given mark at periodic, 60-second intervals. The circular waves created by a drop of water hitting a water surface are also periodic.
Mendelev created a table in which elements with similar properties were grouped together—a periodic table of the elements. His first periodic table, shown in Figure 5-2, was published in 1869. Note that Mendelev placed iodine, I (atomic mass 127), after tellurium, Te (atomic mass 128). Although this contradicted the pattern of listing the elements in order of increasing atomic mass, it allowed Mendelev to place tellurium in a group of elements with which it shares similar properties. Reading horizontally across Mendelev’s table, this group includes oxygen, O, sulfur, S, and selenium, Se. Iodine could also, then, be placed in the group it resembles chemically, which includes fluorine, F, chlorine, Cl, and bromine, Br.

Mendelev’s procedure left several empty spaces in his periodic table (see Figure 5-2). In 1871, the Russian chemist boldly predicted the existence and properties of the elements that would fill three of the spaces. By 1886, all three elements had been discovered. Today these elements are known as scandium, Sc, gallium, Ga, and germanium, Ge. Their properties are strikingly similar to those predicted by Mendelev.
The success of Mendeleev’s predictions persuaded most chemists to accept his periodic table and earned him credit as the discoverer of the periodic law. Two questions remained, however. (1) Why could most of the elements be arranged in the order of increasing atomic mass but a few could not? (2) What was the reason for chemical periodicity?

**Moseley and the Periodic Law**

The first question was not answered until more than 40 years after Mendeleev’s first periodic table was published. In 1911, the English scientist Henry Moseley, who was working with Ernest Rutherford, examined the spectra of 38 different metals. When analyzing his data, Moseley discovered a previously unrecognized pattern. The elements in the periodic table fit into patterns better when they were arranged in increasing order according to nuclear charge, or the number of protons in the nucleus. Moseley’s work led to both the modern definition of atomic number and the recognition that atomic number, not atomic mass, is the basis for the organization of the periodic table.

Moseley’s discovery was consistent with Mendeleev’s ordering of the periodic table by properties rather than strictly by atomic mass. For example, according to Moseley, tellurium, with an atomic number of 52, belongs before iodine, which has an atomic number of 53. Today, Mendeleev’s principle of chemical periodicity is correctly stated in what is known as the periodic law: The physical and chemical properties of the elements are periodic functions of their atomic numbers. In other words, when the elements are arranged in order of increasing atomic number, elements with similar properties appear at regular intervals.

**The Modern Periodic Table**

The periodic table has undergone extensive change since Mendeleev’s time (see Figure 5-6 on pages 130–131). Chemists have discovered new elements and, in more recent years, synthesized new ones in the laboratory. Each of the more than 40 new elements, however, can be placed in a group of other elements with similar properties. The periodic table is an arrangement of the elements in order of their atomic numbers so that elements with similar properties fall in the same column, or group.

**The Noble Gases**

Perhaps the most significant addition to the periodic table came with the discovery of the noble gases. In 1894, English physicist John William Strutt (Lord Rayleigh) and Scottish chemist Sir William Ramsay discovered argon, Ar, a gas in the atmosphere that had previously escaped notice because of its total lack of chemical reactivity. Back in 1868,
another noble gas, helium, He, had been discovered as a component of the sun, based on the emission spectrum of sunlight. In 1895, Ramsay showed that helium also exists on Earth.

In order to fit argon and helium into the periodic table, Ramsay proposed a new group. He placed this group between the groups now known as Group 17 (the fluorine family) and Group 1 (the lithium family). In 1898, Ramsay discovered two more noble gases to place in his new group, krypton, Kr, and xenon, Xe. The final noble gas, radon, Rn, was discovered in 1900 by the German scientist Friedrich Ernst Dorn.

The Lanthanides

The next step in the development of the periodic table was completed in the early 1900s. It was then that the puzzling chemistry of the lanthanides was finally understood. The lanthanides are the 14 elements with atomic numbers from 58 (cerium, Ce) to 71 (lutetium, Lu). Because these elements are so similar in chemical and physical properties, the process of separating and identifying them was a tedious task that required the effort of many chemists.

The Actinides

Another major step in the development of the periodic table was the discovery of the actinides. The actinides are the 14 elements with atomic numbers from 90 (thorium, Th) to 103 (lawrencium, Lr). The lanthanides and actinides belong in Periods 6 and 7, respectively, of the periodic table, between the elements of Groups 3 and 4. To save space, the lanthanides and actinides are usually set off below the main portion of the periodic table, as shown in Figure 5-6 on pages 130–131.

Periodicity

Periodicity with respect to atomic number can be observed in any group of elements in the periodic table. Consider the noble gases of Group 18. The first noble gas is helium, He. It has an atomic number of 2. The elements following helium in atomic number have completely different properties until the next noble gas, neon, Ne, which has an atomic number of 10, is reached. The remaining noble gases in order of increasing atomic number are argon (Ar, atomic number 18), krypton (Kr, atomic number 36), xenon (Xe, atomic number 54), and radon (Rn, atomic number 86). The differences in atomic number between successive noble gases are shown in Figure 5-4. Also shown in Figure 5-4 are atomic-number differences between the elements of Group 1, which are all solid, silvery metals. As you can see, the differences in atomic number between the Group 1 metals follow the same pattern as the differences in atomic number between the noble gases.

Starting with the first member of Groups 13–17, a similar periodic pattern is repeated. The atomic number of each successive element is 8, 18, 18, and 32 higher than the atomic number of the element above it. In Section 5-2, you will see that the second mystery presented by Mendeleev’s periodic table—the reason for periodicity—is explained by the arrangement of the electrons around the nucleus.
Travels with C

From "Travels with C" by Primo Levi in Creation to Chaos

I was to carbon, the element of life, that my first literary dream was turned—and now I want to tell the story of a single atom of carbon.

My fictional character lies, for hundreds of millions of years, bound to three atoms of oxygen and one of calcium, in the form of limestone. (It already has behind it a very long cosmic history, but that we shall ignore.) Time does not exist for it, or exists only in the form of sluggish daily or seasonal variations in temperature. Its existence, whose monotony cannot be conceived of without horror, is an alternation of hots and colds.

The limestone ledge of which the atom forms a part lies within reach of man and his pickax. At any moment—which I, as narrator, decide out of pure caprice to be the year of 1840—a blow of the pickax detached the limestone and sent it on its way to the lime furnace, where it was plunged into the world of things that change. The atom of carbon was roasted until it separated from the limestone's calcium, which remained, so to speak, with its feet on the ground and went on to meet a less brilliant destiny. Still clinging firmly to two of its three companions, our fictional character issued from the chimney and rode the path of the air. Its story, which once was immobile, now took wing.

The atom was caught by the wind, flung down onto the earth, lifted ten kilometers high. It was breathed in by a falcon, but did not penetrate the bird's rich blood and was exhaled. It dissolved three times in the sea, once in the water of a cascading torrent, and again was expelled. It traveled with the wind for eight years—now high, now low, on the sea and among the clouds, over forests, deserts and limitless expanses of ice. Finally, it stumbled into capture and the organic adventure.

The year was 1848. The atom of carbon, accompanied by its two satellites of oxygen, which maintained it in a gaseous state, was borne by the wind along a row of vines. It had the good fortune to brush against a leaf, penetrate it, and be nailed there by a ray of the sun. On entering the leaf, it collided with other innumerable molecules of nitrogen and oxygen. It adhered to a large and complicated molecule that activated it, and simultaneously it received the decisive message from the sky, in the flashing form of a packet of solar light: in an instant, like an insect caught by a spider, the carbon atom was separated from its oxygen, combined with hydrogen, and finally inserted in a chain of life. All this happened swiftly, in silence, at the temperature and pressure of the atmosphere.

Reading for Meaning
Name the various compounds that the carbon atom was a component of during the course of Levi's story.

Read Further
As a component of one particular compound, Levi's carbon atom is breathed in and exhaled by a falcon. Why was it unlikely for the carbon atom to have been taken into the bird's bloodstream?
Aeronautical engineers use wind tunnels and scale models to simulate and test the forces from the moving air on each proposed design. The scale model shown is a physical model. However, not all models are physical. In fact, several theoretical models of the atom have been developed over the last few hundred years. In this section, you will learn about the currently accepted model of how electrons behave in atoms.

**The Development of Atomic Models**

So far in this textbook, the model for the atom consisted of protons and neutrons making up a nucleus surrounded by electrons. After discovering the atomic nucleus, Rutherford used existing ideas about the atom and proposed an atomic model in which the electrons move around the nucleus, like the planets move around the sun. Rutherford's model explained only a few simple properties of atoms. It could not explain, for example, why metals or compounds of metals give off characteristic colors when heated in a flame, or why objects—when heated to higher and higher temperatures—first glow dull red, then yellow, then white, as shown in Figure 5.1. Rutherford's atomic model could not explain the chemical properties of elements. Explaining what leads to the chemical properties of elements requires a model that better describes the behavior of electrons within atoms.

**Figure 5.1** Rutherford's model fails to explain why objects change color when heated. As the temperature of this horseshoe is increased, it first appears black, then red, then yellow, and then white. The observed behavior could be explained only if the atoms in the iron gave off light in specific amounts of energy. A better atomic model was needed to explain this observation.
**The Bohr Model**

Niels Bohr (1885–1962), a young Danish physicist and a student of Rutherford, believed Rutherford’s model needed improvement. In 1913 Bohr changed Rutherford’s model to include newer discoveries about how the energy of an atom changes when it absorbs or emits light. He considered the simplest atom, hydrogen, which has one electron. **Bohr proposed that an electron is found only in specific circular paths, or orbits, around the nucleus.** The timeline in Figure 5.2 shows the development of atomic models from 1800 to 1935.

Each possible electron orbit in Bohr’s model has a fixed energy. The fixed energies an electron can have are called **energy levels**. The fixed energy levels of electrons are somewhat like the rungs of the ladder in Figure 5.3a. The lowest rung of the ladder corresponds to the lowest energy level. A person can climb up or down a ladder by going from rung to rung. Similarly, an electron can jump from one energy level to another. A person on a ladder cannot stand between the rungs. Similarly, the electrons in an atom cannot be between energy levels. To move from one rung to another, a person climbing a ladder must move just the right distance. To move from one energy level to another, an electron must gain or lose just the right amount of energy. In general, the higher an electron is on the energy ladder, the farther it is from the nucleus.

A **quantum** of energy is the amount of energy required to move an electron from one energy level to another energy level. The energy of an electron is said to be quantized. You have probably heard the term **quantum leap** used to describe an abrupt change. The term originates from the ideas found in the Bohr model of the atom.
The amount of energy an electron gains or loses in an atom is not always the same. Like the rungs of the strange ladder in Figure 5.3b, the energy levels in an atom are not equally spaced. The higher energy levels are closer together. It takes less energy to climb from one rung to another near the top of the ladder in Figure 5.3b, where the rungs are closer. Similarly, the higher the energy level occupied by an electron, the less energy it takes to move from that energy level to the next higher energy level.

The Bohr model gave results in agreement with experiment for the hydrogen atom. However, it still failed in many ways to explain the energies absorbed and emitted by atoms with more than one electron.

Figure 5.3 These ladder steps are somewhat like energy levels.  
1. In an ordinary ladder, the rungs are equally spaced.  
2. The energy levels in atoms are unequally spaced, like the rungs in this ladder. The higher energy levels are closer together.
The Quantum Mechanical Model

The Rutherford planetary model and the Bohr model of the atom are based on describing paths of moving electrons as you would describe the path of a large moving object. New theoretical calculations and experimental results were inconsistent with describing electron motion this way. In 1926, the Austrian physicist Erwin Schrödinger (1887–1961) used these new results to devise and solve a mathematical equation describing the behavior of the electron in a hydrogen atom. The modern description of the electrons in atoms, the **quantum mechanical model**, comes from the mathematical solutions to the Schrödinger equation.

Like the Bohr model, the quantum mechanical model of the atom restricts the energy of electrons to certain values. Unlike the Bohr model, however, the quantum mechanical model does not involve an exact path the electron takes around the nucleus. The **quantum mechanical model** determines the allowed energies an electron can have and how likely it is to find the electron in various locations around the nucleus.

How likely it is to find the electron in a particular location is described by probability. If you place three red marbles and one green marble into a box and then pick a marble without looking, the probability of picking the green marble is one in four, or 25%. This means that if you put the four marbles in a box and picked one, and repeated this a great many times, you would pick a green marble in 25% of your tries.

The quantum mechanical model description of how the electron moving around the nucleus is similar to the motion of a rotating propeller blade. Figure 5.4a shows that the propeller blade has the same probability of being anywhere in the blurry region it produces in the picture, but you cannot tell its precise location at any instant. Similarly, in the quantum mechanical model of the atom, the probability of finding an electron within a certain volume of space surrounding the nucleus can be represented as a fuzzy cloud. The cloud is more dense where the probability of finding the electron is high. The cloud is less dense where the probability of finding the electron is low. Though it is unclear where the cloud ends, there is at least a slight chance of finding the electron at a considerable distance from the nucleus. Therefore, attempts to show probabilities as a fuzzy cloud are usually limited to the volume in which the electron is found 90% of the time. To visualize an electron probability cloud, imagine that you could mold a sack around the cloud so that the electron was inside the sack 90% of the time. The shape of the sack would then give you a useful picture of the shape of the cloud.
APPENDIX L

Interview Protocol: Student Responses to VOSSI/Attitudes Survey

Time of Interview:
Date:
Place:
Interviewer:
Interviewee:
Position of Interviewee:
The purpose of this study is to determine the impact of using historical chemistry short stories on high school students understanding of the nature of science. Data has been collected via pre and post surveys and will also be collected through personal interviews. Your information will be confidential and your name will not be associated with your responses. The interview will likely last between 30 minutes to one hour. Interviewee should have previously filled out and signed the consent form.

Questions:

1. How do you think society and culture affect or do not affect scientific research?
2. How do you think scientists use or do not use imagination and creativity in scientific investigations?
3. To what degree do you think that scientists work with other scientists when doing research?
4. Why do you think well supported and established scientific knowledge changes or does not change over time?
5. Explain what you liked about these readings.
6. To what extent did you like or dislike these readings compared to readings from a science textbook or other typical class readings?
7. Learning about how science works and how scientific ideas are developed and become accepted is a goal of science education.
   a. How important do you think this goal is for high school science classes?
   b. Why do you think this is or is not an important goal?
8. To what extent did these stories help you improve your understanding of how science works and how scientific ideas are developed and become accepted?
9. To what extent are you interested in a science-related career? Please explain why you are or are not interested in a science-related career.