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Historical short stories as nature of science instruction in secondary science classrooms: Science teachers’ implementation and students’ reactions

by

Jennifer Ann Reid-Smith

A dissertation submitted to the graduate faculty in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Education

Program of Study Committee:
Michael Clough, Co-Major Professor
Joanne Olson, Co-Major Professor
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Isaac Gottesman

Iowa State University
Ames, Iowa
2013

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DEDICATION

To my son for all the love, laughter, and joy you have given me.

To my parents for your unconditional love, encouragement, and unwavering belief in my ability to complete this journey. Thank you for the many long phone conversations and frequently reminding me of what I am capable of achieving.

To my sister and brother-in-law for the frustrations, happiness, and laughter we’ve shared through graduate school and becoming parents.

To my grandmother for teaching me to persevere in the face of so many obstacles.
    You will be greatly missed.

Thank you all for your love and everything you have done to make this possible.
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Finally, I would like to thank my family for their encouragement, patience, respect, and love, without which I could not have completed this work.
ABSTRACT

This study explores the use of historical short stories as nature of science (NOS) instruction in thirteen secondary science classes. The stories focus on the development of science ideas and include statements and questions to draw students’ and teachers’ attention to key NOS ideas and misconceptions. This study used mixed methods to examine how teachers implement the stories, factors influencing teachers’ implementation, the impact on students’ NOS understanding, students’ interest in the stories and factors correlated with their interest.

Teachers’ implementation decisions were influenced by their NOS understanding, curricula, time constraints, perceptions of student ability and resistance, and student goals. Teachers implementing stories at a high-level of effectiveness were more likely to make instructional decisions to mitigate constraints from the school environment and students. High-level implementers frequently referred to their learning goals for students as a rationale for implementing the stories even when facing constraints. Teachers implementing at a low-level of effectiveness were more likely to express that constraints inhibited effective implementation. Teachers at all levels of implementation expressed concern regarding the length of the stories and time required to fully implement the stories. Additionally, teachers at all levels of implementation expressed a desire for additional resources regarding effective story implementation and reading strategies.

Evidence exists that the stories can be used to improve students’ NOS understanding. However, under what conditions the stories are effective is still unclear. Students reported finding the stories more interesting than textbook readings and many students enjoyed
learning about scientists and the development of science ideas. Students’ interest in the stories is correlated with their attitudes towards reading, views of effective science learning, attributions of academic success, and interest in a science-related career.

If NOS instructional materials are to be used effectively, designers must take into account the needs of classroom teachers by limiting the length of the materials and providing additional teacher support resources. Many teachers will likely require professional development opportunities to build their NOS understanding, develop a compelling rationale for teaching NOS and using the stories, observe modeling of effective implementation, and collaborate with other teachers regarding how to mitigate constraints.
CHAPTER 1: INTRODUCTION

The Nature of Science in Secondary Science Education

Science and technology are pervasive in modern society. Reflecting this, much emphasis has been placed on science, technology, and mathematics education in an effort to improve both understanding and career interest in STEM areas. Despite science and technology education becoming highly publicized, many students leave their secondary education experiences possessing only superficial knowledge of science and technology, and disinterested in science classes and science careers. Tragically, many students wrongly think that science is merely a list of proven ideas to memorize, devoid of personal meaning in their lives, and only for unusually intelligent individuals.

Additionally, a large percentage of students leave their secondary education denying well established, but publically controversial, science ideas (e.g. biological evolution, age of the earth, and global climate change). Many of these K-12 science education shortcomings arise from the way science is taught that results in mistaken notions about the nature of science.

The expression “nature of science” (NOS) has long been used in science education in referring to “issues such as what science is, how it works, the epistemological and ontological foundations of science, how scientists operate as a social group and how society itself both influences and reacts to scientific endeavors” (Clough, p. 463). In addressing these issues, science educators look to the intersection among scholarly work in the history, philosophy, sociology, and psychology of science (McComas, Clough, & Almazroa, 1998; McComas & Olson, 1998). Research continually
indicates students, teachers, and the general public have many strongly held misconceptions regarding the NOS (Abd-El-Kahlick & Lederman, 2000; Clough, 2000; Eflin, Glennman, & Reisch, 1999; McComas, 1998; Ryan and Aikenhead, 1992) that contribute to the development of many of the shortcomings of science education described above. For example, many students do not consider science-related careers because they wrongly view science as a solitary endeavor devoid of social interactions, creativity, and imagination. Misconceptions that scientists follow a universal scientific method, that good science must be experimental and involve control-treatment methodologies, and that science is based on philosophical materialism all contribute to many students rejecting well-supported science ideas. Additionally, the view that good scientists are objective and that science, when done well, results in ontologically true knowledge may lead individuals to reject or be distrustful of changing or reinterpretation of scientific knowledge.

Students’ perceptions of NOS are originally formed and continually influenced by their frequent interactions with media and science classroom experiences. Media representations of scientists and scientific work promote the stereotype of the solitary and “nerdy” male scientist primarily engaged in experimental science at a lab bench. The contributions of women, the social and creative aspects of science, and the role of outdoor and observational science are rarely portrayed. Textbooks frequently portray only the end products of science, and the history of science ideas, when addressed at all, are typically limited to naming individuals who are given credit for “discovering” a particular noteworthy science idea. Thus, science textbooks frequently portray science as a list of final form ideas that develop in a straightforward logical manner due to the
efforts of rather solitary geniuses.

Students’ NOS misconceptions also result from their teachers’ instructional decisions and behaviors. Teachers send students’ frequent and powerful messages regarding NOS by the types of materials, activities, and language they use (Dibbs, 1982; Benson, 1984; Lederman, 1986; McComas et al., 1998; Ryan & Aikenhead, 1992; Zeidler & Lederman, 1989). For example, the frequent use of cookbook and verification labs along with traditional lab reports suggests that scientists utilize a step-by-step method in their work to obtain a ‘correct’ answer while downplaying ambiguity, creativity, imagination, and social interaction in scientific work. Such messages regarding NOS are continually received by students regardless of whether the teacher chooses to explicitly teach NOS concepts or not (Clough & Olson, 2004; Dibbs, 1982). Thus, science teachers cannot avoid teaching about NOS, but can only choose whether they will foster accurate or inaccurate NOS conceptions in their students.

**Rationale for Teaching the NOS in Secondary Science Classes**

The science education community has long recognized the importance of NOS instruction as a component of science education, including arguments dating back to the mid-1800s (Matthews, 2012). Hurd (1960) asserted:

There are two major aims of science-teaching; one is knowledge, and the other is enterprise. From science courses, pupils should acquire a useful command of science concepts and principles. Science is more than a collection of isolated facts… A student should learn something about the character of scientific knowledge, how it has developed, and how it is used (p. 34).

More recently, inclusion of NOS into school science has been widely endorsed by organizations including the American Association for the Advancement of Science
(1989, 1993, 2009), the National Science Teachers Association (1995, 2000), and the National Research Council (1996, 2013). This reflects that an accurate understanding of NOS is a necessary component for developing students’ science literacy (Matthews, 1994; McComas et al., 1998; Shamos, 1995) and preparing students to participate in society and societal and personal decision-making (Allchin, 2011; Driver, Leach, Miller, & Scott, 1996; McComas et al., 1998; Mitchell, 2009; Rudolph, 2005). Not only does accurate NOS understanding support successful learning of science content (Driver et al., 1996; Matthews, 1994; McComas et al., 1998; Meyling, 1997; Rudolph & Stewart, 1998), but when students understand how science ideas develop and why they change, students find science more interesting and their resistance to learning science concepts publically viewed as controversial (e.g. global climate change and evolution) may be reduced. Tobias (1990) reports that NOS education also humanizes science and thus increases students’ interest in science content and science careers.

**Effective NOS Instruction**

Due to the presence of strongly held and frequently entangled misconceptions, effective NOS instruction is a matter of provoking conceptual change (Clough, 2006). Thus, students’ attention must be overtly drawn to accurate NOS ideas in a manner that requires them to think about and wrestle with those ideas. While implicit NOS messages play an important role in the development of students’ initial NOS ideas, once those misconceptions are formed and linked to other misconceptions, changing them to more effective views requires overt attention (Clough, 2006). Repeated exposure to a variety of classroom experiences and activities overtly drawing students’ attention to accurate NOS
views is necessary for effectively changing students’ misconceptions regarding the NOS.

Clough (2006) advocates for the use of a range of classroom experiences along a
continuum of decontextualize to highly contextualized NOS experiences with extensive
scaffolding among them. Decontextualized examples (e.g. black box activities, puzzle
solving, and discrepant events) are useful for introducing students to NOS conceptions
without the need to simultaneously wrestle with complex science content (Clough, 2006;
Lederman & Abd-El-Khalick, 1998). However, decontextualized activities, alone, are
easily dismissed by students as not examples of how science works and are insufficient
for students to develop an accurate understanding of NOS (Clough, 2006). Moderately
contextualized activities include participation in science inquiry activities where the
teacher overtly draws students’ attention to the similarities and differences between their
work and the work of scientists. Still, students may regard such experiences as simply
school science and not representative of how actual science is done. Thus, utilizing
highly contextualized examples drawing from historical and contemporary science work
is a necessary component of efforts to promote deep NOS conceptual understanding
(Clough, 2006). Contextualized examples provide authentic examples for students to
explore the multifaceted dimensions of past and current scientific work, humanize
science, and should be compared and contrasted with students’ own experiences with
decontextualized and moderately contextualized NOS activities. Because highly
contextualized NOS activities present the actual practices of scientists, they cannot easily
dismiss those as not representing the actual nature of science.

Again, highly contextualized NOS instructional experiences demand attention to
the history of science to provide evidence regarding the NOS. The integration of history
of science (HOS) into science content instruction has long been advocated in science education (AAAS, 1993; Bybee, et al., 1991; Clough, 2006; Clough, 2011; Conant 1957; Eichman, 1996; Hagan, Allchin, & Singer, 1996; Klopfer, 1969; Klopfer & Cooley, 1963; Matthews, 1994; Monk & Osborne, 1997; Russell, 1981; Stinner, McMillan, Metz, Jilek, & Klassen, 2003). HOS serves as an ideal tool for providing the contextualized examples necessary for students’ conceptual change regarding NOS, illuminating the human aspects of science, and helping students recognize how and why science ideas were developed. Research indicates that historically contextualized instruction plays an important role in enriching student understanding of science (Clough, 2006; Jung, 1994; Klassen, 2006) by increasing understanding of both NOS (Brush, 1989; Irwin, 2000; Solomon, Scott, & Duveen, 1996) and science content (Galili & Hazen, 2000), enlivening science teaching (Castro & DeCarvalho, 1995), and student attitudes towards science (Allchin, Anthony, & Bristol, 1999). Additionally, the HOS may increase students’ interest in science by both humanizing science education (Tobias, 1990) and preventing science teaching from becoming simply a list of conclusions.

NOS and HOS Curricular Materials

The Problematic Nature of NOS and HOS Curricular Materials

Clough (2006) notes that a plethora of approaches have been put forward for integrating the HOS in science education. These include historical case studies (Allchin, 2012; Conant, 1957; Klopfer 1964; Matthews, 1994), adding significant historical components in the curriculum (Rutherford, Holton, & Watson, 1970; Cassidy et al, 2002; Lin & Chen, 2002), addressing misleading textbook accounts of science content (Rudge,
2000), historical short stories (Clough, 1997; Clough, 2011; Hagan et al, 1996; Leach, Hind, & Ryder, 2003; Solomon et al., 1992; Tao, 2003), and short historical vignettes reflecting the lives of scientists (Wandersee, 1992; Monk & Osborne, 1997).

That these HOS and NOS materials are not widely adopted is related to teachers’ perceptions regarding NOS instruction and the practicality of using such materials in their courses. Many secondary science teachers view NOS instruction as unnecessary, time consuming, and detracting from science content instruction. Additionally, NOS instruction appears to conflict with “expectations held of science and science teaching in schools, not only by teachers and pupils, but also by those perceived as being held by parents and society” (Lakin & Wellington, 1994, p. 186). Monk and Osborne (1997) maintain that many existing materials do not meet the perceived needs of secondary teachers because extensive HOS case studies and curricula are too time consuming, while common decontextualized NOS activities are thought to detract from science content instruction. Perhaps HOS and NOS materials may be more agreeable to teachers if they are contextualized within the science content being taught in their courses and do not require extensive time (Clough, 2006; Monk & Osborne, 1997).

Post-Secondary Historical Short Stories Project

One approach to NOS curriculum development designed to meet the perceived needs of science teachers is creating historical and contemporary science short stories focused on the development of key science concepts frequently taught in science courses. Such stories are tightly linked to science content commonly taught and take relatively little instructional time. This was the approach of the National Science Foundation
supported project *Story Behind the Science: Bring Science and Scientists to Life* (Clough, Olson, Stanley, Colbert, & Cervato, 2006) that developed thirty historical and contemporary science short stories focused on the development of key science ideas commonly taught in introductory post-secondary science courses (http://www.storybehindthescience.org). The developed short stories overtly draw students’ attention to NOS ideas and include questions requiring students to reflect on key NOS ideas relevant to each story. The successful use of these materials to change students’ NOS conceptions in post-secondary science courses (Clough, Herman, & Smith, 2010; Kruse, 2010; Vanderlinden, 2007) raises the question of the potential usefulness of similar materials in secondary science instruction.

**Historical Short Stories for Secondary Science Classrooms**

In a small study exploring the use of these kinds of short stories in a secondary science classroom, two of the post-secondary stories from the project above (Clough et al., 2006) were modified and implemented in a high school biology course (Smith, 2010). Stories about the lives and work of Charles Darwin and Gregor Mendel were modified to be more appropriate for secondary students and incorporated in an introductory high school biology course. Compared to students in a control group, students utilizing the two NOS short stories had a significantly better understanding of three of the six NOS concepts made explicit in the two short stories. Additionally, most students reported preferring the NOS short stories to typical textbook readings (Smith, 2010).

**Study Purpose and Research Questions**

Results from the prior work at the high school level noted above warrant a larger
study investigating the effectiveness of using similar NOS short stories with secondary school science students. In addition to exploring the effectiveness of these stories with students, investigation into the factors influencing secondary science teachers’ implementation of the stories is also needed. The study reported here was designed to determine: (1) what factors impact secondary science teachers’ implementation of the science short stories; (2) the impact of using a greater number of the aforementioned science short stories on secondary students’ understanding of the NOS, perceptions of science, and interest in a science-related career; (3) students’ attitudes toward and interest in the NOS short stories; and (4) potential factors correlated with students’ interest in the stories. The following research questions are the focus of this study:

1) What factors impact secondary teachers’ implementation of the science short stories as part of their classroom instruction?

2) What impact, if any, does the use of NOS short stories in secondary science classes have on students’ understanding of fundamental NOS concepts?

3) Following the use of the short stories, what are secondary science students’ perceptions regarding their interest in:
   a) reading the short stories compared to textbook or other typical course readings?
   b) reading about scientists and how science ideas are developed?

4) What correlation, if any, exists between students’ interest in the short stories and their:
   a) attitude towards reading?
   b) conceptions of learning?
   c) attribution for academic success?
Overview of Methodology

The study reported here utilized stories modified from the post-secondary NOS short stories (Clough et al., 2006) to create a total of fourteen short stories deemed appropriate for secondary school students. The seven stories relevant to biology content typically taught in high school biology courses included stories about genetics, biological evolution, global warming, DNA structure, DNA function, and two stories about the age of the earth. The seven stories relevant to chemistry content typically taught in high school science courses included stories about matter, conservation of mass, atomic model and theory, the periodic table, temperature scales, heat, and entropy. Prior to the beginning of the semester, teacher participants were provided the seven short stories relevant to the courses they taught.

Participants in this study included seven high school biology teachers, six high school chemistry teachers, and the students enrolled in their participating class periods. The study included teachers and students from urban, suburban, and rural high schools in a Midwestern state of the U.S.. Ten of the thirteen teachers participated during the Spring 2012 academic semester; the remaining three teachers joined the study the following academic year and participated in the Fall 2012 semester. Additionally, during the Spring 2012 semester, four teacher participants had student teachers in their classrooms who agreed to participate in the study.

This study used a mixed methods approach to investigate how teachers implement the NOS short stories, what factors impact teachers’ implementation decisions, how the use of such stories impacts secondary science students’ NOS understanding, and students’ perceptions of the stories. Particular quantitative and qualitative methods were
selected for addressing each research question. An overview of the methodological techniques used in this investigation for each research question appears below, but will be more extensively addressed in chapter 3.

To aid the reader in following the research methodology, Figure 1 presents a summary of the participant groups and data collected to answer each research question. The five control-treatment teachers (two biology and three chemistry) participated in a control-treatment quasi-experimental study to assess the impact of story implementation on secondary students’ NOS understanding. Control-treatment teachers agreed to utilize a minimum of three of the seven provided short stories in approximately half their class periods; the other half of their participating class periods served as a control group and did not utilize NOS stories. Students in both the control and treatment groups completed a NOS understanding questionnaire at the beginning and end of the study to measure their understanding of six NOS concepts overtly addressed in the seven provided stories. Pre scores were utilized as covariates to minimize the impact of existing differences between the two groups. Post scores were statistically assessed for significant differences between control and treatment group students’ understanding of the six NOS concepts assessed.
The use of a quasi-experimental design in the control-treatment teachers’ classes constrained their implementation decisions by requiring the utilization of at least three
stories. To gain an understanding of possible factors influencing teachers’ interest in using the stories and their implementation decisions without this constraint, the remaining eight teachers (five biology and three chemistry) were assigned to participate in an open-use situation. Open-use teachers were only required to have students read one of the seven provided stories, but they could elect to implement more. Thus, inclusion of the open-use teachers in this study permitted investigation of what factors may impact the number of stories teachers implement in their classroom instruction.

Classroom observations, teacher interviews, and classroom artifacts were used to investigate factors impacting teachers’ implementation of the NOS short stories. The researcher completed a minimum of three classroom observations of both story implementation and other typical classroom lessons for twelve of the thirteen participating teachers; one chemistry teacher was only observed twice. All teachers and three of the four student teachers completed a post-implementation interview to assess their decisions regarding story implementation, general impressions of the stories, interest in continued use of the stories, and suggestions for beneficial changes to the stories and accompanying resources. Classroom artifacts (e.g. syllabi, worksheets, activities, and assessments) were utilized to determine how consistent teachers’ typical classroom instruction is with NOS ideas presented in the stories and the presence of NOS on summative assessments. Following post-implementation interviews, the researcher reduced data from classroom observation field notes, interview transcripts, and classroom artifacts to assess teachers’ implementation practices for their quality of concept development (i.e. support for understanding the readings and support for reflecting on NOS ideas in the stories), student accountability, and classroom culture. Quantitative
scores for implementation practices were then used to examine correlations with students’ interest in the short stories. Open and axial coding techniques (Strauss & Corbin, 1998) were used to identify emerging themes from the teacher interview transcripts regarding factors influencing teachers’ implementation decisions.

Students from both the control-treatment teachers’ classes and the open-use teachers’ classes completed an interest and attitude questionnaire before and after story implementation. Pre interest and attitude surveys were utilized to provide pre-post reliability data for indices measuring students’ reading attitude, perceptions of effective learning environments, and attributions of academic success. Post interest and attitude surveys were utilized to assess students’ interest and attitudes in the stories and science careers and calculate correlations between students’ interest and their reading attitudes, perceptions of effective learning environments, attributions of academic success, and teachers’ implementation practices. To inform future material development, answers to open-response questions regarding what students did and did not like about the NOS short stories were assessed for common themes using open and axial coding techniques (Strauss & Corbin, 1998).

**Study Limitations**

Purposeful, criterion-based sampling (Isaac & Michael, 1995) was used to select teacher participants for this study. Teacher participants expressed interest in utilizing NOS short stories in their classroom instruction and were willing to provide the researcher access to their classrooms. Although this sample included teachers with differing levels of teaching experience and from a variety of school settings,
generalizability of conclusions to a broader sample of high school science teachers should be done with caution. Additionally, the necessity of obtaining parent consent and student assent to utilize student survey data for research purposes resulted in student self-selection for participation in the study. Many potential student participants had to be removed from the sample population. In some instances, the limited return of informed consent forms may have resulted in sampling of participating students that was not representative of a specific teachers’ student population. Additional study limitations will be discussed in chapter three.
CHAPTER 2: REVIEW OF THE LITERATURE

Introduction: The Goals and the Current State of Science Education

Reflecting the ubiquity of science and technology in modern society, the importance of science, technology, engineering, and mathematics (STEM) education in the United States has received considerable attention and support in recent years. Such interest prompted the development of a *Framework for K-12 Science Education* (NRC, 2012) and new science education standards, *Next Generation Science Standards: For States, By States* (NRC, 2013). While prior science standards and reform documents (AAAS, 1989, 1993, 2009; NRC, 1996) treated science and engineering as separate domains, the *Framework* and *NGSS* promote a more integrated approach to science, engineering, and technology education rather than establishing separate standards for engineering education. Regrettably, such an approach may detract from effective science education as science teachers, ill prepared to teach engineering concepts, are expected to spend already limited class time addressing not only science standards, but additional engineering standards as well.

Much political and media attention regarding STEM education has focused on preparing more students to pursue STEM and STEM-related careers to meet the perceived future needs of an increasingly technological society. Frequently, this attention has specified the need to increase diversity in science and STEM fields by increasing the participation of female and minority students. Additional interest has focused on science and STEM literacy for all students, as needed to successfully participate in and contribute to an increasingly STEM dependent society. In the recent report, *Successful K-12 STEM*
Education: Identifying effective approaches in science, technology, engineering, and mathematics, the National Research Council (NRC, 2011, p. 4-5) put forth three goals for U.S. STEM education:

- **Goal 1:** Expand the number of students who ultimately pursue advanced degrees and careers in STEM fields and broaden the participation of women and minorities in those fields.

- **Goal 2:** Expand the STEM-capable workforce and broaden the participation of women and minorities in that workforce.

- **Goal 3:** Increase STEM literacy for all students, including those who do not pursue STEM-related careers or additional study in the STEM disciplines.

The need to build scientific literacy among our students is not new and has been promoted in many official and semi-official documents (AAAS, 1993; UNESCO, 1993; NRC, 1996; Council of Ministers of Education, 1997; Millar & Osborne, 1998; Organization for Economic Cooperation and Development, 1999; Goodrum Hackling, & Rennie, 2000). However, a lack of consensus regarding a specific definition of scientific literacy and how to achieve it exists (DeBoer, 2001; Hodson, 2009; Laugksch, 2000; Roberts, 2007; Shamos, 1995). Among the simplest views, science literacy may be defined as the ability to read and understand articles about science and technology in magazines, newspapers, and online. Other definitions focus on science content and the knowledge and skills needed to function as a professional scientist. However, these are very limited views of scientific literacy; neither account for what is required for citizens to adequately understand and use scientific knowledge for decision-making. Hodson (2009) argues scientific literacy is:

...as much in learning about science and in doing science as it is in learning science. No science curriculum can equip citizens with thorough first-hand knowledge of all the science underlying every important issue.
Moreover, much of the scientific knowledge learned in school, especially in the rapidly expanding fields of biological sciences, will be out-of-date within a few years of learning school and so of little value in addressing socioscientific issues. However, science education can enable students to understand the significance of knowledge presented by others, and it can enable them to evaluate the validity and reliability of that knowledge and to understand why scientists often disagree among themselves on such major matters as climate change (and its causes) without taking it as evidence of bias or incompetence. What is too often unrecognized by science teachers, science textbooks and curricula, and by the wider public, is that dispute is one of the key driving forces of science. (p. 17)

Hodson (2008, 2009) argues for a more extensive definition, what he calls critical science literacy; he explains:

To be fully literate, students need to be able to distinguish among good science, bad science and non-science, make critical judgments about what to believe, and use scientific information and knowledge to inform decision making at the personal, employment and community levels. In other words, they need to be critical consumers of science. (Hodson, 2008, p. 3)

Allchin (2013) further argues for a science literacy focused on interpreting the reliability of scientific claims:

The informed citizen, then—the mature, well-educated students—will be able (at least) to interact with experts on topics they may know next to nothing about; recognize relevant evidence as well as presentations of bogus evidence; appreciate the limits as well as the foundations of emerging scientific claims; and negotiate through scientific uncertainty. One will be a competent interpreter, or critic, of science, even if not a practitioner of science (in the same way that film or music critics can effectively assess art without necessarily producing art themselves). Interpreting the reliability of scientific claims requires a broad understanding of scientific practice, or how science works, from a simple laboratory or field setting to science journalism. (p. 22)

However, the science education experiences of the typical K-12 student do little to promote critical science literacy of students or reduce the number of students who opt out of continuing their science education past compulsory secondary schooling. Almost 50 years ago, Schwab (1964) noted that science is taught as an “unmitigated rhetoric of
conclusions in which the current and temporal constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths” (p. 24). Regrettably, little has changed in the typical science classroom since that time. Science lessons frequently involve textbook reading, repetitive worksheets or problem sets, and cook-book verification laboratory activities. Science teachers rely heavily on textbooks focused on the end products of science, what Duschl (1990) calls final-form science, rather than expounding on how science ideas came about. Assessments are frequently based heavily on memorization and recall (Millar & Osborne, 1998). Students’ typical science education experiences frequently lack meaning and personal relevance for most students, and thus, serve to disengage students from science (Millar & Osborne, 1998). When describing the problematic nature of school science in the UK, Millar and Osborne (1998) state:

The science curriculum can appear as a ‘catalogue’ of discrete ideas, lacking coherence or relevance. There is an over-emphasis on content which is often taught in isolation from the kinds of contexts which could provide essential relevance and meaning… The existing stress on content limits the study of component such as the nature of science; the role of scientific evidence, probability and risk; and the ways in which scientists justify their knowledge claims—all of which are important aspects necessary to understand the practice of science. (Section 3, Science education: the remaining problems)

Students’ science education experiences in U.S. schools differ little from those reported by Millar and Osborne (1998) in the U.K. In a recent article in the New York Times (Dreifus, 2013), a variety of individuals were asked what one change they would make to improve science education in the United States. The following three students’ responses reflect the common complaints, discussed above. A fifth grade student from Baltimore said, “I need science and math education to be more about life.” A high school
senior from Washington reported, “I’d like more hands-on projects where I would learn something about what I’m doing instead of just memorizing things from a textbook.”

Lastly, a high school senior from Baltimore remarked:

One of the problems I have during math class is not understanding the reasoning behind what we are doing. The teacher will put something on the board and say, ‘This is how you do it,’ and I’m thinking, ‘Why does that make sense?’ The teachers are sometimes reluctant to explain it because they think we won’t understand. But if something doesn’t make sense to me, I can’t do it. I’d rather understand than just memorize formulas.

Despite the recent focus on STEM education and promotion of STEM-related careers, students frequently exit their secondary science education possessing only superficial knowledge of science and technology and disinterested in further science education or careers. Sadly, many students wrongly think that science is merely a list of proven ideas to memorize and devoid of personal meaning in their lives. Additionally, a large portion of students leave their secondary education denying well established, but publically controversial, science ideas (e.g. evolution, global climate change, and age of the earth). Many of these K-12 science education shortcomings arise from the way science is taught that result in mistaken notions about what science is and how it works (i.e., the nature of science). For example, many students do not consider science-related careers because they wrongly view science as a solitary endeavor devoid of social interactions, creativity, and imagination; thus, students who view themselves as creative individuals may opt out of science in favor of courses and careers they view as more creative than science (e.g. art, music, and writing).
The Nature of Science and Why NOS Instruction is Crucial

Characteristics of NOS

“The phrase ‘nature of science’ (NOS) is often used in referring to issues such as what science is, how it works, the epistemological and ontological foundations of science, how scientists operate as a social group and how society itself both influences and reacts to scientific endeavors” (Clough, 2006, p. 463). In addressing these issues, science educators look to the intersection among scholarly work in the history, philosophy, sociology, and psychology of science (McComas et al., 1998; McComas & Olson, 1998). Although consensus exists among science education literature and science standards documents that the nature of science should be accurately and effectively taught along with science content, the diversity of science disciplines and methods employed in scientific enterprise and the complexity of NOS issues result in limited agreement among philosophers of science about how science should be defined and what aspects of the nature of science should be taught to our students (Osborne, Ratchiffe, Collins, Millar, & Duschl, 2003; Smith & Scharmann, 1999; Stanley & Brickhouse, 2001). Yet, while philosophers and historians of science have failed to provide precise demarcation criterion (Alters, 1997; Laudan et al., 1986; Taylor, 1996; and Ziman, 2000), there are many common characteristics of science agreed upon by philosophers of science that are accessible and can be taught to secondary students (Abd-El-Khalick, Bell, & Lederman, 1998; Clough, 2000; Clough, 2006; Clough, 2007; Driver, Leach, Miller, & Scott, 1996; Eflin, Glennan, & Reisch, 1999; Hodson, 1991; Matthews, 1994; McComas, 2008; McComas & Olson, 1998; Osborne et al., 2003; Smith, Lederman, Bell, McComas, & Clough, 1997). Abd-El-Khalick et al. (1998) contend:
The disagreements that continue to exist among philosophers, historians, and science educators are far too abstract for K-12 students to understand and far too esoteric to be of immediate consequence to their daily lives… There is, however, an acceptable level of generality regarding the NOS that is accessible to K-12 students and also relevant to their daily lives. At this level of generality we can see clear connections between students’/citizens’ knowledge about science and decisions made regarding scientific claims. Also, at this level of generality, virtually no disagreement exists among historians, philosophers, and science educators. (p. 418)

Many lists of NOS ideas the science education community has come to consensus on have been developed and used to guide NOS education and research. One of the most commonly used of these lists comes from Lederman and colleagues (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002) and was used to shape their Views on Nature of Science Questionnaire (VNOS). Lederman’s list includes the following seven NOS ideas students and teachers should come to know:

- The empirical nature of scientific knowledge
- Distinguishing between scientific laws and theories
- The creative and imaginative nature of scientific knowledge
- The theory-laden nature of scientific knowledge
- The social and cultural embeddedness of scientific knowledge
- The myth of the scientific method
- The tentative nature of scientific knowledge

McComas (2008) presents a somewhat more encompassing list including nine “ideas appropriate to inform K-12 curriculum development, instruction and teacher education” (p. 251). The following are abbreviated descriptions of the NOS ideas McComas lists:

- 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.

While these, and other, lists of NOS ideas have provided a starting point for consideration by K-12 teachers when deciding what NOS ideas are important for their students to come to understand, concerns exist among the science education community about how such lists may limit NOS education in the classroom.

**Inadequacy of consensus lists and tenets**

The adequacy of NOS tenets for promoting science literacy and deep understanding of NOS concepts in K-12 science education has been repeatedly questioned (Allchin, 2011, 2013; Clough, 2007; Eflin et al., 1999; Hodson, 2009; Irzik & Nola, 2011; Matthews, 2012). Several science educators have warned of the danger in using a list of NOS tenets that can easily become more material for students to memorize and may limit which NOS ideas are taught in the classroom. Of primary concern is that a
list of NOS tenets may promote dogmatic NOS education rather than guiding students to explore the complexities and contextual nature of NOS concepts necessary for science literacy (Allchin, 2011, 2013; Clough, 2007; Hodson, 2009; Matthews, 2012). Clough (2007) explains:

The problem is NOS tenets, like any list of key ideas, may be easily distorted by researchers, teachers, and students. The problem is that tenets, like established scientific knowledge, become something to be transmitted rather than investigated in a science classroom. For students the tenets become something to know rather than understand. (p.2)

Allchin (2013) further argues:

Ultimately, nature of science is poorly profiled by a list of general declarations. Understanding needs to be functional and concrete, as expressed in the principle of teaching through historical and contemporary cases… Here, it is helpful to recall the broader goal of scientific literacy. Students should be able to interpret scientific practice in particular cases, not abstractly. A general level of understanding, as exhibited in the current consensus list… is not specific enough, say, for interpreting the safety of high-voltage power lines, waste incinerators, or pain-killing drugs. Memorizing or explaining a short list of principles is inadequate, even if they serve as convenient benchmarks for teachers. As AAAS noted in presenting its revised benchmarks in 2009, NOS is not dilute philosophy of science. Focusing on a prescribed set of stated concepts, then, misplaces the goal of NOS understanding. NOS understanding is best characterized functionally, towards supporting analytical skills in personal and public decision making. (p. 16)

Several alternative approaches to the use of tenets have recently been promoted in the literature. Clough (2007) argues for an approach using questions rather than tenets to promote deeper understanding of the contextual nature of key NOS concepts. For example, instead of teaching students that science ideas are tentative, one might ask questions such as, “In what sense is scientific knowledge tentative? In what sense is it durable?” Rather than telling students science is empirically based, teachers might ask, “To what extent is scientific knowledge empirically based? In what sense is it not always
empirically based?” Such an approach no longer limits NOS instruction to a prescribed set of NOS tenets, may increase classroom discussion of the complexities involved in NOS, and diminish the risk of NOS instruction being reduced to additional declarative knowledge for teachers to transmit and students to memorize.

Allchin (2011, 2013) promotes an alternative to the NOS tenets focused on students’ development of the rich understanding of NOS required for science literacy and decision-making. He states:

Although the NOS consensus list of the 1990s sketched an important core, when viewed in the context of science literacy, it also now seems significantly incomplete. That is, the limited set of principles – even if learned in fully functional terms – is insufficient to address the diverse and sometimes complex cases encountered by consumers and citizens in daily life and public discourse. (Allchin, 2013, p. 16)

Allchin (2011, 2013) argues for what he calls the Whole Science approach to NOS education that frames NOS “as a set of dimensions about how reliability is achieved as knowledge develops and how it is preserved as it moves from one place to another” (Allchin, 2011, p.524). Allchin (2013) explains:

One might call this framing of NOS, sensitive to all the dimensions of reliability in scientific practice, Whole Science. Whole Science, like whole food, does not exclude essential ingredients. It supports healthier understanding. Metaphorically, educators must discourage a diet of highly processed, refined “School Science.” Short or truncated lists of NOS features are simply unhealthy for understanding sciences… Many characterizations of the nature of science are incomplete. Targeting Whole Science helps restore the fullness of science. (p. 25)

Irzik and Nola (2011) and Matthews (2012) further argue against the use of NOS tenets in science education by asserting that NOS tenets distort the complexity of NOS and belie the science demarcation dispute. As no one set of criteria can be used to adequately distinguish all types of science, a “family resemblance” (Irzik & Nola, 2011)
or “features of science” (Matthews, 2012) approach may be more appropriate than a list of tenets. When speaking of the NOS tenets frequently put forth by the science education community, Matthews (2012) states:

Science is a human and thus historically-embedded truth seeking enterprise that has many features: Cognitive, social, commercial, cultural, political, structural, ethical, psychological etc. All of these features are worthy of study by science students as well as by disciplinary specialists; and different of them come into clearer focus when considering different sciences, and when considering different aspects of history, achievements and practice of the different sciences. Some of the features are shared to a large degree with other knowledge-acquiring enterprises, some are shared to a limited degree, and some are not shared at all. Given these characteristics of science, it is useful to understand NOS not as some list of necessary and sufficient conditions for a practice to be scientific, but rather as something that, following Wittgenstein’s terminology, identifies a ‘family resemblance’ of features that warrant different enterprises be called science. (p. 4)

**Rationales for Including NOS in Secondary Science**

The science education community has long recognized the importance of NOS instruction as a component of science education, including arguments dating back to the mid-1800s (Matthews, 2012). Modern organizations and reform documents consider the incorporation of NOS in school science to be crucial (National Research Council, 1996, 2013; National Science Board, 1996; National Science Teachers Association, 1995, 2000; AAAS, 1989, 1993, 2009). The writers of these documents have taken into account the important role an accurate understanding of NOS plays in preparing students for citizenship and participation in modern society, building science literacy, supporting the successful learning of science content, and increasing students’ interest in science and science-related careers.

Understanding NOS is a prerequisite for scientific literacy (Allchin, 2013;
Collette & Chiappetta, 1984; Hodson, 2009; Lederman, 1992; McComas et al., 1998; Matthews, 1989, 1994; Shamos, 1995; Shahn, 1988), and, therefore, essential for preparing students for their role as citizens and participation in a modern society heavily reliant on science and technology. NOS education prepares our students to be contributing citizens in our democratic society able to make informed decisions and judgments (Allchin, 2011; Driver et al., 1996; McComas et al., 1998; Millar & Osborne, 1998; Mitchell, 2009). An accurate understanding of NOS is necessary for effectively evaluating scientific claims impacting personal and community decisions regarding, among others, health, the environment, and public funding of science and technology. Additionally, an accurate understanding of NOS enables citizens to make sense of science and manage the technological objects/processes prevalent in our society (Driver et al., 1996; McComas et al., 1998). McComas et al. (1998) state:

Science has a pervasive, but often subtle, impact on virtually every aspect of modern life – both from the technology that flows from it and the profound philosophical implications arising from its ideas. However, despite this enormous effect, few individuals even have an elementary understanding how the scientific enterprise operates. This lack of understanding is potentially harmful, particularly in societies where citizens have a voice in science funding decisions, evaluating policy matters and weighing scientific evidence provided in legal proceedings. At the foundation of many illogical decisions and unreasonable positions are misunderstandings of the character of science. (p.3)

Furthermore, developing students’ accurate understanding of NOS supports successful learning of science content (Driver et al., 1996; Matthews, 1994; McComas et al., 1998; Meyling, 1997; Rudolph & Stewart, 1998), and interest in science and science careers. Effective NOS education illuminates the often hidden process of scientific knowledge development and humanizes science, both of which are indispensible for improving students’ attitudes toward science and increasing students’ interest in science
and science related careers. One way NOS understanding may support successful learning of science content is by increasing students’ interest in science and reducing their resistance to learning (McComas et al., 1998; Meyling, 1997; Driver et al., 1996). Additionally, when students understand how science ideas develop and why they change, their resistance to learning about integral science ideas that are publically controversial (e.g., evolution and global climate change) may be reduced (Mitchell, 2009; Rudolph, 2007).

During a time when increasing the participation of women and minorities in science and science-related careers is a goal of effective STEM education (NRC, 2011), improving students’ attitudes toward science and science careers is crucial. However, misconceptions about what science is, how science works, and characteristics of science damage scientific literacy and cause many individuals to opt out of science to pursue careers perceived as more humane and creative than science (Eccles, 2005; Tobias, 1990). Sadly, students frequently view science as a solitary endeavor devoid of social and collaborative aspects. Eccles (2005) maintains:

We as a culture do a very bad job of telling our children what scientists do. Young people have an image of scientists as eccentric old men with wild hair, smoking cigars, deep in thought, alone. Basically, they think of Einstein. We need to change that image and give our children a much richer, nuanced view of who scientists are, what scientists do and how they work.

The incorporation of NOS into science education provides a way to humanize science while illuminating the creative, social, and collaborative nature of scientific work; thereby, students’ interest in science content and science careers may be increased (Eccles, 2005; Tobias, 1990).

Regrettably, research continually demonstrates that students, teachers, and the
general public have inaccurate views regarding NOS and how science operates (Abd-El-Kahlick & Lederman, 2000; Clough, 1995; Clough, 2000; Durant, Evans, & Thomas, 1989; Eflin et al., 1999; Lederman, 1992; Mackay, 1971; McComas, 1998; Millar & Wynne, 1988; Miller, 1983, 1987; NAEP, 1989; National Science Board, 2002; Rubba, Horner, & Smith, 1981; Ryan and Aikenhead, 1992; Zeidler & Lederman, 1989; Ziman, 1991). The frequency of teachers’ NOS misconceptions is highly problematic as it prevents accurate and effective inclusion of NOS in science classrooms and inhibits all the positive impacts, described above, effective NOS instruction may have on students. Additionally, the negative impact of teachers’ NOS misconceptions cannot be mitigated by simply avoiding the teaching of NOS; regardless of their intent, science teachers cannot help but teach students about NOS through their choice in language and classroom activities.

**Inevitability of NOS Instruction**

Students’ perceptions of NOS are originally formed and continually influenced by their frequent interactions with media and classroom experiences. Media representations of scientists/scientific work promote stereotypes by misrepresenting or ignoring the role of women, the social and creative aspects of science, observational science, and outdoor science. High school textbooks largely misrepresent NOS, often explicitly (Abd-El-Khalick, 2009; Abd-El-Khalick, Waters & Le, 2008; Binns, I.C., 2009; Irez, 2009). Furthermore, teachers’ instructional decisions and behaviors frequently contribute to students’ NOS misconceptions:

…despite teachers’ intentions, science courses cannot escape conveying an image of the NOS to students. Teachers’ language (Benson, 1984;
Dibbs, 1982; Lederman, 1986; Zeidler & Lederman, 1989), cookbook laboratory activities, textbooks that report the end products of science without addressing how the knowledge was developed, misuse of important words having special meaning in a science setting, and traditional assessment strategies are just some of the ways students develop conceptions about the NOS. Ever present in science content and science teaching are implicit and explicit messages regarding the NOS. The issue is not whether science teachers will teach about the NOS, only what images will be conveyed to students.” (Clough, 2006, p.464)

Teachers send students’ frequent and powerful messages regarding NOS by the types of materials, activities, and language they use (Dibbs, 1982; Benson, 1984; Lederman, 1986; McComas et al., 1998; Munby, 1976; Ryan & Aikenhead, 1992; Zeidler & Lederman, 1989). These messages are continually received by the students regardless of whether teachers choose to explicitly teach NOS concepts or not (Clough & Olson, 2004; Dibbs, 1982). Thus, science teachers cannot avoid teaching about NOS, but can only choose whether they will foster accurate or inaccurate NOS conceptions among their students.

**Components of Effective NOS Instruction**

Teaching NOS concepts, as with science content concepts, is a matter of conceptual change (Clough, 2006). As with science content, students have many misconceptions regarding NOS that are highly resistant to change. Students’ NOS misconceptions are, in part, formed by their prior experiences with media portrayals of science and scientists, textbooks and teachers that represent the end products of science without addressing how scientific knowledge if developed, classroom experiences with cookbook laboratory activities, teacher and societal language and misuse of words with special scientific meaning, and traditional classroom assessments. Teacher behaviors,
activities, and language influence students’ accurate understanding of NOS (McComas et al., 1998; Ryan and Aikenhead, 1992), and students’ views of the NOS are influenced by the way they are taught science, even if their teacher does not attempt to do so explicitly (Dibbs, 1982). Unfortunately, many teachers consistently use classroom behaviors, activities, and language that misrepresent NOS (McComas et al., 1998; Ryan & Aikenhead, 1992); thus, reinforcing students’ NOS misconceptions. To effectively teach the nature of science, science teachers must be aware of previous misconceptions students hold regarding the nature of science. To change students’ misconceptions about the nature of science, teachers must use behaviors and language consistent with accurate portrayal of the nature of science throughout the year.

Implicit approaches to NOS education have frequently been promoted and assume NOS will be accurately learned as a by-product of engagement in science-based activities (e.g. inquiry laboratory activities that do not overtly draw students’ attention to how these activities are similar to or distort the NOS and student research activates). However, although many of students’ NOS misconceptions were instilled through implicit messages from the media and school experiences, implicit instruction is insufficient for changing students’ tightly held views of NOS once such conceptions are formed. Research indicates NOS instruction is more effective at changing students’ NOS conceptions when it has both an explicit and reflective character (Abd-El-Khalick & Lederman, 2000; Abd-El-Khalick et al., 1998; Akerson et al., 2000; Khishfe & Abd-El-Khalick, 2002). Explicit teaching requires teachers to plan for the instruction of particular NOS concepts and overtly draw students’ attention to these concepts, while reflective teaching involves using pedagogical approaches that help students make
connections between the classroom activities and the targeted NOS concepts. Allchin (2012) explains:

Activities and discussion should actively engage students in thinking about NOS problems and in articulating their developing perspectives. The effectiveness of active learning has already been widely acknowledged throughout all types of education (Bonwell and Eison 1991; National Research Council (NRC) 1997; Mayer, 2004; Michael, 2006): NOS education is no exception. (p. 1274)

However, explicit reflective instruction, alone, may not be enough to cause conceptual change. Effective NOS instruction capable of changing students NOS conceptions requires teachers consider how various NOS activities and experiences are integrated into the content and course and scaffold student thinking.

Explicit/reflective NOS learning experiences exist along a continuum of decontextualized to highly contextualized instruction with contextualized and decontextualized instructional activities playing different, but important, roles in NOS instruction (Clough, 2006). Decontextualized NOS activities overtly introduce and draw students’ attention to important NOS ideas without being integrated into the context of specific science content (Clough, 2006). Examples include, among others, black-box activities, discrepant events, puzzle solving activities, and pictorial gestalt switches (Clough, 2006; Clough, 1997; Lederman & Abd-El-Khalick, 1998). Decontextualized NOS activities are essential for providing opportunities for students to internalize NOS concepts without simultaneously struggling with unfamiliar and complex science concepts (Clough, 2006; Lederman & Abd-El-Khalick, 1998). However, decontextualized NOS activities do not match students’ perceptions of authentic science; thus, students may create two alternative conceptions of NOS, one for these types of NOS activities and one for authentic science (Clough, 2006). Consequently, frequently no
conceptual change regarding NOS concepts will have occurred following the use of decontextualized activities alone. Furthermore, teachers often perceive decontextualized NOS activities as additions to their curriculum that take time away from science content instruction, thus reducing the likelihood they will be utilized (Clough, 2006; Abd-El-Khalick et al., 1998).

Explicit/reflective moderately contextualized activities involve students’ own experiences in inquiry labs when students design procedures, wrestle with data, and report their work for peer review while the teacher draws students’ attention to how these experiences are or are not similar to the work of scientists (Clough, 2006). Such classroom experiences explicitly draw students’ attention to how what they are doing is similar and different from authentic science. However, moderately contextualized NOS activities may still be disregarded by students as not representative of authentic sciences. Students often perceive scientists as smarter, having more or better resources, and larger research teams. Thus, even with the inclusion of moderately contextualized NOS activities, students may still maintain a dualistic conception of science with one set of characteristics for school science and a separate set of characteristics applicable to authentic science.

Highly contextualized NOS activities overtly draw students’ attention to NOS issues embedded within science content and the development of scientific knowledge. Clough (2006) states, “Inescapably, highly contextualizing the NOS means integrating historical and contemporary science examples that are tied to the fundamental ideas taught in particular science subjects” (p. 474). Highly contextualized NOS lessons drawing from the history of science may demonstrate challenges scientist or the scientific
community face while constructing new ideas and determining their relationship with empirical evidence, illustrate important epistemological and ontological lessons integral to understanding both science content and NOS, and demonstrate the human aspects of science (Clough, 2006). The more contextualized an example is, the harder it is for students to dismiss the NOS idea or teaching scenario as misrepresenting authentic science. However, students may misinterpret explicit NOS ideas from highly contextualized examples because they are modifying them to fit their prior conceptions. Alternatively, unless they have first been introduced to the NOS idea in a less contextualized and complex situation, students may miss or downplay explicit NOS ideas from highly contextualized examples when focused on their struggle to understand new science content.

Students’ perspectives of the NOS and the ability to apply their understanding to other situations are partially dependent on the science content and context framing NOS discussion (Abd-El-Khalick, 2001; Brickhouse, Dagher, Letts, & Shipman, 2000; Driver et al, 1996; Ryder, Leach, & Driver, 1999). Thus, highly contextualized activities are necessary for students to develop a deep understanding of NOS ideas that are transferable to new situations (Clough, 2006). However, to prevent students from narrowly applying NOS concepts to very specific examples, highly contextualized NOS activities must be integrated throughout the course/school year pulling from multiple episodes from the history of science (Clough, 2006). To maximize the likelihood of effective conceptual change, continually scaffolding activities along the decontextualized – moderately contextualized – highly contextualized NOS activities continuum throughout the course is necessary. While highly contextualized examples are necessary to prevent students
disregarding the NOS ideas being taught, comparing and contrasting these examples with students’ personal experiences with decontextualized and moderately contextualized NOS activities is necessary to help students identify and accurately interpret the NOS ideas represented in highly contextualized examples.

**The Role of History of Science in NOS Instruction**


Conant (1951) asserted that since every citizen is expected to have informal opinions on the relationships among government, education, and issues of scientific research and development; it is imperative that some appreciation of the past complexities of science and society be a part of the education of both scientists and non-scientists. (p. 173)

Historically contextualized instruction not only assists in the teaching and learning of NOS concepts (Bauer, 1992; Clough, 2006; Irwin, 2000; Kolsto, 2008; Matthews, 1994; Monk & Osborne, 1997; Solomon, Scott, & Duveen, 1996; Brush, 1989), but may also increase students’ understanding of science content (Galili & Hazen, 2000; Lin, 1998), enrich student understanding of science content (Clough, 2006; Klassen, 2006; Jung, 1994), enliven science teaching and provide variation in instruction
(Castro & DeCarvalho, 1995; Millar & Osborne, 1998; Shamos, 1995), enable students to connect science content with their learning of other disciplines (Chamany, Allen, & Tanner, 2008; Matthews, 1994), and humanizes and reveals the social side of science. Allchin (2013) states:

> Historical context inevitably highlights the human and cultural dimensions of science. The context connects the abstract—and, for students, often lifeless—scientific concepts to human concerns, values, and emotions. History contextualizes, and thereby motivates, the science. It matters little that the science may have happened at some other place or time. Good stories are compelling. Science is a human endeavor. It is conducted by and for real people. Research is fueled by sheer curiosity and the desire to improve the human condition—feelings that students share or readily appreciate. The human element is inherently engaging, even if not completely the same as the students’ own lives. When well framed, history inspires students to appreciate scientific problems, experiments, debates, and concepts. (p.30)

Using HOS in the science classroom may reveal the human and social aspects of science (Irwin, 2000; Thomsen, 1998); this may be especially important for increasing students’ interest and attitudes toward science (Allchin, Anthony, & Bristol, 1999) and improving students’ motivation to learn science by making it seem more relevant (Allchin, 2013; Metz, 2003; Meyling, 1997). Allchin (2013) states, “History allows teachers to shift from the alienation of prescribed answers to the wonder or unsolved problems that motivate learning. The original context makes the reasons for doing science ‘real’” (p. 30). HOS may also promote students’ interest in science careers by establishing role models in science (Allchin, 2013). Allchin (2013) explains:

> History helps render science as human endeavor. That includes, of course, the human flaws. Historical portraits thus can help students address the stereotypes, so prevalent in our culture, of scientists as perfect, yet also impersonal and inhuman. Thus, students benefit from hearing how sometimes scientist’ personalities may affect their research style or even
the content of their theories. Scientists’ very human motives are visible through their acrimonious priority disputes, behind-the-scenes politics in publishing or getting grants, ambitions for Nobel prizes, and even reporting of fraudulent results. Yet great scientific achievements emerge all the same. Students should see the human elements as a part of the scientific process, reconciled with the efficacy and general reliability of scientific conclusions. (p. 34)

However, not all studies show that incorporation of HOS leads to increases in students’ NOS understanding; the most effective studies utilized an explicit approach to teaching the NOS and included overt NOS learning objectives (Abd-El-Khalick & Lederman, 2000; Lederman, 1998). As with science content instruction, teachers must carefully consider how to effectively integrate HOS into classroom instruction. Students will not implicitly learn NOS ideas from historical examples without overtly drawing their attention to and having them reflect on key NOS ideas from the examples. If not chosen with care, HOS examples may inadvertently reinforce students’ naive NOS conceptions. For example, short biographical excerpts in text boxes in science textbooks typically do not portray the contextual nature of the scientist’s work or the collaborative nature of science and may confirm students’ view of science as a solitary endeavor. Thus, to serve as effective NOS instruction, historical examples should “involve enough depth, details and societal context to illustrate a sophisticated account of NOS. Superficial accounts will easily reinforce a naïve positivistic view of science…” (Kolsto, 2008, p. 995).

Many approaches for effectively incorporating HOS into science education have been advocated. These approaches include:

Irwin, 2000; Klopfer 1964; Matthews, 1994; Millar & Osborne, 1998; Stinner et al, 2003),

- significant historical components in the curriculum (Cassidy, Holton, & Rutherford, 2002; Lin & Chen, 2002; Rutherford, Holton, & Watson, 1970; Taylor, 1941),

- addressing misleading textbook accounts of science content (Rudge, 2000).

- Historical short stories (Solomon et al., 1992; Hagan et al., 1996; Clough, 1997, 2011; Leach, Hind, & Ryder, 2003; Tao, 2002, 2003),

- short historical vignettes reflecting the lives of scientists (Wandersee, 1990; Monk & Osborne, 1997),

- and historical excurses (Galili, 2012).

The use of historical narrative in the science classroom may be of particular value for effective NOS education. Martin and Brouwer (1991) argue that science narrative stories are particularly useful for humanizing science instruction:

> The narrative mode is essential to a science education that values the belief that students must have a personal engagement with the ideas they are to learn. Stories are our natural means of sharing in the lives of others and of more fully exploring meaning in our own. Through stories students may more successfully begin to see the subtle dimensions of science and of understanding the ways in which science, culture, and worldview interact. (p. 708)

Narrative is a powerful way of communicating ideas and makes “ideas coherent, memorable and meaningful” (Millar & Osborne, 1998), and thus promotes long-term understanding of science ideas. Metz, Klassen, McMillan, Clough, & Olson (2007) assert:

> Historical narratives when sensitively constructed naturally include a humanizing element that raises personal, ethical, sociological,
philosophical and political concerns which tend to increase interest and motivation in students (Myling 1997; Metz 2003). (p. 315)

**Teachers’ Use of NOS and HPS Curricular Materials**

**The Scarcity of Effective NOS Instruction**

Despite continued emphasis on primary through postsecondary NOS education and extensive research regarding students’ and teachers’ NOS understandings and effective NOS teaching practices, teachers rarely address NOS accurately or effectively in science education (Abd-El-Khalick, Bell, & Lederman, 1998; Bell, Lederman, & Abd-El-Khalick, 1997; Capps & Crawford, 2013; Hodson, 1993; King, 199; Lederman, 1999). Many potential obstacles to effective NOS teaching exist, including: (1) teachers’ NOS understanding; (2) teachers’ perceptions of the importance of NOS for science education; (3) teachers’, administrators’, parents’, and students’ expectations of science teaching; and (4) how teachers’ perceive constraints to their instructional decision-making (e.g., time limitations, classroom management concerns, student ability and resistance).

Although a necessary condition of effective teaching is deep understanding of the content to be taught (Osborne & Simon, 1996; Shulman, 1986; Turner-Bissett, 1999), many science teachers are a product of a science education that largely ignored the NOS (Brickhouse, 1991; Gallagher, 1991; Kouladis & Ogborn, 1989; Lakin & Wellington, 1994; Lederman, 1992; Mellado, 1998). Thus, science teachers frequently hold inadequate views of NOS (Abd-El-Khalick & BouJaoude, 1997; Abd-El-Khalick et al., 1998; Abd-El-Khalick & Lederman, 2000; Abell & Smith, 1994; Abell, Martini, & George, 2001; Aguirre, Haggerty, & Linder, 1990; Haidar 1999; King, 1991; Koulaidis & Ogborn, 1989; Lederman, 1992, 1999; Lederman, Schwartz, Abd-El-Khalick, & Bell,
preventing effective NOS instruction. Additionally, science teachers often do not
consider NOS an important component of science education and therefore do not
extremely plan for NOS instruction (Abd-El-Khalick et al., 1998; Bell et al., 1997; King,
1991). Regrettably, NOS instruction appears to differ from “expectations held of science
and science teaching in schools, not only by teachers and pupils, but also those perceived
being held by parents and society” (Lakin and Wellington, 1994, p. 186).

Furthermore, NOS understanding is a necessary but insufficient condition for
meaningful and effective NOS instruction (Abd-El-Khalick, Bell, & Lederman, 1998;
Frequently, inconsistencies exist between teachers’ NOS understanding and their
teaching of NOS concepts. Teachers’ perceptions of constraints on their teaching (e.g.,
limited time, classroom management concerns, expectations of colleagues and
administrators, curricular/content requirements; and lack of resources) often reduce the
presence of NOS instruction even in teachers who possess higher levels of NOS
understanding (Abd-El-Khalick et al., 1998; Hodson, 1993; Lederman, 1999). In a study
of 15 preservice teachers’ NOS understanding and their use of NOS activities, Lederman
et al. (2001) report four primary factors influencing their implementation of the NOS
activities: knowledge of NOS, knowledge of subject matter, pedagogical knowledge, and
intention to teach NOS.

Teachers are also frequently hesitant to include NOS instruction when they
perceive it will take limited class time away from science content instruction (Abd-El-
Khalick, 1998). Consequently, teachers may be more likely to utilize highly contextualized NOS materials in which the NOS ideas are intertwined with science content. Clough and Olson (2008) remark, “teaching the NOS in this highly contextualized manner is important in persuading teachers that NOS instruction need not detract from, and can likely promote, science content learning” (p. 144).

**Recent research regarding teachers’ incorporation of NOS**

With the many potential obstacles to effective NOS teaching, research reporting limited NOS instruction occurring in classrooms is unsurprising. Recently, Capps and Crawford (2013) conducted a professional development program for 5th grade through 9th grade science teachers focused on inquiry-based teaching practices and NOS instruction. Capps and Crawford researched the teaching practices of 26 teachers following the professional development program. Disappointingly, they reported no evidence of explicit NOS instruction in any of their participants’ classes.

In another recent study, Herman, Clough, and Olson (2013) investigated the NOS instructional practices of thirteen teachers 2-5 years after completing an intensive secondary science education program that included an extensive NOS education component throughout the program (Herman, 2010; Herman, Clough, & Olson, 2013). In contrast to Capps and Crawford’s findings, participants in Herman et al.’s study displayed a range of NOS implementation in their classrooms. Only one of the thirteen participating teachers did not explicitly teach NOS, and nine of the thirteen participants implemented explicit NOS instruction at a moderate to high level. No relationship between teachers’ years of teaching experience and the effectiveness of their NOS
instruction was observed. While promising that the teachers in Herman’s study were implementing NOS instruction in their classrooms, even high implementers struggled with some aspects of highly effective NOS instruction. Their participants frequently struggled to scaffold along a continuum of decontextualized, moderately contextualized, and highly contextualized NOS instructional experiences and rarely drew students’ attention to the ways in which classroom practices distorted NOS.

Importantly, Herman et al.’s (2013) study demonstrates that an effective teacher education program that stresses NOS understanding and pedagogy can positively impact the NOS implementation practices of their graduates. However, even with an atypical science education program that requires both more science education coursework and NOS coursework than the typical program, many teachers struggled to implement NOS at a high level. Herman et al. conclude that more factors than teachers’ NOS understanding and teaching experience likely impact teachers’ implementation of NOS instruction in their classroom.

In addition to teachers’ understanding of and comfort with NOS, their learning goals for students, classroom culture, and school culture may determine how effectively they are able to teach the NOS. Bartholomew, Osborne, & Ratcliffe (2004) examined the issues and problems primary and secondary teachers faced when attempting to teach NOS to their students. They identified five dimensions of practice impacting the effectiveness of NOS instruction: (1) teachers’ knowledge and understanding of the NOS, (2) teachers’ conceptions of their own role, (3) teachers’ use of discourse, (4) teachers’ conceptions of learning goals, and (5) the nature of classroom activities. They report that teachers with more effective instruction were confident they have sufficient understanding of NOS,
viewed themselves as facilitators of learning, promoted open and dialogic discourse, includes the development of reasoning skills as a learning goal, and utilized authentic activities. In contrast, teachers who’s NOS instruction was less effective tended to be anxious about their NOS understanding, viewed themselves as dispensers of knowledge, their classroom discourse was authoritative, limited their learning goals to knowledge gains, and utilized contrived and inauthentic activities. Hottecke and Silva (2011) analyzed obstacles to implementing history and philosophy of science (HPS) in school physics education. They structured the obstacles into four categories: (1) culture of teaching physics, (2) teachers’ skills, epistemological and didactical attitudes and beliefs, (3) institutional framework of science teaching, and (4) the use of textbooks as fundamental didactical support.

The Problematic Nature of Curricular Materials for Teaching NOS and HPS

Although there is a long history of materials created for teachers to incorporate NOS, HOS, and HPS into the curriculum, these materials have not always been successfully implemented (Monk & Osborn, 1997). Teachers often do not recognize NOS instruction as necessary (Abd-El-Khalick et al., 1998; Lederman, 1998; Lederman, 1999), and feel time spent on explicit NOS and HPS instruction is time taken away from teaching science content. Even when they recognize HPS as an important component of science education, many teachers do not utilize an HPS perspective in their classroom teaching because they feel ill-prepared to do so (Wang & Cox-Peterson, 2002). Teachers frequently will not use HPS activities if they are viewed as add-on material. Monk and Osborn (1997) propose that HPS materials must be integrated into the content curriculum
and take little time if teachers are to implement them. Therefore, longer approaches for integrating NOS and HPS into the science classroom, such as extensive case studies and significant historical components in the curriculum, are often not used.

Galili (2012) conducted research to obtain practicing high school physics teachers’ perceptions of historical excursion modules. Galili found using historical materials with teachers is problematic because teacher preparation programs do not require HPS courses. Therefore, “practicing teachers normally lack background knowledge and hold strong naïve views of the subject of HPS” (p. 1305). Teachers in the study expressed concern about the lack of available class time for adding additional materials in an already crowded curriculum. Some teachers expressed concern that utilizing material from the excurses would lead to increased teacher lecture instead of student activity and problem solving. Additionally, some teachers expressed concern that teaching about historical views of scientific phenomena would just confuse students, because these alternate views appear reasonable and not obviously refutable.

**Using Science Short Stories to Teach the NOS**

Historical short stories have repeatedly been promoted as an effective medium for NOS instruction (Clough, 1997, 2011; Hagan et al., 1996; Leach, Hind, & Ryder, 2003; Solomon et al., 1992; Tao, 2002, 2003). Short stories are an instructional resource that may meet the perceived needs of science teachers, and thus more likely to be utilized. Compared to many other approaches advocated for incorporating the HOS and NOS, short stories take relatively little instructional time. Short stories can also be written in a way that they are directly related to the science content being taught. Thus, instructors
are less likely to perceive the stories take instructional time away from the science content. This was the approach of the National Science Foundation supported project *The Story Behind the Science: Bringing Science and Scientists to Life* (Clough, Olson, Stanley, Colbert, & Cervato, 2006) that developed thirty historical and contemporary science short stories focused on the development of key science ideas commonly taught in introductory post-secondary science courses (http://www.storybehindthescience.org). Reflecting the importance of NOS instruction with an explicit/reflective character, the developed short stories overtly draw students’ attention to NOS ideas and include questions requiring students to reflect on key NOS ideas relevant to each story (Clough, 2011).

Multiple studies regarding the efficacy of the project stories have been conducted with post-secondary students at a large research-intensive university in the Midwestern region of the United States. In the first study, four of the stories and their embedded questions were assigned as homework in a large introductory geology course (Vanderlinden, 2007; Olson & Clough, 2007). Students’ responses to the embedded questions were analyzed to determine how students interpreted the short stories and their ideas regarding the NOS. Significant gains were reported in students’ understanding of targeted NOS ideas. In the second study, five project stories were utilized in a post-secondary introductory biology course during a study researching students’ and the instructor’s reaction to the use of the stories (Kruse, 2010; Kruse, Clough, Olson, & Colbert, 2009). The stories positively impacted students’ interest in science careers and the biology instructor expressed desire to continue to explicitly address NOS in his course because he perceived it reduced students’ resistance to biological evolution and
can be used while addressing the science content he teaches. In a third study, Clough, Herman, & Smith (2010) reported positive impacts on students’ NOS understanding, interest in science careers, and interest in science content following the use of five stories used in a large introductory majors biology course. The successful use of these materials to change students’ NOS conceptions in post-secondary courses (Clough et al., 2010; Kruse, 2010; Vanderlindin, 2007) raises the question of the potential usefulness of similar materials in secondary science instruction.

Previous studies have utilized historical short stories about the development of science ideas to teach NOS concepts to secondary students. In a study of secondary students in Hong Kong, students worked in pairs with very little teacher intervention to read and discuss four NOS stories. Tao (2002, 2003) reports that students often attend to aspects of the stories that reinforce their prior conceptions about the NOS. Tao (2003) explains:

> When studying the science stories, many students selectively attend to certain aspects of the stories that appear to confirm their inadequate views; they are unaware of the overall theme of the stories as intended by the instruction… Many students interpret the science stories in idiosyncratic ways other than that intended by the instruction and subsequently change from one set of inadequate views of NOS to another rather than to adequate views. (p. 168)

Thus, students’ inadequate views of the NOS may not change when using NOS and HPS curricular materials (Tao, 2002, 2003). Additionally, peer collaboration strategies may not be sufficient for causing change of students’ NOS conceptions; teachers may need to play a more active role (Tao, 2003). A teachers’ mediation is likely necessary to overtly draw students’ attention to key aspects of the stories and confront students’ prior NOS conceptions.
Smith (2010) conducted an exploratory study incorporating the use of two historical NOS short stories into a high school biology course. The two stories focused on the lives and work of Mendel and Darwin and were included in instructional units on genetics and biological evolution, respectively. These two stories were adapted from the post-secondary stories used in the *Story Behind the Science: Bringing Science and Scientists to Life* website (Clough, 2011) to be more accessible to secondary students.

The two NOS short stories included questions and bulleted points to overtly draw students’ attention to key NOS ideas relevant to the stories. Implementation in this study differed from Tao’s (2002, 2003) study in that that teacher played an active role during instruction by overtly drawing students’ attention to their prior knowledge and NOS conceptions, supporting students’ understanding of the stories while reading, providing discussion points for small group discussion, and leading whole class discussion of the embedded NOS questions to overtly draw students’ attention to key NOS aspects of the stories and challenge students’ inadequate NOS views and erroneous interpretation of the stories. Compared to a control group, students who utilized the NOS short stories in their instruction developed a significantly better understanding of three of the six NOS concepts made explicit in the stories and embedded questions. Thus, such historical short stories can be utilized to effectively change students’ NOS conceptions (Smith, 2010), but the role of the teacher in actively mediating students’ reading and discussion of the stories and embedded NOS concepts is likely necessary for successfully changing students NOS conceptions. Additionally, most students in Smith’s (2010) study reported preferring the historical short stories to their typical textbook readings.
However, Smith’s study was limited in scope and treatment; the study was conducted with a single teacher, only in biology classes, and utilized only two stories. A larger scale study using multiple teachers in multiple science disciplines is needed to determine if similar historical short story materials are a viable structure for effective NOS instruction at the secondary level. Additionally, research is needed to determine how and if secondary teachers will implement the stories, what factors impact their implementation of the stories, and what factors may be correlated with students’ interest in and attitudes towards the stories.

**In Summary**

NOS instruction is necessary for forming a scientifically literate citizenry, improving student understanding of science content, and improving students’ attitudes towards science. While students’ NOS conceptions are initially developed through implicit messages from the media and classroom experiences, once NOS misconceptions are formed, implicit NOS instruction is inadequate for changing students’ NOS conceptions. Effective NOS instruction must be explicit and reflective in character, utilized throughout the course, and involve instructional activities that scaffold along the decontextualized - moderately contextualized - highly contextualized NOS experience continuum. Integration of HOS is needed to contextualize NOS instruction within the science content. HOS also provides students opportunities to learn about the social and humanistic side of science, which has been shown to increase student interest in science content and careers.

While curricular materials for teaching NOS and HOS exist, they are only
sporadically used by teachers. For more widespread use of NOS instruction by secondary science teachers, curricular materials likely must be perceived as being highly integrated with the content and not requiring extensive time be taken from content instruction. Carefully structured short historical narratives focused on the development of science may be a resource secondary teachers are more likely to use for classroom instruction. Such narratives are, by nature, highly contextualized with science content already viewed as important by teachers. If the narratives are kept short, teachers may not object to the use of class time needed to utilize these activities. Instruction utilizing such narratives may have an explicit/reflective character if comments and questions are embedded within the narrative which overtly draw both students’ and teachers’ attention to important NOS ideas.

Further research is needed to determine: (1) if and how secondary science teachers implement such stories, (2) what factors impact teachers’ implementation of the stories, (3) if the utilization of such short historical narratives in secondary science classes can positively impact secondary students’ accurate understanding of the NOS, (4) students’ attitudes and interest in the stories, and (5) what factors may be correlated with students’ interest in the stories.
CHAPTER 3: METHODOLOGY

Overview

The science education community has long regarded nature of science (NOS) instruction to be an essential component of science education necessary for developing students’ science literacy (Matthews, 1994; McComas et al., 1998; Shamos, 1995) and preparing students to participate in society and societal and personal decision-making (Allchin, 2011, 2013; Driver et al., 1996, McComas et al., 1998; Mitchell, 2009; Rudolph, 2005). Accordingly, inclusion of NOS into school science has been widely endorsed by organizations including the American Association for the Advancement of Science (1989, 1993, 2009), the National Science Teachers Association (1995, 2000), and the National Research Council (1996).

Unfortunately, most secondary science teachers neglect incorporating explicit attention to NOS in their classroom instruction. Although curricular materials have been developed for including NOS and the history and philosophy of science (HPS) concepts in science courses, such materials typically fail to be widely adopted. A variety of factors likely contribute to classroom teachers’ failure to implement NOS and HPS curricular materials in their instruction. Regrettably, most secondary science teachers are a product of a science education that largely ignored the NOS (Brickhouse, 1991; Gallagher, 1991; Kouladis & Ogborn, 1989; Lakin & Wellington, 1994; Lederman, 1992; Mellado, 1998). Thus, science teachers frequently hold inadequate views of the NOS (Abd-El-Khalick & Lederman, 2000) and may not have enough expertise in NOS and HPS to feel comfortable teaching these concepts (Wang & Cox-Peterson, 2002). Due to their lack of
experience with NOS in their own science education, science teachers often do not perceive NOS education as important and fail to explicitly plan for NOS instruction (Abd-El-Khalick et al., 1998; Bell et al., 1997). Science teachers frequently regard NOS instruction as an additional concept to add into the curriculum that may take time away from content instruction. Furthermore, the inclusion of NOS may be perceived as contrary to the science education expectations of schools, administrators, teachers, pupils, and society (Lakin & Wellington, 1994).

Thus, curriculum designers must carefully consider the perceived needs of secondary science teachers if developed materials are to be successfully implemented in the science classroom (Monk & Osborne, 1997). Materials perceived as taking little instructional time, highly contextualized with the science content being taught, and supportive of teachers’ developing NOS conceptions are perhaps more likely to be implemented.

**Study Purpose and Research Questions**

The purpose of this study was to investigate the viability of short stories about the development of science ideas and the work of scientists as NOS instruction in high school science classes. The study investigated factors influencing teachers’ implementation of stories, impact of the stories on students’ NOS understanding, students’ interest and attitude towards the stories, and factors potentially correlated with students’ interest in the stories. More specifically, this study was designed to answer the following research questions:

1) What factors impact secondary teachers’ implementation of the science short
stories as part of their classroom instruction?

2) What impact, if any, does the use of NOS short stories in secondary science classes have on students’ understanding of fundamental NOS concepts?

3) Following the use of the short stories, what are secondary science students’ perceptions regarding their interest in:
   a) reading the short stories compared to textbook or other typical course readings?
   b) reading about scientists and how science ideas are developed?

4) What correlation, if any, exists between students’ interest in the short stories and their:
   a) attitude towards reading?
   b) conceptions of learning?
   c) attribution for academic success?

**Overview of Methodological Framework**

The researcher holds a pragmatist view of research design, and thus rejects the incompatibilist view that necessitates choosing between qualitative and quantitative methodologies (Johnson & Onwuegbuzie, 2004). Instead, the researcher accepts that qualitative and quantitative methods have their own strengths and weaknesses. Mixed methods research permits the researcher to take advantage of the strengths of various approaches and collect multiple forms of data by selecting methods, approaches, and strategies to best answer specific research questions (Johnson & Onwuegbuzie, 2004).

The current study utilized a mixed methods design combining both quantitative
and qualitative methodologies deemed most appropriate for investigation of each research question. Thus, various forms of data suitable for qualitative and quantitative analysis were collected for this study. Data sources included classroom observations with extensive researcher field notes, classroom artifacts, teacher interviews, and survey data requiring both open-ended and restricted categorical responses.

For qualitative portions of the study, the researcher drew from grounded theory techniques, including constant comparison and coding for common themes grounded in the data (Charmaz, 2006; Strauss & Corbin, 1998). Classical grounded theory views the researcher as an objective observer with themes and theories discovered in the descriptive data (Charmaz, 2006; Cresswell, 2013). However, the researcher recognizes that objectivity of the researcher and discovery of themes from the data are impossible, as all data collection and analysis is interpreted through the researchers’ social and theoretical background. Data analysis and conclusions are interpretations, not reconstructions of an objective reality. Thus, the researcher holds a view more consistent with constructivist grounded theory (Charmaz, 2006). Charmaz (2006) explains:

I assume that neither data nor theories are discovered. Rather, we are part of the world we study and the data we collect. We construct our grounded theories through our past and present involvements and interactions with people, perspectives, and research practices. (p.10)

Saldana (2009) further describes the many influences on researchers’ data gathering, coding, and interpretation of qualitative data:

The collection of coding methods… is a repertoire of possible filters to consider and apply to your approaches to qualitative inquiry. But even before that, your level of personal involvement as a participant observer – as a peripheral, active, or complete member during fieldwork – filters how you perceive, document, and thus code your data (Adler & Adler, 1987). So do the types of questions you ask and the types of responses you receive during interviews (Kvale, 1996; Rubin & Rubin, 1995), the detail
and structuring of your field notes (Emerson, Fretz, & Shaw, 1995), the gender and race/ethnicity of your participants – and yourself (Behar & Gordon, 1995; Stanfiled & Dennis, 1993), and whether you collect data from adults or children (Green & Hogan, 2005; Zwiers & Morrissette, 1999). (p. 7)

**Short Story Materials Utilized in the Study**

The original NOS short stories were developed for an NSF funded project for use in post-secondary introductory science classes (Clough et al., 2006; Clough, 2011). The *Story Behind the Science: Bring Science and Scientists to Life* project created 30 short stories describing the development of key science content ideas frequently taught in post-secondary introductory biology, chemistry, geology, and physics courses (http://www.storybehindthescience.org). The post-secondary NOS short stories were designed to reflect previous research in NOS education indicating the need for NOS instruction to overtly draw students’ attention to relevant NOS ideas and require students to mentally wrestle with these ideas. Therefore, the stories include bolded statements to draw students’ attention to common NOS misconceptions and embedded questions requiring students to reflect on key NOS ideas pertinent to each story.

For this study, the researcher modified stories from the post-secondary project above (Clough et al., 2006) to be more appropriate for secondary students. Modifications included: (1) shortening the length of the story text or, when appropriate, dividing a post-secondary story into two stories, (2) reducing the complexity of vocabulary in the stories, (3) embedding more NOS and content specific questions throughout the stories to divide up the text, keep students engaged with the reading, and help students identify key NOS and content ideas within the stories, and (4) 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 abstract or complex ideas described in the stories.

Fourteen NOS short stories were developed for use in this study. Including embedded questions, bolded key ideas, and graphics, the stories ranged from three to seven pages in length. Seven stories related to ideas frequently taught in secondary biology courses (Appendix A) were developed from post-secondary biology and geology stories. The seven stories provided to biology teachers, ranging in length from three to five pages, are listed in Table 1. The remaining seven stories, related to ideas frequently taught in secondary chemistry courses (Appendix B), were developed from post-secondary chemistry stories. Table 2 lists the seven stories provided to chemistry teachers, which range in length from four to seven pages.

Table 1. NOS Short Stories Provided to Participating Biology Teachers

<table>
<thead>
<tr>
<th>Story Title</th>
<th># of Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Efforts to Understand the Earth’s Age: Naturalists and Chronologists</td>
<td>5</td>
</tr>
<tr>
<td>A Very Deep Question: Just How Old is the Earth?</td>
<td>5</td>
</tr>
<tr>
<td>Charles Darwin: A Gentle Revolutionary</td>
<td>5</td>
</tr>
<tr>
<td>Understanding the Structure and Function of DNA Part One: Pre 1950</td>
<td>3</td>
</tr>
<tr>
<td>Understanding the Structure and Function of DNA Part Two: Post 1950</td>
<td>4</td>
</tr>
<tr>
<td>The Realization of Global Warming</td>
<td>5</td>
</tr>
<tr>
<td>Creativity and Discovery: The Work of Gregor Mendel</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 2. NOS Short Stories Provided to Participating Chemistry Teachers

<table>
<thead>
<tr>
<th>Story Title</th>
<th># of Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Ideas: The Origins of Modern Atomic Theory</td>
<td>7</td>
</tr>
<tr>
<td>Conservation of Mass: The Interplay of Creativity and Collaboration Between Scientific Laws and Theories</td>
<td>5</td>
</tr>
<tr>
<td>The Origins of Entropy: How Culture Influences Scientific Progress</td>
<td>6</td>
</tr>
<tr>
<td>The Study of Matter: What is the Basic Stuff of the Universe</td>
<td>4</td>
</tr>
<tr>
<td>A Puzzle With Many Pieces: Development of the Periodic Table</td>
<td>6</td>
</tr>
<tr>
<td>A Matter of Degrees: The Struggle for a Standard Measure of Temperature</td>
<td>4</td>
</tr>
</tbody>
</table>

Study Participants and Context

Participants included seven high school biology teachers, six high school chemistry teachers, and the secondary students enrolled in their participating class periods. Ten of the thirteen teachers participated in the study during the Spring 2012 semester; the remaining three teachers participated in the Fall 2012 semester. The thirteen teachers came from a variety of school settings, including one rural, three suburban, and two urban schools in a Midwestern U.S. state. Teacher participants’ classroom experience ranged from first year teachers to 25 years. Additionally, four of the participating teachers (e.g. Laura, Beth, Karen, and Ken) had a student teacher in their classroom during the semester they participated in the study. Jill was Karen’s student teacher during the spring 2012 semester; she later joined the study as a teacher participant during the fall 2012 semester. Table 3 presents an overview of the teacher participants (identified by pseudonym), their length of teaching experience, and school settings.
Table 3. Overview of Teacher and Student Teacher Participants

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Teaching Experience</th>
<th>Student Teacher</th>
<th>Discipline</th>
<th>School Setting</th>
<th>Semester Participated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laura</td>
<td>4th year</td>
<td>Liz b</td>
<td>Biology</td>
<td>Urban school 1</td>
<td>Spring 2012</td>
</tr>
<tr>
<td>Rick</td>
<td>18th year</td>
<td>Biology</td>
<td>Suburban school 1</td>
<td>Spring 2012</td>
<td></td>
</tr>
<tr>
<td>Vicki</td>
<td>5th year</td>
<td>Biology</td>
<td>Suburban school 1</td>
<td>Spring 2012</td>
<td></td>
</tr>
<tr>
<td>Beth</td>
<td>17th year</td>
<td>Amy</td>
<td>Biology</td>
<td>Suburban school 2</td>
<td>Spring 2012</td>
</tr>
<tr>
<td>Karen</td>
<td>5th year</td>
<td>Jill b, c</td>
<td>Biology</td>
<td>Suburban school 2</td>
<td>Spring 2012</td>
</tr>
<tr>
<td>Jill b, c</td>
<td>1st year</td>
<td>Biology</td>
<td>Suburban school 2</td>
<td>Fall 2012</td>
<td></td>
</tr>
<tr>
<td>Kaleb</td>
<td>2nd year</td>
<td>Biology</td>
<td>Suburban school 3</td>
<td>Fall 2012</td>
<td></td>
</tr>
<tr>
<td>Henry</td>
<td>5th year</td>
<td>Chemistry</td>
<td>Suburban school 1</td>
<td>Spring 2012</td>
<td></td>
</tr>
<tr>
<td>Jessica</td>
<td>12th year</td>
<td>Chemistry</td>
<td>Suburban school 1</td>
<td>Spring 2012</td>
<td></td>
</tr>
<tr>
<td>Carol</td>
<td>25th year</td>
<td>Chemistry</td>
<td>Suburban school 2</td>
<td>Spring 2012</td>
<td></td>
</tr>
<tr>
<td>Ken b</td>
<td>4th year</td>
<td>Sam b</td>
<td>Chemistry</td>
<td>Suburban school 2</td>
<td>Spring 2012</td>
</tr>
<tr>
<td>Will b</td>
<td>3rd year</td>
<td>Chemistry</td>
<td>Rural school 1</td>
<td>Spring 2012</td>
<td></td>
</tr>
<tr>
<td>Hillary b</td>
<td>1st year</td>
<td>Chemistry</td>
<td>Urban school 2</td>
<td>Fall 2012</td>
<td></td>
</tr>
</tbody>
</table>

a. Teachers are identified by pseudonym.
b. Teachers graduating from the same teacher preparation program, including a course on teaching the NOS.
c. Jill was Karen’s student teacher during the spring 2012 semester and then joined as a teacher participant during the fall 2012 semester.

Criterion-based sampling (Isaac & Michael, 1995) was utilized to select teacher participants for this study. Teachers were selected based on their expressed interest in utilizing NOS short stories in their classroom instruction and proximity to the researcher. Teacher participants came from six different schools, and all schools were within a three-hour driving distance of each other. Eight of the thirteen teachers (e.g. Laura, Karen, Jill, Kaleb, Henry, Ken, Will, and Henry) came from the same teacher education program at a large university in the Midwestern region of the United States, which included a course on NOS and effective NOS pedagogy. These eight teachers were previously exposed to...
the post-secondary NOS short stories from The Story Behind the Science: Bring Science and Scientists to Life project (Clough, 2011) and had expressed interest in utilizing similar NOS short stories in their secondary classrooms. The remaining five teacher participants worked in schools with one or more of the teachers from the program and expressed interest in utilizing NOS short stories.

Student participants were selected from the population of students enrolled in teacher participants’ biology and chemistry classes. All students enrolled in participating classes were asked to participate in the study and completed study surveys as part of their normal classroom instruction. However, due to the restriction of required parent consent and student assent to utilize student survey data, student participants were unavoidably self-selected. Surveys completed in class by students who did not return signed consent forms were not provided to the researcher.

Data Collection and Analysis

Overview of Participant Subgroups and The Research Questions

To permit the simultaneous investigation of the four research questions, teacher and student participants were divided into subgroups. Figure 2, below, provides an overview of the participant groups and how they were utilized to answer each research question. To investigate the impact of NOS short stories on students’ NOS understanding, a quasi-experimental nonrandomized control-group pretest-posttest design was used (Isaac & Michael, 1995). Five teachers were assigned to participate as Control-Treatment teachers. Although individual students could not be randomly assigned to control and treatment groups, Control-Treatment teachers’ participating class periods
were randomly assigned to control and treatment groups.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Control Students</th>
<th>Treatment Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control-Treatment Teachers</td>
<td>Read No Short Stories</td>
<td>Read a Minimum of 3 Short Stories</td>
</tr>
<tr>
<td>Open-Use Students</td>
<td>Read a Minimum of 1 Short Story</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Research Questions About Teacher Participants</th>
<th>Participants:</th>
<th>Data Collected:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 1: Factors influencing teachers’ implementation of the short stories</td>
<td>Control-Treatment Teachers and Open-Use Teachers</td>
<td>NOS understanding questionnaire and Minimum of 3 classroom observations and Classroom artifacts and Post-implementation interviews</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Research Questions About Student Participants</th>
<th>Participants:</th>
<th>Data Collected:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 2: Impact of stories on students’ NOS understanding</td>
<td>Treatment Students and Open-Use Students</td>
<td>Pre and post NOS understanding questionnaires</td>
</tr>
<tr>
<td>Question 3: Students’ interest in the stories</td>
<td>Treatment Students and Open-Use Students</td>
<td>Student Interest and Attitude Survey 1</td>
</tr>
<tr>
<td>Question 4: Factors correlated with students’ interest in the stories</td>
<td>Treatment Students and Open-Use Students</td>
<td>Student Interest and Attitude Survey 2</td>
</tr>
</tbody>
</table>

Figure 2. Summary of participants and the data collected for each research question
Students in approximately half of the teacher’s class periods served as a treatment group and read a minimum of three of the seven provided short stories. Students in the remaining class periods served as a control group and did not read any of the NOS short stories. Control-Treatment teachers decided when and how to implement the short stories in their treatment class periods as well as what alternative instruction to implement in their control class periods. By utilizing student control and treatment groups from the same teacher, the study controlled for each teachers’ pedagogy and NOS instruction.

Table 4, below, summarizes the type of participation and the number of participating class periods, enrolled students, and student participants returning student consent forms for each teacher participant. In order to permit investigation of students’ interest in and attitudes towards the stories, both Control-Treatment teachers and Open-Use teachers were constrained by the need for minimum implementation requirements. At a minimum, implementation of a short story in classroom instruction required students to read the entire story and answer the embedded questions. To permit investigation of teacher implementation of the stories with as few researcher-induced constraints as possible, all other implementation decisions were left to the individual teachers.
Table 4. Student Participants for Each Participating Teacher

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Participant Type</th>
<th># of Participating Class Periods</th>
<th># of Enrolled Students</th>
<th># of Student Participants with Consent</th>
<th>% of Students with Consent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laura</td>
<td>Treatment</td>
<td>2</td>
<td>52</td>
<td>33</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>2</td>
<td>39</td>
<td>26</td>
<td>67</td>
</tr>
<tr>
<td>Rick a</td>
<td>Treatment</td>
<td>4</td>
<td>79</td>
<td>49</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>3</td>
<td>55</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vicki a</td>
<td>Treatment</td>
<td>1</td>
<td>23</td>
<td>17</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Beth</td>
<td>Open Use</td>
<td>3</td>
<td>62</td>
<td>47</td>
<td>76</td>
</tr>
<tr>
<td>Karen</td>
<td>Open Use</td>
<td>5</td>
<td>115</td>
<td>91</td>
<td>79</td>
</tr>
<tr>
<td>Jill</td>
<td>Open Use</td>
<td>3</td>
<td>76</td>
<td>61</td>
<td>80</td>
</tr>
<tr>
<td>Kaleb</td>
<td>Open Use</td>
<td>1</td>
<td>27</td>
<td>26</td>
<td>96</td>
</tr>
<tr>
<td>Henry</td>
<td>Treatment</td>
<td>4</td>
<td>60</td>
<td>53</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>2</td>
<td>40</td>
<td>28</td>
<td>70</td>
</tr>
<tr>
<td>Jessica</td>
<td>Treatment</td>
<td>3</td>
<td>72</td>
<td>66</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>2</td>
<td>48</td>
<td>46</td>
<td>96</td>
</tr>
<tr>
<td>Carol</td>
<td>Open Use</td>
<td>4</td>
<td>82</td>
<td>77</td>
<td>94</td>
</tr>
<tr>
<td>Ken</td>
<td>Open Use</td>
<td>4</td>
<td>87</td>
<td>49</td>
<td>56</td>
</tr>
<tr>
<td>Will</td>
<td>Open Use</td>
<td>3</td>
<td>78</td>
<td>46</td>
<td>59</td>
</tr>
<tr>
<td>Hillary</td>
<td>Treatment</td>
<td>1</td>
<td>25</td>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>1</td>
<td>26</td>
<td>20</td>
<td>77</td>
</tr>
</tbody>
</table>

a. Rick and Vicki failed to obtain consent from their control class periods.

Investigation of Factors Influencing Teachers’ Implementation

**Teachers’ NOS Understanding**

Teachers’ level of NOS understanding likely influences their implementation of NOS curricular materials (Bartholomew et al., 2004; Lederman et al., 2001). Thus, prior to providing teachers’ with the seven short stories for the study, teachers completed a
survey to measure their NOS understanding. *The Views on Science and Scientific Inquiry* (VOSSI) questionnaire (Appendix C) measures participant understanding of twelve NOS constructs (Table 5).

Table 5. NOS constructs measured in the VOSSI questionnaire

<table>
<thead>
<tr>
<th>VOSSI Item</th>
<th>NOS Construct</th>
<th>Item Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Subjectivity of Scientific Observations</td>
<td>SUSSI Construct</td>
</tr>
<tr>
<td>2</td>
<td>Social and Cultural Influences on Science</td>
<td>SUSSI Construct</td>
</tr>
<tr>
<td>3</td>
<td>Established Science Ideas</td>
<td>Added Construct</td>
</tr>
<tr>
<td>4</td>
<td>Imagination and Creativity in Science</td>
<td>SUSSI Construct</td>
</tr>
<tr>
<td>5</td>
<td>Methodologies of Scientific Investigations</td>
<td>SUSSI Construct</td>
</tr>
<tr>
<td>6</td>
<td>Social Interaction Among Scientific Researchers</td>
<td>Added Construct</td>
</tr>
<tr>
<td>7</td>
<td>Time for Development and Acceptance of Science Ideas</td>
<td>Added Construct</td>
</tr>
<tr>
<td>8</td>
<td>Tentativeness of Scientific Knowledge</td>
<td>SUSSI Construct</td>
</tr>
<tr>
<td>9</td>
<td>Methodological Naturalism and Science Explanations</td>
<td>Added Construct</td>
</tr>
<tr>
<td>10</td>
<td>Scientific Laws Compared to Theories</td>
<td>SUSSI Construct</td>
</tr>
<tr>
<td>11</td>
<td>Discovery and Invention of Laws and Theories</td>
<td>Added Construct</td>
</tr>
<tr>
<td>12</td>
<td>Science and Religion</td>
<td>Added Construct</td>
</tr>
</tbody>
</table>

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 participant understanding of six NOS constructs with four Likert sub-items followed by an open-response question. The combination of Likert sub-items with an open-response question provides a powerful tool for assessing understanding of NOS constructs both quantitatively and qualitatively. Qualitative responses may be used to verify validity of the quantitative scores obtained from the Likert sub-items and provide richer information about respondents’ thinking regarding each NOS construct (Liang et al., 2008). The VOSSI includes items assessing understanding of six NOS constructs.
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 six 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, 2010; Herman, Clough, & Olson, 2011).

Due to small sample size, teachers’ VOSSI scores were not analyzed statistically. Instead, following recommendations made by Herman et al. (2011), Likert sub-items and open-ended responses for each of the twelve constructs were used to determine if the views teachers expressed for each construct were informed, in transition, or naïve. For each of the twelve NOS constructs, responses to the four Likert sub-items were assigned a numerical score with 5 being most informed and 1 being the least informed view of the NOS construct. Teachers scoring above 3 on all four items were assigned a rating of “informed” for that particular NOS construct. Respondents who scored above 3 on all four sub-items of a particular VOSSI item were coded as possessing an “Informed” view of that NOS construct. Likert responses consisting of all 3 and below were coded as “Naïve. All other combinations of Likert responses were coded as “Transitional” views of the NOS construct. This coding system slightly differs from that recommended by Herman et al. (2011) and Herman and Clough (2013), who only coded respondents as “Naïve” if they scored below three (scores of 1 and 2) on all four Likert sub-items for a particular NOS construct. However, the teacher participants in Herman’s study only included graduates from a teacher preparation program with an extensive NOS component and fully naïve views were not evident in their participants. The researcher does not accept that respondents who only include uninformed and uncertain responses
for the four Likert sub-items (scores of 1, 2, or 3) have demonstrated any transitional views regarding the NOS construct; the respondent may just have uninformed views and not understand how to interpret one or more of the sub-items. Thus, the researcher chose to use a more conservative coding scheme in which respondents were coded as holding “Naïve” views if they scored 3 and below on all four Likert sub-items of a particular VOSSI NOS construct.

Teachers’ qualitative responses to the open-response question of each VOSSI item were also assigned a rating of “Informed”, “Transitional”, or “Naïve”. Teachers’ final rating for each of the twelve VOSSI items was determined by comparing their rating on the Likert and qualitative responses. Teachers who’s responses to both the Likert items and the open-responses item were rated as “Informed” were coded as having a an informed view of that construct. If both the Likert items and open-response item were rated as “Naïve”, the teacher was coded as having a naïve view of the construct. Teachers with any other combination of Likert items and open-response item ratings were coded as possessing a transitional understanding of the NOS construct. A total NOS understanding score ranging from 0 through 22 was calculated for each teacher by assigning a numeric value to each VOSSI item and summing the eleven items; “Naïve”, “Transitional”, and “Informed” responses were assigned a value of 0, 1, or 2 respectively.

Classroom Observations

The researcher conducted classroom observations of participating teachers to gather data regarding teachers’ implementation of the NOS short stories and typical classroom practices. An observation of a typical 40-50 minute class period was recorded
as a single classroom visit. Both Laura and Will worked with a blocked-period schedule; a classroom observation occurring during a blocked class period was recorded as two observations. Each teacher’s class, except for Carol’s, was observed a minimum of three times. Teacher participants were asked to notify the researcher when they intended to implement a short story, and observations were conducted at the convenience of each teacher. Except for Carol, who did not inform the researcher when she implemented a short story, each teacher was observed both during the implementation of at least one story and during typical classroom instruction. Table 6, below, summarizes teachers’ type of participation (Control-Treatment or Open-Use) and number of classroom observations.

During observations, the researcher sat in the back of the class and did not interrupt nor participate in classroom instruction. The researcher recorded detailed field notes regarding the layout of the room, organization of classroom instruction, specific classroom activities and discussions, interaction between teacher and students, interaction among students, implementation of stories, and teachers’ portrayal of NOS. Following each observation, the researcher clarified and added memos to the field notes. Teacher/student teacher comments to the researcher regarding the implementation of stories, perceptions of the stories, and perceptions of how the stories impacted students were also added to the field notes.
Table 6. Teacher Participation Type and Classroom Observations

<table>
<thead>
<tr>
<th>Teacher / Student Teacher</th>
<th>Participant Type</th>
<th>Discipline</th>
<th># Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laura / Liz</td>
<td>Control-Treatment</td>
<td>Biology</td>
<td>16</td>
</tr>
<tr>
<td>Rick</td>
<td>Control-Treatment</td>
<td>Biology</td>
<td>4</td>
</tr>
<tr>
<td>Vicki</td>
<td>Open-Use</td>
<td>Biology</td>
<td>3</td>
</tr>
<tr>
<td>Beth / Amy</td>
<td>Open-Use</td>
<td>Biology</td>
<td>3</td>
</tr>
<tr>
<td>Karen / Jill</td>
<td>Open-Use</td>
<td>Biology</td>
<td>8</td>
</tr>
<tr>
<td>Jill</td>
<td>Open-Use</td>
<td>Biology</td>
<td>6</td>
</tr>
<tr>
<td>Kaleb</td>
<td>Open-Use</td>
<td>Biology</td>
<td>7</td>
</tr>
<tr>
<td>Henry</td>
<td>Control-Treatment</td>
<td>Chemistry</td>
<td>13</td>
</tr>
<tr>
<td>Jessica</td>
<td>Control-Treatment</td>
<td>Chemistry</td>
<td>4</td>
</tr>
<tr>
<td>Carol</td>
<td>Open-Use</td>
<td>Chemistry</td>
<td>2</td>
</tr>
<tr>
<td>Ken / Sam</td>
<td>Open-Use</td>
<td>Chemistry</td>
<td>10</td>
</tr>
<tr>
<td>Will a</td>
<td>Open-Use</td>
<td>Chemistry</td>
<td>6</td>
</tr>
<tr>
<td>Hillary</td>
<td>Control-Treatment</td>
<td>Chemistry</td>
<td>6</td>
</tr>
</tbody>
</table>

a. Indicates teachers who worked in blocked class periods.
b. Blocked class periods were recorded as two observations.

Teacher Post-Implementation Interviews

Semi-structured interviews with teacher participants and three of the student teachers were conducted after each teacher completed implementing NOS short stories in their courses for the semester. Liz, Jill, and Sam completed post-implementation interviews as student teacher participants. Amy, Beth’s student teacher, agreed to participate in the study, but she declined to complete a post-implementation interview.

Interview questions were developed to reflect questions that arose during classroom observations and obtain information regarding teachers’ implementation of the stories, rationale for implementation decisions, and opinions of the NOS short stories. Appendix D contains the interview guide used during semi-structured interviews.

Interviews were conducted at the convenience of the participant, and interviews of the
teacher participants were conducted at their schools. Interviews of the student teachers were conducted at either their school or the university. Prior to conducting interviews with the study participants, the researcher conducted two pilot interviews with student teachers who had utilized post-secondary story from the *Story Behind the Science* website during classroom instruction. Pilot interviews were used to clarify interview questions.

**Classroom Artifacts**

Classroom artifacts were collected from each teacher. Based on their preference, teachers provided either paper or electronic copies of artifacts. Collected artifacts varied by teacher, but they typically included class syllabi, worksheets, activities, and assessments. Classroom artifacts were used to triangulate information provided during observations and interviews regarding teachers’ implementation of NOS instruction and inclusion of NOS on assessments.

**Data Reduction and Analysis**

As a data reduction tool, following observations conducted in the spring 2012 semester, the researcher developed an implementation evaluation protocol (Appendix E) for comparing teachers’ implementation of the NOS short stories. The protocol was developed based on researcher observed differences in classroom implementation, including differences in concept development (i.e., support for student understanding of the reading and support for student reflection on the NOS concepts in the stories) and student accountability (i.e., how students were held accountable for putting effort towards the reading, embedded questions, and understanding NOS ideas from the stories). The
researcher also noted marked differences in the classroom culture in teacher participants’ classes; such differences likely impact students’ attitude towards and interest in the NOS short stories. Thus, the Classroom Culture section of the Local Systemic Change Classroom Observation Protocol (LSC-COP) (Banilower, 2005; Horizon Research Inc., 2006) was added as a third section on the evaluation protocol.

The implementation evaluation protocol was utilized to summarize teachers’ typical implementation practices and classroom culture following their participation in the study. Teachers were rated on a 1-5 scale (1 representing ineffective implementation practices and 5 representing highly effective implementation practice) for each of the following four sections: (1) support for reading, (2) support for reflecting on NOS ideas, (3) student accountability, and (4) classroom culture. The scores on the support for reading and support for reflecting on NOS ideas were utilized to assign a synthesis rating for each teacher’s concept development. Data from observation field notes, teacher and student teacher post-implementation interviews, and classroom artifacts were utilized to complete the implementation evaluation and summarize typical story implementation and classroom culture practices for each teacher. Detailed justification, in relation to the exemplars (Appendix E), was provided for teachers’ numeric scores on the implementation evaluation protocol. The implementation evaluation protocol and research-derived exemplars for the various categories of implementation will be described in more detail in chapter 4.

To investigate factors influencing teachers’ implementation of the short stories, Dedoose (2012) web application for analyzing qualitative and mixed methods data was used to analyze teachers’ and student teachers’ post-implementation interview transcripts
and comments to the researcher recorded in field notes. Reiterative rounds of open/initial, focus, and axial coding (Charmaz, 2006; Saldana, 2009; Strauss & Corbin, 1998) were utilized to identify and structure relationships among themes. Triangulation of data from observation field notes, teacher interviews, and student teacher interviews were used to support researcher-identified themes and relationships. Additionally, comparisons were made between teacher implementation practices (Implementation Evaluation scores), NOS understanding (VOSSI scores), and themes identified from interviews and field notes.

Investigation of the Impact on Students’ NOS Understanding

Students’ NOS understanding was measured with a subset of six of the twelve VOSSI items (Table 7). Particular VOSSI items were chosen to be congruent with NOS concepts most apparent in the seven stories provided for each discipline. Thus, the Biology Student VOSSI (Appendix F) and Chemistry Student VOSSI (Appendix G) surveys did not measure all of the same NOS constructs.

Table 7. NOS constructs included in biology and chemistry student VOSSI surveys

<table>
<thead>
<tr>
<th>Biology Student VOSSI NOS Constructs</th>
<th>Chemistry Student VOSSI NOS Constructs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjectivity of Scientific Observations</td>
<td>Social and Cultural Influences on Science</td>
</tr>
<tr>
<td>Social and Cultural Influences on Science</td>
<td>Imagination and Creativity in Science</td>
</tr>
<tr>
<td>Imagination and Creativity in Science</td>
<td>Social Interaction Among Scientific Researchers</td>
</tr>
<tr>
<td>Methodologies of Scientific Investigations</td>
<td>Time for Development and Acceptance of Science Ideas</td>
</tr>
<tr>
<td>Time for Development and Acceptance of Science Ideas</td>
<td>Tentativeness of Scientific Knowledge</td>
</tr>
<tr>
<td>Methodological Naturalism and Science Explanations</td>
<td>Scientific Laws Compared to Theories</td>
</tr>
</tbody>
</table>
Data Analysis

For each Control-Treatment teacher, statistical analyses were used to determine if significant differences exist, following implementation of NOS short stories in their science course, between the NOS understanding of treatment students and control students. For each of the six NOS constructs measured, students were assigned a score based on their responses to the four Likert sub-items. Each Likert sub-item was assigned a numerical value, with 5 representing the most informed view and 1 the least informed view. For each NOS construct, values for the four Likert sub-items were totaled, providing a score ranging from 4 through 20. SPSS version 20 statistical software was used to conduct multivariate analysis of covariance (MANCOVA) and subsequent analysis of covariance (ANCOVA) of control and treatment students’ VOSSI post-implementation scores for the six assessed NOS constructs. To correct for any initial differences between the control and treatment group students’ NOS understanding, VOSSI pre-implementation scores were included as a covariate.

Investigation of Students’ Interest in and Attitudes Toward the Stories

Student Interest and Attitude Surveys

Student interest and attitude surveys were constructed by the researcher to reflect results from Smith’s (2010) study. Student comments during the previous study raised the question of whether students’ interest in the stories is related to their attitudes towards reading, conceptions of effective science learning, and attribution of academic success. Thus, items were included to investigate the possible correlation between students’ interest in the stories and these three constructs. Student interest and attitude surveys
were piloted in a 10th grade biology classroom during the 2010/2011 school year. Comments made by students completing the pilot surveys were used to refine questions prior to this study.

All participating students completed *Interest and Attitude Survey 1* (Appendix H) prior to story implementation in their science class. *Interest and Attitude Survey 1* includes three multi-item indices of Likert items to measure students’ attitudes towards reading, conceptions of an effective science learning environment, and attributions of academic successes and failures. The survey design, using multi-item indices, reflects the complex nature of these three constructs. For complex constructs that may be influenced by multiple attributes, a multi-item index provides a better measure of the underlying dimension the index questions have in common than could any single item (Fowler, 1995). Appendix I contains a list of individual survey items utilized in each index. The survey contains a 7-item index to assess students’ attitude towards reading, a 10-item index to assess students’ perceptions of an effective learning environment and the alignment of their views with reform-based teaching practices, and an 8-item index to assess whether students attribute their academic success to factors within their control (e.g., effort) or factors outside of their control (e.g., luck, fixed intelligence, teachers). Students’ responses to the index questions on *Interest and Attitude Survey 1* were used to gather data for calculating pre-post reliability of the three indices.

Following story implementation, all students completed *Interest and Attitude Survey 2*. This survey was utilized to assess students’ attitudes and interest in the stories and determine other factors that may be correlated with students’ interest in the stories. Three separate versions of the survey were used: (1) a biology version (Appendix J) for
students who read biology stories, (2) a chemistry version (Appendix K) for students who read chemistry stories, and (3) a control version (Appendix L) for students in the control class periods. The biology and chemistry versions of *Interest and Attitude Survey 2* only differed in the introduction to the survey listing the possible stories they may have read. The survey includes the three multi-item indices measuring students’ reading attitude, perception of an effective science learning environment, and attributions of academic success. Additional Likert questions are included to assess students’:

- interest in the stories,
- interest in the stories compared to 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 NOS goal.

Control students completed a version of *Interest and Attitude Survey 2* without the questions regarding students’ perceptions of the short stories; control students still answered questions regarding their reading attitude, perceptions of an effective learning environment, attributions of academic success, and perceived importance of NOS goals for science education.

**Data Analysis**

SPSS version 20 was used to conduct statistical analyses of student responses to *Interest and Attitude Surveys 1 and 2*. Several statistical analyses were conducted to determine the reliability of the three multi-item indices (reading attitude, science learning environment, and attributions). Student responses to *Interest and Attitude Survey 1 and
*Interest and Attitude Survey 2* were utilized to calculate test-retest reliability of the three indices. Only students’ responses on *Interest and Attitude Survey 2* were used to determine correlations between students’ interest in the stories and the other measured constructs. Therefore, internal reliability tests (i.e. Cronbach’s alpha and mean inter-item correlation) of the three multi-item indices were conducted using students’ responses to *Interest and Attitude Survey 2*. Items with low inter-item correlations were removed from the indices; this resulted in the removal of one item from the reading attitude index, three items from the effective learning environments index, and two items from the attribution index. Removed items are indicated in Appendix I. Final statistical analyses used indices without the removed items. Results of the test-retest reliability and the inter-item correlations for the three multi-item indices will be discussed further in Chapter 4.

Following story implementation, SPSS was used to calculate descriptive and frequency statistics regarding students’: (1) interest in the stories, (2) interest in stories compared to other typical class readings, (3) perception of the importance of NOS in science education, and (4) perception of whether the stories promoted the NOS goal. Pearson’s product-moment correlation was also conducted to look for significant correlations between students’ interest in the stories and their:

- interest in the stories compared to other typical class readings,
- perception of the importance of a NOS goal,
- perception of how well the stories supported the NOS goal,
- attitudes towards reading,
- perception of effective science learning, and
- attribution of academic success.
Dedoose (2012) web application for analyzing qualitative and mixed methods
data was used to code and analyze students’ responses to open-response items regarding
what students’ liked and disliked about the NOS short stories. Reiterative rounds of
open/initial and focus coding (Charmaz, 2006; Saldana, 2009) were used to identify
common themes from students’ responses. The researcher began the coding process by
open coding student responses from each teacher participant. Following initial open
coding of all student responses, the researcher went through a second round of coding to
develop consistent codes. Next, focus codes were developed to combine similar initial
codes into focused categories. For example, in students’ response to the question about
what they liked about the short stories, open codes included Interesting, Thought
Provoking, Intriguing, and Attention Catching. The researcher interpreted students’
responses included under these four codes as being related to students’ mental
engagement when reading the stories; thus, these four initial codes were combined under
the focus code Engaging. Some focus codes related to a larger category of responses.
For example, the focus codes Questions, Visuals, Detailed, Not Too Long, and
Organization were categorized as being related to the structure of the reading. Therefore,
the larger category Reading Structure was included for analysis of student responses
while still maintaining the individual focus codes that may be of interest to the
researcher. Once focus codes and larger categories of responses were developed, the
researcher conducted a minimum of two additional rounds of coding to ensure consistent
coding of all student responses. Codes were not exclusive; a single student response
could mention multiple reasons why they did or did not like the stories and was coded
accordingly. Following the coding process, descriptive statistics were calculated for all
focus codes and categories related to what students reported liking and disliking about the stories.

**Study Assumptions and Limitations**

This study was conducted under the following assumptions: (1) teacher and student participants took their participation in the study seriously and put forth effort to honestly and accurately answer all survey questions; (2) teacher participants honestly and accurately answered interview questions; and (3) teacher participants’ instruction was not significantly influenced by the researcher’s presence during classroom observations. However, the accuracy of these assumptions cannot be determined.

Although the study included teacher participants with a wide variety of teaching experience and from multiple school settings, generalizability of the study findings is limited. All schools in the study were from a single Midwestern state in the United States and, prior to the study, all teacher participants expressed interest in utilizing NOS short stories in their class instruction to teach about NOS. Additionally, eight of the thirteen teacher participants graduated from a teacher education program including a course about NOS and effective NOS pedagogy. Therefore, the experiences of these teachers and their implementation decisions may differ from the typical secondary science teacher.

Study results for research question 1, regarding factors influencing teachers’ implementation of the NOS short stories, are limited by the artificial restrictions placed on teachers’ implementation practices introduced by both the inclusion of a quasi-experimental study to assess the impact of stories on students’ NOS understanding and minimum implementation requirements necessary to assess students’ interest and
attitudes towards the stories. For increased understanding of teachers’ use of NOS short stories and factors influencing their implementation decisions, further study without restrictions on the number of stories to be implemented or minimum implementation requirements may be beneficial.

Research questions 2, 3, and 4 relate to the impact of the NOS short stories on student participants. These results may be limited by the need for parent consent and student assent to utilize student survey data; this created a situation in which students self-selected for participation in the study. Furthermore, due to absences from class, not every student participant completed all surveys needed for the study. Thus, data sets for each student participant are not necessarily complete. Limited return of consent forms from students and non-completion of student surveys in some teacher participants’ classes may have resulted in a student sample that is not representative of the target population.
CHAPTER 4: RESULTS AND ANALYSES

Overview and Research Questions

This chapter presents results of a study that investigated the classroom implementation and impact of short historical science stories designed to improve students’ understanding of the NOS. The specific research questions were as follows:

1) What factors impact secondary teachers’ implementation of the science short stories as part of their classroom instruction?

2) What impact, if any, does the use of NOS short stories in secondary science classes have on students’ understanding of fundamental NOS concepts?

3) Following the use of the short stories, what are secondary science students’ perceptions regarding their interest in:
   a) reading the short stories compared to textbook or other typical course readings?
   b) reading about scientists and how science ideas are developed?

4) What correlation, if any, exists between students’ interest in the short stories and their:
   a) attitude towards reading?
   b) conceptions of learning?
   c) attribution for academic success?
Research Question 1:  
Factors impacting Teachers’ Implementation of Stories

Teacher participants’ implementation of the short stories in their classroom instruction varied greatly, including where they placed the stories within a unit, the assistance provided students for understanding the stories and reflecting on the NOS ideas and embedded questions in the stories, use of small group and whole class discussions, class time devoted to implementation of the stories, student accountability for the reading the stories and answering the embedded questions, and general classroom culture. The case studies below summarize each teacher’s instructional context, implementation decisions, and general classroom culture.

Case Studies of Teacher Participants’ Story Implementation

Henry

Context

Henry is a 5th year teacher working in the same suburban high school as Jessica, Vicki, and Rick. During this study, Henry taught three sections of Chemistry (two serving as the treatment group and one as a control group) and three sections of a lower-level General Chemistry course (two treatment and one control).

Implementation in Chemistry Classes

Henry implemented three stories (Development of the Periodic Table, Conservation of Mass, and the Development of the Atomic Model) in both his treatment sections. These three stories were chosen in conjunction with Jessica who taught the same Chemistry course. The Development of the Atomic Model story was used at the end
of the semester as a review prior to semester final exams. Except for the *Atomic Model* story, stories were implemented very early in the units. Henry expressed that the stories worked well to introduce units and raise questions students could come back to throughout the unit.

Except for the *Conservation of Mass* story (read individually in class when Henry was absent from school), reading the stories and answering the embedded questions was assigned as homework. Henry’s rationale for having students read the stories individually was because he felt the students had the ability to read the stories without assistance and would do so. He also expressed concerns with limited class time in the Chemistry course. Because all Chemistry teachers were expected to give students the same exams at set intervals, Henry felt restricted by the need to keep moving through the curricula at a similar pace to the other teachers. Thus, he felt class time would be better utilized discussing the stories and embedded questions.

Classroom implementation frequently included small group discussion of the embedded questions and always included extensive whole class discussion. When small group discussions were used, students worked in pairs to discuss specific section of a reading and come to consensus regarding an embedded question. Henry often moved among students when they worked in small group discussions to provide support, answer questions, and monitor their behavior and progress. To encourage extensive and quality whole class discussion, participation points were included for answering questions from the teacher or their peers and asking or making relevant questions and comments. Throughout whole class discussions, Henry asked probing, elaboration, and clarification questions to assist students in reflecting more deeply on the NOS ideas in the stories. Due
to the extensive discussions, implementation for two of the three stories lasted two class periods. Students’ written responses to the embedded questions were collected and graded for completion.

**Implementation in General Chemistry Classes**

Henry selected three stories (*Conservation of Mass, Development of Temperature Scales, and Heat*) for use in his lower level General Chemistry course based on how well they fit with the science content in the course. All three stories were used early in the units when students had little background knowledge of the relevant science content. Implementation of the stories typically lasted two to three class periods.

Henry often read portions of the stories aloud to the General Chemistry Students. At other times, students read sections of the stories individually in class. Smaller portions of stories were occasionally sent home to be read as homework. Henry decided to have General Chemistry students primarily read in class rather than homework because he perceived they might struggle with the readings or not complete them at home. Because he was the only instructor for the General Chemistry course, Henry was not constrained by the pace of other course sections.

Henry frequently clarified terminology and asked questions. Students individually addressed questions as they read. At times, Henry lead a short class discussion and had a few students share ideas for each question. At other times, student pairs were assigned a question to address and present to the class. Similar to the discussions in Henry’s Chemistry classes, General Chemistry students earned points for meaningful participation in whole class discussions. Throughout class discussions,
Henry asked questions to draw students’ attention to NOS ideas in the stories, promote deeper reflection about their answers to the embedded questions, ask for evidence to support their answers, or make connections to previous conversations and experiences. Following reading and discussion, students’ written responses to the embedded questions were collected and graded for completion.

**Classroom Culture**

Henry was always positive and friendly with his students and frequently promoted active participation and engagement. Lessons included frequent small group discussions, group problem solving, and whole class discussions. Students were often expected to work together to generate ideas, solve problems, pose questions, and evaluate ideas. When discussions were used, the teacher carefully used questioning to scaffold students’ thinking and prompt deeper reflection. However, when presenting new information, his teaching often became more lecture-based with interspersed problem solving. During individual and small group work, Henry typically moved among students to assist them and monitor their progress and behavior. Off-task student behaviors were only occasionally observed.

**Jessica**

**Context**

Jessica is a 12th year teacher working in the same suburban high school as Henry, Vicki, and Rick. During this study, she taught five sections of a Chemistry course. Three sections participated as a treatment group and two sections served as a control group.
Implementation

Jessica utilized three stories (Development of the Periodic Table, Conservation of Mass, and Development of the Atomic Model) in her treatment class periods. These stories were chosen in conjunction with Henry because they best fit with their curriculum. Except for the Atomic Model story, which was used as a review prior to semester final exams, Jessica implemented the readings early in her units. Jessica provided little justification for the placement of the stories other than it was what she and Henry had decided.

Jessica had extensive absences during the semester that impacted her implementation of the stories. She assigned two of the readings on days she was absent and had students read the stories and answer the questions in class. For the Periodic Table and Atomic Model stories, students read and answered the questions individually. When implementing the Conservation of Mass story, students worked in pairs on the embedded questions help them make sense of the questions. Jessica chose to have students do all their reading individually in class because she did not trust students to complete the readings otherwise. Because the reading was typically done individually and while she was absent, no support was available to help students understand the reading or reflect on the NOS ideas.

Jessica held students accountable for completing the readings and embedded questions by providing homework points for completion. During her interview, Jessica reported that she held class discussion of the embedded questions. However, the researcher only observed an extremely limited discussion of the Conservation of Mass story when a few students responded to one question about the story at the very
beginning of class; Jessica asked no elaboration or clarification questions, and then
moved on to a lesson regarding stoichiometry. During her interview, Jessica reported
that implementation of the stories lasted just over one class period; one day was spent
reading and answering the questions and a small portion of the next day a few of the
questions were discussed. She also indicated she was unhappy with her implementation
and would have preferred spending more time discussing the stories, but she felt that her
students were too far behind in the curriculum because of her absences to be able to
provide more class time for discussion.

*Classroom Culture*

While there was a friendly atmosphere between Jessica and her students, the
classroom culture promoted limited active student engagement. Students were expected
to participate in completion of class assignments and small group work. However, the
majority of students could avoid active participation in whole class discussions. Wait
time after questions was almost non-existent. Jessica moved between questions and
activities very quickly providing limited time for students to respond, participate, or think
deeply about the questions being asked. While students’ answers were always treated
respectfully, her limited use of wait time, tendency to summarize and correct students’
ideas, and quick change of topics during discussions served to devalue students’ ideas
and contributions. The teacher played a heavy role in providing information instead of
asking probing and elaboration questions or using students’ ideas.
Carol

Context

Carol is in her 25th year teaching and taught in the same suburban high school as Ken, Beth, Karen, and Jill. Her four sections of a Chemistry course participated in the study.

Implementation

Carol had an extended absence during the semester that she felt put her progress through the curriculum behind schedule and limited the time she was willing to spend on the stories in class. Towards the end of the semester, Carol implemented the story about Development of the Atomic Model as a review prior to final exams. Regrettably, Carol repeatedly rescheduled when she was going to use the story in her class and did not inform the researcher when it was eventually implemented. Thus, the researcher did not have the opportunity to observe Carol’s implementation, and all evaluations of her implementation are based on what she told the researcher during her post-implementation interview. Her implementation lasted two class periods.

Carol did not follow minimum implementation requirements for the study. At a minimum, students were expected to read an entire story and answer the embedded questions. However, due to limited class time remaining in the school year, Carol chose to break the story into three sections (The work of Dalton, Thompson’s model, and Rutherford and Chadwick’s contributions) and used a jigsaw technique where students were assigned a specific section to read and present to the class. Unfortunately, when students only read selected sections of the story, the storyline is lost and students’ ability
to understand and make sense of the reading is reduced.

Students were provided a worksheet listing the embedded questions from the story and a framework table for students to complete. The framework table listed four scientists from the story (Dalton, Thomson, Rutherford, and Chadwick); for the section they read, students were expected to describe that particular scientist’s contributions to understanding the particle model, changes they made to the model, what evidence prompted the change in the model, and how the scientists exhibited creativity. All students answered the pre-reading question and then spent approximately 20 minutes individually reading their assigned section and answering one or two of the embedded questions related to their section. Once finished reading, students worked in small groups to discuss the section they read and prepare a whiteboard to present their section of the framework to the class. Students’ worksheets with the framework and selected embedded questions were collected and graded for completion. Carol reported that she decided to focus on creativity for the NOS portion of their discussion; the embedded questions and other NOS ideas from the story were not specifically addressed during the discussion.

Classroom Culture

Carol’s general classroom culture promoted active engagement of students and student development of ideas to a moderate extent. Students were expected to contribute to small group discussions and occasionally to whole class discussions. Whiteboards were frequently used in small groups to elicit student ideas for the class to discuss. However, there were no assurances that all students in a group were participating; frequent off task behaviors were observed. During whole class discussions, often only a
small group of students actively participated analyzing and critiquing students’ ideas presented on whiteboards. Students’ ideas were always treated respectfully, and Carol would ask occasional probing or elaboration questions during class discussions. However, Carol frequently gave information or clarified students’ students answers in a way that undermined students’ ideas and contributions.

**Ken**

**Context**

Ken is a 4th-year teacher and taught in the same suburban high school as Carol, Beth, Karen, and Jill. Ken taught two sections of a Chemistry course and two sections of an Advanced Chemistry course. Sam student taught in Ken’s classroom during the study.

**Implementation**

Ken and Sam implemented two stories in each of the courses, and implementation procedures were very similar in both courses. The *Conservation of Mass* and the *Atomic Model* stories were utilized in the Chemistry classes. The Advanced Chemistry students read the *Conservation of Mass* and *Periodic Table* stories. Ken chose these particular stories because they best fit with the curricula and the content students were already familiar with. Implementation typically lasted three class periods.

Ken purposefully implemented the stories later in the units when students had already been exposed to the majority of the science content relevant to each story. Prior to having students read the first story, Ken and Sam led a class discussion regarding potential difficulties students might face with this type of reading and strategies the
students could use while reading. Students decided they should take notes regarding important points and big ideas, questions they had, vocabulary they were unsure of, and answer the embedded questions as they read. On the first day, following class discussion regarding reading strategies, students read the stories individually and answered the embedded questions in class. Ken and Sam moved among the students and answered questions students had as they read the stories. However, time spent reading was not interspersed with any other activities or class discussion; students often became fidgety and had to be reminded to stay focused on the reading and answering the embedded questions. On the second and potentially third day, students finished reading and answering questions, if needed, and then participated in small group and whole class discussion. Students worked in small groups to discuss each embedded question and prepare whiteboards with their answers while Ken and/or Sam circulated answering questions and monitoring students’ progress.

During whole class discussion, whiteboards from each group were displayed on the wall and compared. However, individuals and groups did not have to present their ideas to the class and students could avoid participation in the discussion. Throughout class discussion, Ken asked probing and elaboration questions to promote students’ deeper reflection about the NOS ideas and embedded questions. Yet, he told the researcher that he occasionally found himself unsure of where to go with the answers students provided to his questions and how to further scaffold their thinking. Following discussion of the second story, students also worked in small groups to identify big ideas that related to both stories. Thus, Ken prompted students to reflect more deeply on NOS ideas and how they related to multiple contexts. In addition to small group and whole
class discussions, students’ written answers to the embedded questions were graded based for completion.

**Classroom Culture**

Ken’s classroom climate was one in which students’ active participation was expected and promoted. Students frequently worked in small groups to develop ideas, come to consensus on ideas, and prepare whiteboards to present to the class. However, students could avoid participation in the whole class discussions. Ken maintained a positive classroom climate where students’ ideas were treated with respect and he could question students to promote deeper thinking and understanding and students frequently evaluated and critiqued each other’s ideas.

**Will**

**Context**

Will is a third-year teacher. He taught four sections of a Chemistry course in blocked class periods at a rural high school. All his Chemistry courses were taught in a Community College classroom separate from the main high school building. Thus, Will had more autonomy and faced less constraints from administrators and science department colleagues.

**Implementation**

Three stories (Heat, Development of the Periodic Table, and Development of the Atomic Model) were utilized during the semester he participated. These particular stories
were chosen because he felt they fit well with the science content he was teaching that semester. Because he perceived the stories would be more difficult for students to understand if they were also facing unfamiliar science content, Will intentionally implemented stories towards the middle to end of units after students had been exposed to most relevant science content. Typical implementation for each story lasted approximately one and a half to two blocked class periods.

To permit more time for extensive class discussions, students typically read portions of the story in class and portions as homework. However, he never sent stories home to be read in their entirety; portions of the stories Will thought were more difficult or important were read in class. Students read and answered embedded questions individually, but students never read for extended lengths of time. Reading time was interspersed with small group and whole class discussions and evaluations of students’ responses to the embedded questions. When students read in class or worked in groups, Will was always walking among students, monitoring behavior, and answering student questions. Students often worked in small groups to come to consensus about their answers to the embedded questions and present their ideas on whiteboards for the class to evaluate. Group responses were compared and differences among them discussed. During discussion of the first story, Will spent significant time questioning the class to help them compare and evaluate group responses and learn to write more thorough responses to the embedded questions using evidence from the stories.

Students were required to answer all the questions in each story. Will extensively questioned students to help them reflect more deeply on NOS ideas in the stories; students’ ideas were questioned, challenged, and expanded upon by both Will and other
students. Additionally, Will extended the class discussions to highlight further NOS ideas he felt were relevant but not extensively drawn out through the embedded questions. For example, Will thought the *Periodic Table* story should draw more attention to the differences between Mendeleev’s notebook and the work he published, and he thought the *Heat* story should discuss the role of scientific theories in more detail. Following class discussions, students’ responses to the embedded questions were collected and graded for completion points.

*Classroom Culture*

Will’s classroom culture was highly interactive and intellectually rigorous. All students were expected to participate in both small group and whole group discussions regularly. Will moved among his students and monitored their on-task behavior and progress during individual and small group work. The class climate was relaxed and friendly, but students typically stayed on task and worked effectively. Students were expected to generate ideas and ask questions, and students’ ideas were always treated respectfully. Will expected sharing and evaluating of ideas and constructive criticism.

*Hillary*

*Context*

Hillary is a first-year teacher and taught two sections of a Chemistry course in a large urban high school. One section served as a treatment group and the other as a control group.
Implementation

Hillary utilized three stories (Conservation of Mass, Development of the Atomic Model, and Development of the Periodic Table) in her treatment class period; these three stories were selected because they fit with the science content she was teaching. Although her implementation of each story varied greatly, students were always provided some exposure to the relevant science content prior to reading. She believed that having concrete experiences prior to reading would make it easier for students to relate to the stories. Implementation of each story typically lasted between one and two class periods.

Hillary’s students read the Conservation of Mass story in class, but limited class time was provided. Hillary circulated among students and answered questions as needed while students read individually. Students who did not finish at the end of the class period were instructed to finish the reading and questions for homework. On the second day, students worked in small groups to discuss their answers to the embedded questions, come to consensus, and put their ideas on a white board to share during whole class discussion. Following small group discussion of each question, the white boards from all the groups were displayed and compared. Hillary frequently asked probing questions to help scaffold students’ thinking about the NOS ideas. However, during her interview, she expressed that she was not always sure how much scaffolding was needed and thought she probably needed to include more scaffolding questions to help students make connections between the NOS ideas in the stories and their previous class experiences. Questions from this story were collected and graded for completion.

Reading and answering the embedded questions from the Atomic Model story was assigned as homework. Hillary had hoped assigning the reading for homework would
provide more class time for discussion; however, she found many students had not read and were not prepared for discussion. Thus, she postponed discussion. Small group and whole class discussion the second day was run similarly as implementation of the *Conservation of Mass* story. Students were expected to answer the embedded questions for this story, but they were not collected.

The *Periodic Table* story was implemented on the last day of the trimester when and Hillary did not follow the minimum implementation requirements. Because of limited time, Hillary felt she needed to focus more on science content; rather than utilizing the embedded questions, she provided other questions that focused more on the science content and relating the story to an activity they had completed the day before. Thus, students’ reflection on the NOS ideas from this story was limited. Students read in class individually and time spent reading was interspersed with small group discussion as students worked together to answer questions. Students’ written answers were collected and graded for completion.

*Classroom Culture*

Hillary wanted to establish an intellectually rigorous classroom culture involving active student participation and mental engagement. However, her desired classroom culture was not fully established during her first semester teaching. Although she frequently asked probing questions, attempted to utilize students’ ideas, and structured lessons such that students needed to generate, share, and critique ideas, Hillary struggled with classroom management issues that impeded students’ active engagement in class. Students were frequently off task during the early portions of the semester. Hillary
continually tried new strategies to improve classroom management, increase participation of her students, and hold students’ accountable for their behavior and engagement in class. Significant improvements in classroom management and student participation were observed by the end of the semester. Hillary was also still struggling with a lack of pedagogical content knowledge; she frequently used highly interactive activities to provide concrete experiences for students to relate to, but her instruction became more lecture-based when presenting new information. She was still learning how to scaffold students’ thinking from concrete activities to the science content being taught.

Laura

Context

Laura is a 4th year teacher working in a large urban high school. She taught three sections of a Biology course on a blocked schedule. Two sections served as a treatment group. The third section served as a control group. Liz student taught in Laura’s classroom during the study.

Implementation

Laura and Liz implemented three stories (Darwin, Mendel, and the Structure of DNA) in her treatment periods. These specific stories were chosen because they fit best with the content being taught. Stories were typically implemented very early in the unit prior to students having any significant exposure to the relevant science content, but the exact placement was sometimes influenced by other school activities. Implementation typically lasted the majority of a blocked class period; occasionally discussion continued
into a second day

Prior to implementation, Laura often used a PowerPoint lecture presentation to introduce students to the scientists in the stories and provide a very limited introduction to the content. Because Laura perceived her students would need assistance, the stories were always read in class. Portions of each story were read aloud by Laura and Liz while other portions were read aloud by students in small groups. As a reading strategy, students worked in small groups and took turns reading aloud and summarizing what the previous student read. Laura and Liz both frequently circulated through the classroom answering student’ questions and helping them make sense of the stories.

Time spent reading was interspersed with students working in small groups to answer the embedded questions followed by limited whole class discussion. However, whole class discussion was primarily limited to having a few students share their answers to the question; only rarely did Laura or Liz use questioning or other strategies to have students reflect on, clarify, or expand upon their answers to the embedded questions. Typically, Laura did not expound any further on the NOS ideas from the stories. While students had to participate in small group discussions, most students could avoid participation in the whole class discussions. Students’ written responses to the embedded questions were collected, but only graded for completion.

Classroom Culture

Laura had a friendly and positive demeanor with her students and habitually moved among her students during class. Students’ ideas were always treated respectfully, and the classroom culture, at times, required extensive student participation
and mental engagement. Her instruction frequently included concrete activities, sharing student data from class activities, asking students questions, and students working collaboratively in small groups. While students were often expected to generate ideas and questions during class, this alternated with PowerPoint presentations and extended teacher talk. Whole class discussions rarely promoted in-depth student reflection and students’ ideas were only occasionally used or extended upon during class. Constructive criticism and challenging of ideas were rarely evident.

Rick

Context

Rick is in his 18th year teaching. He taught seven sections of Biology in the same suburban high school as Henry, Jessica, and Vicki. Four sections served as a treatment group, while the three remaining sections served as a control group.

Implementation

Students read the Global Warming and Age of the Earth stories individually in class because Rick did not trust that students would read them at home. The Structure of DNA story was sent home as homework at the end of the semester because he had not yet implemented a third story in his treatment class periods. Both the Age of the Earth and Global Warming stories were implemented prior to students learning relevant content and were used as filler activities when transitioning between units. Implementation of each story lasted approximately one class period.

When implementing the first two stories in class, the stories were read
individually with no support from other students and very limited support from Rick. Students were expected to sit quietly and read each section and answer the questions. When students were done with a section, they waited for the rest of the class to finish and class discussion. Much class time was wasted when students were not working. Rick spent most of his time behind his desk while students worked. He occasionally walked among the students to be sure they remained on task; most interactions with students were limited to classroom management concerns.

Students were expected to answer and turn in all the embedded questions to be graded for completion. However, students were not expected to expand upon or evaluate their answers to the questions in any way. No small group discussion was implemented, and whole class discussion consisted of Rick calling on between three to five students to share their ideas for the questions in each section. Rick occasionally rephrased or repeated students’ answers, but he did not use questioning to help students focus on big ideas, evaluate their answers, or extend answers. A small portion of the students dominated whole class discussions; most students successfully avoided participation and sharing their ideas. Rick did not express any clear views about the NOS and did not expound on the NOS ideas included in the stories. When students misinterpreted the embedded questions, he did nothing to help them better understand the questions. Key NOS ideas were mostly ignored during discussion.

**Classroom Culture**

While Rick appeared friendly with his students, his classroom culture did little to promote students’ active mental engagement. Content was introduced through lecture
and the textbook with limited questioning of students. Rick reported using frequent hands-on inquiry activities because he thought students enjoyed them and they kept students’ attention. However, the only activity the researcher observed was structured such that the need for student decision-making and thinking was limited. Students were never observed working collaboratively to discuss and elaborate on ideas from their lessons. Nor was Rick ever observed asking probing or elaboration questions or utilizing students’ ideas in class. The focus of his class appeared to be on student recall of information rather than promoting critical thinking. Class time was frequently wasted and students were often off task. Rick stayed behind his desk at the front of class, only moving among students periodically to maintain classroom management and keep students quiet while working individually.

**Vicki**

**Context**

Vicki is a 5th year teacher in the same suburban high school as Henry, Jessica, and Rick. Vicki taught two sections of a Biology course. One section participated as a treatment group. The second section served as a control group.

**Implementation**

Vicki implemented the *Global Warming* and *Darwin* stories prior to formally introducing relevant science content. She reported intending to implement the *Mendel* reading as well, but could not due to time and scheduling constraints. Implementation of each story only lasted one class period.
Both the *Global Warming* and the *Darwin* stories were read individually in class. Vicki indicated she attempted to read aloud a portion of one of the stories to her class, but could not keep her students on task. Her primary form of implementation required students to read a section of the story, individually answer the embedded question(s) for the section, and then discuss their answers with a partner. This process was repeated until students completed the entire story. When the *Darwin* reading was observed, very little time was spent on small group discussion; instead, students seemed focused on getting through the entire reading quickly so they could return to their dissection lab; thirty minutes into the class period, half the students had turned in their papers and were back in the lab.

During implementation, neither whole class discussion nor teacher questioning was included to help students understand the stories or promote deeper student reflection about the NOS ideas in the stories. While students were expected to provide written answers to all the embedded questions, they were only graded for completion; Vicki did nothing to ensure students provided thorough responses to or reflected deeply on the embedded questions. She did not express any inaccurate views of NOS during observations, but she also did not expound on the NOS ideas from the stories in any way. Stories and the relevant NOS ideas were never discussed with the class.

*Classroom Culture*

Vicki had a positive demeanor when working with her students, and her classroom culture occasionally promoted student engagement and critical thinking. One activity was observed that required students to work collaboratively to explore new
material and problem solve. More frequently the class was lecture and textbook based and focused on recall of factual information. Vicki was never observed asking probing or elaboration questions of her students to promote more in-depth understanding or reflection and student ideas were not used or critiqued in class. Because the class was highly lecture-based, Vicki typically stayed in the front of the class only moving among students when they were working on activities or assignments. Frequent student off-task behaviors were also observed. No intellectual rigor, constructive criticism, or challenging of ideas was observed.

**Beth**

**Context**

Beth is in her 17th year teaching and taught three sections of a Biology course at the same suburban high school as Carol, Ken, Karen, and Jill. Amy served as a student teacher in Beth’s classroom during the study.

**Implementation**

Beth and Amy utilized the two DNA stories (*DNA Function* and *DNA Structure*) towards the beginning of the DNA unit. Implementation of the two stories, together, lasted two class periods. Beth and Amy read small portions of the stories aloud; other times, the students chose whether to read in small groups or individually. Beth and Amy were both present in class while the stories were read; however, assistance was limited. Amy frequently walked among the students, but most interactions were to ensure students stayed on task. At times, Beth or Amy would sit down and read aloud to a group of
lower ability readers. Students were expected to read and answer embedded questions as they appeared in the story. Although some students chose to discuss the embedded questions in small groups prior to answering on their individual paper, many students chose to work individually or participated in very limited discussion of the questions. Thus, small group discussion typically did not effectively break up extended periods of reading time. Whole class discussion was not utilized to help students make sense of the readings or NOS ideas. Many students finished quickly and were allowed to waste the remaining class period. Student written responses were collected for completion points, but there was no impetus for students to evaluate or expand upon their original answers.

Beth also reported using portions of the second *Age of the Earth* and *Darwin* stories early in her unit on evolution before students were formally introduced to the relevant science content. For these sections, students read the assigned portions of each story then went back and answered the embedded questions individually. Beth indicated she included small group discussion of the *Age of the Earth* story and whole class discussion for the *Darwin* story so she could assess students thinking about these topics prior to formally introducing the content. Neither Beth nor Amy expounded upon the NOS ideas included in the stories. No guidance was provided to help students clarify, expand upon, or evaluate their ideas regarding the NOS ideas from the stories or embedded questions.

*Classroom Culture*

Beth’s class occasionally promoted students’ participation and active mental engagement. She typically introduced content through lecture and textbook reading.
Wasted class time and student off-task behaviors were frequently observed. However, Beth did indicate she value students’ critical thinking. Because other teachers in her department (including Karen, Ken, and Carol) utilized frequent small group white boarding sessions to promote students’ collaboration and reflection, Beth now utilized this strategy as well. At times, her students did collaborate on activities, participate in small group discussion of ideas, and share ideas during whole class discussion of activities. Beth attempted to ask some probing and elaboration questions, but she was not skilled at scaffolding students’ thinking or promoting students’ deeper reflection about the content.

Karen

Context

Karen is a 5th year teacher and taught five sections of Biology in the same suburban high school as Carol, Ken, Beth, and Jill. During the spring 2012 semester when Karen participated in the study, Jill was her student teacher.

Implementation

Karen utilized the two DNA stories (*DNA Function* and *DNA Structure*) as a review activity prior to her DNA unit exam. Karen indicated she would have preferred to use them throughout the unit to illustrate NOS and content ideas rather than having students read them all at once at the end of the unit. However, her student teacher, Jill, felt uncomfortable trying to implement the stories. Thus Karen waited until Jill had completed her student teaching. Implementation of the two stories, together, lasted
During the first two days of implementation, students worked in small groups to read and answer the embedded questions. Karen constantly circulated among student groups; she frequently asked probing and guiding questions to help students make sense of the story and embedded questions. Several of her students had low reading abilities and required modifications; for these students she provided copies of the stories that included underlining of particularly important ideas needed to make sense of and answer the embedded questions. Occasionally she read portions of the story aloud to a group of students who struggled with reading. Extensive small group discussion of the embedded questions prevented extended periods of reading.

The last two days were spent on additional small group and whole class discussions of the stories and questions. However, due to limited class time at the end of the school year, whole class discussion did not cover all the embedded questions. In class periods where students were reluctant to participate in whole class discussions, Karen required students to white board their responses in small groups and then called upon groups to share their ideas. During discussions, Karen portrayed accurate NOS understanding and extensively questioning to help students identify big ideas from the stories and refine or challenge students’ thinking about the NOS questions.

Students were required to answer all the embedded questions. The questions were not collected and graded; however, Karen provided incentive for students to put forth effort on the questions by permitting students to use their responses during the unit exam only if they had written extensive answers to each question.
Karen’s classroom culture extensively promoted students’ active mental engagement and participation. Karen had a friendly demeanor with her students and excellent classroom management. Students were required to participate in both small group and whole class discussions; student disengagement was not an option. When students were reluctant to participate, Karen intentionally made pedagogical decisions that made it difficult for students to avoid participation (e.g., small group white boarding of specific questions). Students’ ideas and questions were always encouraged and treated with respect. Students frequently worked collaboratively in small groups to complete activities relevant to their lessons and discuss and evaluate ideas. Karen habitually used questioning to help students identify big ideas, develop questions and ideas, challenge their thinking, and solve problems. Intellectual rigor, constructive criticism, and challenging and extending of students’ ideas were frequently observed.

Jill

Context

Jill is a first-year teacher teaching three sections of Biology in the same suburban high school as Carol, Ken, Beth, and Karen. She participated in the study during the fall 2012 semester after having student taught with Karen the previous school year. Jill taught in a room adjoined with Karen’s and they regularly planned lessons together. Thus, Jill’s implementation decisions were highly influenced by Karen and Karen’s prior experiences with the stories the previous school year.
Implementation

Jill implemented the two DNA stories (DNA Function and DNA Structure) early in her DNA unit. The stories were read in sections to both breakup the time students spent reading and to enable Jill to introduce relevant science content before students read about it in the stories. However, student exposure to concrete examples of DNA and its structure was limited prior to reading the stories. Time spent reading was interspersed with relevant lessons, activities, video segments, small group discussion, and whole class discussion. Because implementation of the stories was interspersed with other activities and lessons, estimating the amount of class time spent implementing each story is difficult. However, both stories were completed over approximately two weeks.

Both stories were read in class; some portions were read aloud by Jill and others read individually by students. While students were reading and answering embedded questions, Jill always circulated among the students monitoring behavior, answering questions, and clarifying vocabulary students were struggling with during class discussions. Students were expected to complete all the embedded questions and explain their answers through both small group and large group discussion; occasionally Jill used effective questioning to increase students’ reflection on the NOS ideas in the questions. However, students frequently just shared their answers without being pushed further.

Jill used multiple additional strategies, designed in conjunction with Karen, to help students better understand and relate to the reading. As a reading strategy and a way for students to organize information they read, Jill provided the students with a table including all the scientists from the two DNA stories; students completed the table by describing how each scientist contributed to the modern understanding of the structure
and function of DNA. During the second DNA story, Jill interspersed segments of the video *Photo 51*, which illustrated much of the history included in the story. While students worked through the video and story, the class built a diagram on the front board explaining the relationships between Watson, Crick, Franklin, and Wilkins. This diagram was used to assist in discussion of the social interactions among scientists and social/cultural influences on science.

**Classroom Culture**

As a first year teacher, Jill was striving to develop a classroom culture that consistently promoted intellectual rigor, constructive criticism, and the challenging of ideas. Students’ ideas, questions, and contributions were always treated respectfully. Jill occasionally struggled with classroom management issues that impeded students’ active engagement in class; however, classroom management problems decreased throughout the semester. Additionally, Jill still struggled asking appropriate questions to scaffold students’ thinking for both science content and NOS concepts. Jill frequently asked probing questions, attempted to utilize students’ ideas, and structured lessons such that students needed to generate, share, and critique ideas. Small group white boarding sessions and whole class critic of group ideas occurred frequently. However, she was not yet skilled at effectively pushing students to challenge each other’s ideas and present constructive criticism.
Kaleb

Context

Kaleb is a 2nd-year teacher and taught a single section of Biology at a suburban high school.

Implementation

Kaleb utilized three short stories (Darwin, Mendel, and the Structure of DNA) during his units on Evolution, Genetics, and Inheritance. The Mendel and DNA stories were utilized towards the beginning of their respective units prior to significant development of students’ understanding of relevant science content. Because Kaleb was concerned about students’ reaction to Darwin’s name, the Darwin story was used midway through an evolution unit after students had developed an understanding of natural selection. Implementation of each story usually lasted between one and two class periods.

The majority of each story was read in class. At times, Kaleb read portions of the stories aloud, but the majority of each story was read in small groups or individually. He encouraged students to highlight passages they found important or confusing as they read. When story implementation lasted longer than usual, students were expected to finish the reading at home. Time spent reading was interspersed with limited discussion of the embedded questions or points in the story Kaleb wanted to emphasize. Students were expected to answer all the questions and share their ideas in small groups, but discussion was limited and students were rarely pushed to expand upon their answers. Whole class discussion typically involved Kaleb eliciting responses from a few students.
and then answering the question himself. He only occasionally used questioning to increase students’ reflection. Kaleb rarely expounded upon the NOS ideas presented in the stories other than to repeat the NOS ideas from the bolded key point boxes.

Classroom Culture

Kaleb’s lessons were designed in such a way that they had the potential to promote extensive active student participation and critical thinking. Unfortunately, his decisions during class discussions often inhibited extensive student engagement. He frequently asked questions promoting critical thinking and had students work in small groups to discuss their ideas. While students worked, Kaleb always circulated among his students observing and asking questions. However, following small group discussions, Kaleb often either summarized what he saw students write on their whiteboards or called on a few students to share their ideas and then told the students what he thought. Such teacher behaviors served to devalue students’ contributions to class discussions. The researcher never observed Kaleb using students’ ideas in class and only occasionally observed him asking students probing, elaboration, or clarification questions. While students were never disruptive, off-task behavior was frequently observed.

Development and Analysis of the Story Implementation Evaluation Protocol

Development of the Story Implementation Evaluation Protocol

Following observations conducted in the spring 2012 semester, an implementation evaluation protocol (Appendix E) was developed for comparing teachers’ implementation of the NOS short stories. The protocol developed was based on researcher observed
differences in teacher participants’ classroom implementation described above. Marked differences were noted in concept development (i.e., support for student understanding of the reading and support for student reflection on the NOS concepts in the stories) and student accountability (i.e., how students were held accountable for putting effort towards the reading, embedded questions, and understanding NOS ideas from the stories). Marked differences were also observed in teacher participants’ classroom culture. Because such differences can impact students’ attitude towards and interest in the NOS short stories, the Classroom Culture section of the Local Systemic Change Classroom Observation Protocol (LSC-COP) (Banilower, 2005; Horizon Research Inc., 2006) was added as a third section on the evaluation protocol.

The implementation evaluation protocol was utilized to summarize teachers’ typical implementation practices and classroom culture. Teachers were rated on a 1-5 scale (1 representing ineffective implementation practices and 5 representing highly effective implementation practice) for each of the following individual four sections: (1) support for reading, (2) support for reflecting on NOS ideas, (3) student accountability, and (4) classroom culture. The scores on the support for reading and support for reflecting on NOS ideas were utilized to assign a synthesis rating for each teacher’s concept development. Tables 8 and 9 provide exemplars illustrating high and low support for reading, reflecting on NOS ideas, and student accountability sections of the Evaluation protocol (see Appendix E for the Implementation Evaluation Protocol).

Teachers with highly effective concept development implementation practices attempted to help students understand and make sense of the reading and reflect more deeply on the NOS ideas from the stories (see Table 8). Highly effective implementation
of the stories also held students accountable for putting effort towards understanding the reading, answering the embedded questions, and understanding the NOS ideas from the stories (Table 9).

In addition to concept development and student accountability, the quality of teacher participants’ implementation also included assessment of how consistent the classroom culture reflected the following (Banilower, 2005; Horizon Research Inc., 2006):

- active participation of all students is encouraged and valued;
- students’ ideas, questions, and contributions are respected;
- interactions reflect collegial working relationships among students (e.g., students working together, talking with each other about the lessons);
- interactions reflect collaborative working relationships between teacher and students;
- students are encouraged to generate ideas, questions, conjectures, and/or proposals; and
- intellectual rigor, constructive criticism, and the challenging of ideas are evident.
Table 8 Implementation decisions impacting concept development

**Teacher Implementation Decisions That Impact Concept Development**

<table>
<thead>
<tr>
<th>Implementation Decisions Impacting Support Student Understanding of the Reading</th>
<th>High Support Understanding</th>
<th>Limited Support for Understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stories are read in class with assistance available from the teacher or peers.</td>
<td>Large portions or the entire story are read at home where assistance from the teacher or peers is unavailable.</td>
<td></td>
</tr>
<tr>
<td>Stories are read in small groups or aloud by the teacher.</td>
<td>Students read individually class when the teacher is not present or unavailable to provide assistance.</td>
<td></td>
</tr>
<tr>
<td>Stories are implemented after students were familiar with the relevant science content. This may include splitting the story into several sections to be interspersed with relevant content instruction prior to reading each section of the story.</td>
<td>Stories are implemented prior to teaching the relevant science content needed for students to make sense of the story.</td>
<td></td>
</tr>
<tr>
<td>Extended periods of reading are avoided. This may be accomplished through interspersing small group discussions, whole class discussions, or relevant activities.</td>
<td>Students read uninterrupted for more than 20 minutes at a time without interspersing discussion or other activities.</td>
<td></td>
</tr>
</tbody>
</table>

**Implementation Decisions Impacting Support Student Reflection on NOS**

<table>
<thead>
<tr>
<th>High Support for Reflection</th>
<th>Limited Support for Reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small group and whole class discussion of NOS ideas from the stories.</td>
<td>Limited or lack of whole class and/or small group discussion of NOS ideas from the stories.</td>
</tr>
<tr>
<td>Students’ initial answers to the embedded questions are frequently challenged or expanded upon through small group and whole class discussions.</td>
<td>Students are not required to answer all the embedded questions and/or they are not pushed to expand upon or refine their initial answers.</td>
</tr>
<tr>
<td>Students present and defend their ideas to the class and/or working towards consensus of ideas in small groups.</td>
<td>Students do not have to communicate their ideas regarding the NOS to others.</td>
</tr>
<tr>
<td>Extensive teacher questioning to increase students’ reflection about their responses to the NOS questions.</td>
<td>The teacher never or only occasionally questions students regarding their responses to the embedded questions.</td>
</tr>
<tr>
<td>The teacher accurately portrays NOS views related to the stories during class activities and discussions.</td>
<td>The teacher inaccurately portrays NOS ideas from the stories or avoids discussion of the NOS ideas in the stories. Discussion may only center on the science content in the stories.</td>
</tr>
</tbody>
</table>
Table 9. Implementation decisions impacting student accountability

<table>
<thead>
<tr>
<th>Teacher Implementation Decisions That Impact Student Accountability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Support High Student Accountability</strong></td>
</tr>
<tr>
<td>NOS concepts from the stories are included on summative assessments.</td>
</tr>
<tr>
<td>Students’ responses to the embedded questions are graded on their content and thoroughness.</td>
</tr>
<tr>
<td>Lessons structured such that all students communicate their ideas regarding the embedded questions through small group and whole class discussions.</td>
</tr>
<tr>
<td>The teacher moves among students to extensively monitor students’ on-task behavior and progress while students work individually or in small groups.</td>
</tr>
<tr>
<td><strong>Promote Low Student Accountability</strong></td>
</tr>
<tr>
<td>NOS concepts are rarely or never included on summative assessments.</td>
</tr>
<tr>
<td>Students’ responses to the embedded questions are not collected or only graded for completion.</td>
</tr>
<tr>
<td>Lessons structured such that all or most students could avoid participation in discussion of the NOS concepts from the stories.</td>
</tr>
<tr>
<td>The teacher is not present or only occasionally monitors students’ on-task behavior and progress during individual and small group work.</td>
</tr>
</tbody>
</table>

**Analysis of Teachers’ Implementation of the Stories**

Based on the researcher’s classroom observations, field notes, post-implementation interviews, and classroom artifacts, teacher participants’ implementation of the short stories was coded into numeric scores (1-5) using the Story Implementation Evaluation Protocol and the guidelines summarized above. A total implementation score, ranging from 3 through 15, was calculated by summing each teacher’s concept development, accountability, and classroom culture scores. Teachers were subsequently ranked as high, medium, or low-level story implementers; coding was determined by dividing the range of potential scores (3-15; 12 points) by 3 creating 4-point intervals. Thus, teachers with total implementation scores 12 and above were labeled as high-level implementers, total implementation scores 8 through 11 were labeled as mid-level
implementers, and total implementation scores 7 and below were labeled as low-level implementers. Teacher participants in the study included four high-level implementers (Will, Karen, Ken, and Henry), four mid-level implementers (Jill, Laura, Kaleb, and Hillary), and five low-level implementers (Carol, Jessica, Beth, Vick, and Rick). Table 10 lists the implementation scores and implementation level for each teacher participant.
<table>
<thead>
<tr>
<th>Teacher</th>
<th>Implementation Level</th>
<th>Total Implementation (3-15)</th>
<th>Accountability (1-5)</th>
<th>Classroom Culture (1-5)</th>
<th>Concept Development (1-5)</th>
<th>Support for Understanding the Reading (1-5)</th>
<th>Support for Reflecting on NOS (1-5)</th>
</tr>
</thead>
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</tbody>
</table>

a. Teachers who attended the same teacher education program emphasizing NOS and effective NOS instruction
b. Carol did not follow minimum implementation requirements
c. Total Implementation score is the sum of the Accountability, Classroom Culture, and Concept Development scores
d. Concept Development score summarizes the Support for Understanding Reading score and Support for Reflecting on NOS score
Factors Potentially Influencing Teachers’ Implementation

Teachers’ NOS Understanding

Teacher participants’ understanding of twelve NOS constructs was assessed with VOSSI items, each consisting of four Likert sub-items and an open-response question (Appendix C). For the purpose of this study, the 12th VOSSI item (Science and Religion) was not utilized due to questionable validity. The decision to remove the 12th item was made based off of teachers’ written responses, teachers’ comments during the interview, and the high level of Uncertain responses included on the Likert sub-items. Many of the teachers’ qualitative responses were unclear and did not fully answer the question, thus would have been rated as naïve. During interviews, several teachers mentioned struggling to answer the question or being uncomfortable with the question. Analysis of teachers’ Likert responses to the Science and Religion VOSSI item reveals a higher percentage (21 percent) of responses marked Uncertain compared to the other eleven VOSSI items (Uncertain responses ranged from 0% to 13%). Additionally, one teacher reported that she marked a neutral response (Uncertain) on one of the four Likert sub-items because she did not understand the statement. Whether the vague and incomplete written responses and the high percentage of Uncertain responses on the Likert sub-items were due to teachers’ holding naïve and uncertain views of the construct, not understanding the questions, or being uncomfortable with the content of the question is unclear; thus the item was removed for analyses.

Teachers’ responses to the VOSSI items were evaluated to determine their congruence with informed views of each of the eleven NOS constructs. Teachers’ final rating for each of the eleven VOSSI items analyzed was determined by comparing their
rating on the Likert and qualitative responses. A total NOS understanding score ranging from 0 through 22 was calculated for each teacher by assigning a numeric value to each VOSSI item and summing the eleven items; “Naïve”, “Transitional”, and “Informed” responses were assigned a value of 0, 1, or 2 respectively. Table 11 indicates the number of NOS constructs recorded as “Naïve”, “Transitional”, and “Informed” and the total NOS understanding score for each teacher participant.

Table 11. Teachers' VOSSI NOS Understanding Scores

<table>
<thead>
<tr>
<th>Teacher</th>
<th># Naïve Items (0-11)</th>
<th># Transitional Items (0-11)</th>
<th># Informed Items (0-11)</th>
<th>Total NOS Understanding Score (0-22)</th>
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</thead>
<tbody>
<tr>
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<td>20</td>
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<td>Karen</td>
<td>0</td>
<td>5</td>
<td>6</td>
<td>17</td>
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<tr>
<td>Ken</td>
<td>0</td>
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<td>Henry</td>
<td>0</td>
<td>9</td>
<td>2</td>
<td>13</td>
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<td>Jill</td>
<td>0</td>
<td>6</td>
<td>5</td>
<td>16</td>
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<td>Laura</td>
<td>0</td>
<td>8</td>
<td>3</td>
<td>14</td>
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<td>Kaleb</td>
<td>0</td>
<td>3</td>
<td>8</td>
<td>19</td>
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<td>Hillary</td>
<td>0</td>
<td>6</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>Carol</td>
<td>0</td>
<td>7</td>
<td>4</td>
<td>15</td>
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<tr>
<td>Jessica</td>
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<td>10</td>
<td>1</td>
<td>12</td>
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<td>Beth</td>
<td>1</td>
<td>8</td>
<td>2</td>
<td>12</td>
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<tr>
<td>Vicki</td>
<td>1</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Rick</td>
<td>4</td>
<td>7</td>
<td>0</td>
<td>7</td>
</tr>
</tbody>
</table>

a. Teachers who attended the same teacher preparation program, which included extensive instruction regarding NOS and effective NOS pedagogy
b. Teachers are ordered by their story implementation scores and separated into high, medium, and low-level implementers.

Table 12 compares teachers’ NOS understanding scores with their story implementation scores. In line with previous research findings (Abd-El-Khalick et al,
accurate NOS understanding is a necessary but insufficient condition of effective NOS instruction. The four teachers with the lowest story implementation scores (Rick, Vicki, Beth, and Jessica) also had the lowest NOS understanding scores, and the teacher with the highest implementation score, Will, also had the most informed view of the eleven NOS constructs. However, Kaleb had the second highest NOS understanding score, but was on the lower end of the mid-level story implementers. All the high and mid-level story implementers attended the same teacher preparation program that emphasized both understanding NOS and effective NOS instruction.

Table 12. Comparison of teachers’ experience, NOS understanding, and implementation

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Teaching Experience</th>
<th>Total NOS Understanding Score (0-22)</th>
<th>Total Implementation (3-15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Will a</td>
<td>3rd year</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Karen a</td>
<td>5th year</td>
<td>17</td>
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<td>Ken a</td>
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<td>Henry a</td>
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<td>13</td>
<td>12</td>
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<td>1st year</td>
<td>16</td>
<td>10</td>
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<td>Laura a</td>
<td>4th year</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Kaleb a</td>
<td>2nd year</td>
<td>19</td>
<td>8</td>
</tr>
<tr>
<td>Hillary a</td>
<td>1st year</td>
<td>16</td>
<td>8</td>
</tr>
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<td>Carol</td>
<td>25th year</td>
<td>15</td>
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<td>Jessica</td>
<td>12th year</td>
<td>12</td>
<td>6</td>
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<td>Beth</td>
<td>17th year</td>
<td>12</td>
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</tr>
<tr>
<td>Vicki</td>
<td>5th year</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Rick</td>
<td>18th year</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

a. Teachers who attended the same teacher preparation program, which included extensive instruction regarding NOS and effective NOS pedagogy
Teaching Experience

Overall, teaching experience was a poor indicator of teachers’ level of implementation. Teachers with the most experience (Carol, Jessica, Beth, and Rick) were all low implementers. However, the high implementers (Will, Ken, Karen, and Henry) were at least in their third year teaching. Implementation of the NOS short stories by the two first-year teachers, Jill and Hillary, was limited by their early struggles with content, pedagogical content knowledge, and classroom management. Both Jill and Hillary frequently asked the researcher for feedback regarding classroom management issues following classroom observations. During her post-implementation interview, Hillary repeatedly described her own struggles as a first-year teacher as an obstacle to effective NOS instruction and implementation of the stories. Example quotes from Jill and Hillary illustrate their struggles teaching NOS and implementing the stories as first-year teachers.

Referring to obstacles she faced attempting to teach NOS, Jill stated:

I want to incorporate it more, and I do incorporate it when I can. But it’s not up to my standards. For me, right now, just being a new teacher. Just trying to remember what I’m doing that day, and then trying to add that in. Which, it’s not supposed to be two separate things, but, you know, just even starting to learn my content and then trying to figure out how science, how scientists use that content. (Jill, Interview 12-21-12)

Hillary explains why she did not include NOS instruction as much as she would like to during her first semester:

Not as much as I would like. Mostly I think part of it is being a first year teacher, so figuring out what I’m teaching. But, how do I put this? One, I feel just pressured in general to, you know, to cover a lot of information. But, in moments where I know I can, what is it? Where I feel like I have the time to make them go from beginning to end. What is a question we can develop, and how can we solve this problem. I think there are some opportunities. I would say, not as many as I would like, probably maybe only 25% of the time did I, do I pursue these opportunities. Mostly because those take time. But I also am optimistic that that’s going to
increase after this. Because I’m seeing more opportunities, and now that I’m getting my feet under me, I’m seeing, I’m optimistic that this is going to change. (Hillary, interview 12-17-12)

Hillary further explains why she decided to assign one of the three stories she implemented as homework:

Again, time. I thought, for some reason, them taking it home would mean that they would take their time with the reading more. But that was not the case. It was the exact opposite, so part of that I attribute to being a first year teacher learning. (Hillary, interview 12-17-12)

During the post-implementation interviews, Jill expressed less discontent with her implementation of the stories than did Hillary. However, Jill had the support of a more experienced teacher, Karen, whom she had developed a close working relationship with during her student teaching experience the year before. During the Fall 2012 semester when Jill participated in the study, she and Karen shared adjoining classrooms and both taught biology. Jill had been planning many of her lessons, including the lessons utilizing the NOS short stories, in conjunction with Karen. Additionally, Karen had utilized two of the short stories during the previous school year and could build from her prior experience implementing the stories. Thus, while Jill still struggled, as most first-years teachers do, she had a significant support system that heavily influenced her decision-making regarding the implementation of the short stories.

**Factors Teachers Report Impacting their Implementation Decisions.**

During post-implementation interviews, teachers were asked about how they selected which stories to implement, factors influencing their implementation decisions, difficulties and concerns using the stories, their interest in using the stories in the future, and what changes to the stories or additional resources would be helpful for future
implementations. Tables 13-15 summarize the factors teachers reported impacted their selection and implementation of the stories, obstacles they faced implementing the stories, and how they perceived the stories impacted their students.
Table 13. Factors teachers reported influenced their decisions regarding implementation of the short stories

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Fit with Curricula</th>
<th>Time</th>
<th>Student Resistance</th>
<th>Students’ Understanding</th>
<th>Student Participation</th>
<th>Promote Student Thinking</th>
<th>Students’ Ability</th>
<th>Presence of a Student Teacher</th>
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Table 14. Teacher reported obstacles and difficulties with story implementation

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<th>Student Resistance</th>
<th>Student Ability</th>
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<th>Difficult Vocabulary</th>
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<th>Student Absences</th>
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Table 15. Teachers’ reported perceptions of how the stories impacted students

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<tr>
<th>Teacher</th>
<th>Increased Participation of Students Who Rarely Participate</th>
<th>Promotes Other Goals for Students</th>
<th>Assisted Students’ Learning of Science Content</th>
<th>Increased and/or Reinforced Student Understanding of NOS</th>
<th>Increased Interest in Class or Science Content</th>
<th>Students Pulled from the Stories to Provided Evidence on Exams</th>
<th>Students May Have Been Intimidated by the Length</th>
<th>High Achieving Students Found Them Interesting, but Unmotivated Students Were Disengaged</th>
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All teacher participants reported that their primary consideration when deciding which stories to implement was how well the story fit with the science content they were teaching that semester. For example, when asked why she chose to implement the two DNA stories, Jill stated, “Oh, it just fit in nicely with where we were in biology” (Interview 12-21-12). Similarly, when Will was asked why he chose the three stories he implemented, he said, “Because they pretty honestly fit into my curriculum as I progressed through the semester. So, the other stories didn't fit in throughout the material we were covering” (Interview 5-10-12).

Jessica, Carol, and Rick all expressed some discomfort about selecting stories they did not feel were a good fit with their curricula for the semester. For example, Jessica and Henry had difficulty selecting a third story that would fit with the Chemistry curricula for the spring semester. To ensure implementation of three stories, they decided to utilize the Atomic Model story at the end of the semester as a review prior to semester tests. Jessica expresses her frustration trying to select a third story:

The frustration of the length of them. And having to get three done. The time of year. If this were done at the beginning of the year, I think it would have been easier to understand. Then having the added stress of the end of the school year and trying to get everything crammed in. There were articles that just didn’t fit. I mean, when we had to pick 3 articles and… there were 2 that fit in naturally. It was a stretch to pull in that 3rd one. (Jessica, Interview 5-29-12)

Rick taught evolution, genetics, and ecology the semester he participated, and yet he also expressed discomfort with how the provided stories fit with his course content. When asked how he decided where in his units to implement the stories, Rick explained:

Well, there’s where lied a little bit of the issues. We started this, was already into the school year a little bit. So, I tried to pick and choose
where it was most palatable, you know, with some of the units we were doing. So though, although it was not a perfect match, we slid it in where it was the best fit, is what we did. (Rick, Interview 5-29-12)

*Student Understanding*

Every teacher participant, except Beth and Rick, reported that concerns about student understanding influenced their implementation of the stories. Four of the eight high and mid-level implementers (Will, Ken, Hillary, and Jill) specifically mentioned intentionally placing stories after students were exposed to the science content and would therefore be better able to make sense of the stories. For example, when Jill was asked why she chose to insert activities and other lessons between sections of the DNA stories, she said:

To prevent students from being overwhelmed. To be sure that students were actually comprehending what they were reading. To provide them with more of, like, a concrete experience before the more abstract reading. And I think because of that we had a lot more in-depth questions and discussions. (Jill, Interview 12-21-12)

When asked about where in their units they placed the stories, Ken and Will gave the following responses:

Towards the end [of the unit]. Reading strategy wise, it's a little bit more abstract so it works better to come at the end. And we made it act as kind of a summary, too…. The stories I picked I felt fit best with what I'm teaching. And even then there was, there were a few times when I felt that I wanted to do them earlier, but I knew that if I waited one more unit some of that material would be better addressed. And so, I think that's part of the reason they ended up getting shoved towards the end, too…. The periodic table I felt like they needed more than just one example of a pattern or a period to be able to really fully appreciate the organization of it. So, I waited a unit so they could have more than just the 1st layer of organization. (Ken, Interview 5-14-12)
That was one of the things I thought a lot about. Where they best fit, and, and I guess I wanted them more so after we had done something with the ideas of the story presented. Like with the content matter within the story.... I wanted them after we had discussed more of the ideas. So like the heat one, we didn't read until after we have thoroughly discussed the nature of heat. Same with like any of those... So that they would have some actual background behind the content and some activities to think about when they read through it. So, I felt that if they, if they read it up front, a lot of the ideas would be new ideas or possibly even they just wouldn't have any experience with any of the ideas in the stories, so the stories themselves would've been very difficult and too much new information at once. So it wouldn't really, they'd be struggling to understand the content as opposed to being able to look deeper behind the history and understand how the ideas developed. (Will, Interview 5-10-12)

Another decision teachers made to help students understand the readings were including small group and whole class discussions. For example, Will stated:

[My] rationale for small groups was that, in groups, they can discuss the ideas from the story and they can draw each other's attention to insights that the other might not have had or some details the other might not of seen. And then large group discussions do the same thing at a larger level. (Will, Interview 5-10-12)

When asked why she chose to have students discuss the embedded questions with a partner, Vicki said, “Just so they could process it. Some kids... it’s a lot of reading for them, and I think it’s just easier if they don’t get it on their own. Maybe talking to the person next to them will help them process what’s in there” (Interview, 5-29-12). In addition to both small group and whole class discussions, Jill also chose to insert segments of a video and diagram the relationships between scientists on the board to help students make sense of the DNA Structure story. She explains:

What we found that helped with students a lot through the reading and through the video, was we had four pictures... of, like, Watson and Crick, Franklin, and Wilkins. And we just had lines going between, and then we had them describe the relationships between them and had that posted on the board. And students, that helped them tremendously. And I even had students from last year who saw that, and they were like, “Wow, that would have been helpful.” And so, it kind of helped them sort of follow
the storyline, understand the relationships between people, and what was actually occurring. (Jill, Interview 12-21-12)

School Constraints

Every teacher except Rick and Beth reported that constraints from the school environment, in some way, impacted their implementation of the stories. Time constraints were a significant factor influencing story implementation decisions. Teachers frequently felt pressured to move through the curricula at the same pace as their colleagues. In some cases, the school requirement that teachers simultaneously administer summative assessments prevented implementation. Vicki explains why she did not implement three stories as she agreed to do as a Treatment-Control teacher:

I wanted to do the Mendel one, but the way it worked out with our 8-week test and the library time that I could get for the genetics thing, that didn’t work out, unfortunately. (Vicki, Interview 5-29-12)

Additionally, Vicki expressed feeling restricted by other colleagues teaching the Biology course:

I think using it over in Molecular [Biology course] you’d probably get more of a reception, not a reception to it. But you know, it just, there seems like there’s no time, you know, in our curricula to try and do that. And over there [in the Molecular Biology course], there’s more freedom for the individual teacher. So, I don’t know, it’s kind of, it’s politics part of it. (Vicki, Interview 5-29-12)

Teachers also frequently just expressed an overall concern with the amount of class time they had available. When asked why she chose to read portions of the stories aloud to the class, Jill explained, “I think for me, initially, it was for time’s sake. If I read it, it went a little bit faster” (Interview 12-21-12). Even the high-level implementers indicated that limited class time was a concern and reduced the number of stories they
were able to use during the semester. Due to the extended time spent on small group and whole class discussions, high and medium-level implementers frequently spent two to three class periods implementing each story. For example, when asked which stories he chose to implement, Ken said, “I know we did two in each [course]. I wanted to do three but I just couldn't” (Interview 5-14-12). Furthermore, when asked what obstacles he faced implementing the stories, Ken stated:

> Time, you know. It's the time crunch. It took us, in both, in all cases at least three, at least parts of three class periods. And even then, I felt like I could spend more time on them. But, some of these philosophical conversations and science process conversations are not the most - It's not that they're not engaging, but it's hard to maintain the engagement over long periods of time. Because it's pretty, it's pretty deep stuff. So, after three days they’re ready to be done. Even though there may still be more ideas to investigate or discuss. (Ken, Interview 5-14-12)

When Will was asked about obstacles he faced implementing the stories, he stated, “I'd say the biggest obstacle was time. They all took more time than I thought they would. [I] consider the biggest obstacles just simply time” (Interview 5-12-12). When asked why he assigned portions of the stories to be read at home, Will explained:

> Reading at home was primarily due to time constraints. So, it was usually if we, like if we would leave off after a discussion, it would be you need to read this by next time or if we first got them going it would be read up to the first two questions and have them answer for next time. So, that was time constraints. Because I thought that would allow working class time for us to use them. (Will, Interview 5-12-12)

Additionally, teachers frequently mentioned timing with availability of other school resources (e.g., library and computer lab availability), school activities, and the end of grading periods as obstacles or challenges to their implementation of the stories. The following teacher responses illustrate this concern:

> Having the student teacher was a challenge. In hindsight, I wish I would have instructed her to do them or implemented them myself at different
times. I just, the nature of the school year ending was a challenge. (Karen, Interview 5-25-12)

The Periodic Table I thought was an awesome reading for putting together how useful it was. Unfortunately, because of it being the last day of the tri[mester], I didn’t emphasize the nature of science ideas. (Hillary, Interview 12-17-12)

It definitely was a time issue. But you know, my dad died, we had the band trip, and I lost a lot of my kids after that band trip. Some never did recover. And then, I mean, May doesn’t exist. And I don’t even teach 9th hour, and I was getting hit like crazy. It was awful, but they were taking kids out left and right [for school activities]. (Carol, Interview 5-25-12)

Student Resistance and Ability

Every teacher participant, except Will and Carol, reported that student resistance impacted their implementation decisions. Additionally, except for Beth, all the medium and low-level implementers reported student resistance as an obstacle they faced implementing the short stories. Rick, Vicki, Jessica, and Beth all indicated they had students read the stories in class because they did not trust students to do the reading otherwise. The following teacher responses illustrate their concerns with student resistance to completing the reading or discussing ideas in class:

It was kind of the same thing I did with the one you watched. I’d tried doing something where kids would take turns reading, and that just didn’t work, ’cause half of them don’t pay attention while someone else is talking. So I just ended up giving it to them. They read a section, answered the question, then talked to their neighbor just so they could process it. Some kids, like as you walk around, they, it’s like they don’t , it’s a lot of reading for them, and I think it’s just easier if they don’t get it on their own. Maybe talking to the person next to them will help them process what’s in there. (Vicki, Interview 5-29-12)

Their biggest thing, I think, was just, you know, they didn’t want to do it. You know, their thoughts. I think they, some of the questions, not that they were really worded very difficult, but they weren’t quite sure what
the question is asking. (Jessica, Interview 5-29-12)

You know, just the typical like, ‘This is too long, I don't want to read.’ Which I'm sure you'll see in the surveys. It's just the initial student kickback of it, of doing anything in class usually. But, when they see, you know, small font and many multiple pages. That freaks them out because there used to ‘Here, read those 2 paragraphs’, you know, which is like 16 words. So, you know, I think it's good getting them to read more, and like real reading. That’s super important. And so, I talked about that too. (Laura, Interview 5-24-12)

Something I struggled with, with this group particularly, was getting people to share responsibility in speaking during discussions. That’s been very problematic. Something we’ve been working on. Applying pressure to kids who don’t and won’t step up. (Carol, Interview 5-25-12)

Karen, Laura, and Carol reported that their perceptions on students’ ability impacted their implementation decisions as illustrated in the following excerpts from Carol and Laura. Carol explains how the diverse student abilities in her class influenced her decision to jigsaw the story she implemented:

Time. Well, actually there’s two things. There’s more than just time going on. My classes were extraordinarily diverse this year. I had kids from ITEDS at 37, 35 to 37 percent, with kids that were 98, 99 percentile in the same room. So, I actually was a little bit more Machiavellian in the matter. So, basically, I gave my lower kids, they got the Dalton reading. That’s another reason that I did it. I wanted, I figured the lower kids were basically reviewing previous information plus a little extra that they hadn’t encountered. But, at least they had a stronger basis of maybe being able to interact with that material. And I gave my higher kids Rutherford / Chadwick, which was, for the most part, all new. So, that was part of the reason I jigsawed, because I just didn’t see. Number one, we didn’t have time for them to really develop their ideas for all the scientists. But then what end up happening, my upper kids really had to explain what they were talking about to the lower kids, which actually worked out quite smashing because it was coming from them not from me. (Carol, Interview 5-25-12)

When asked why she chose to read portions of the stories aloud or have students read aloud, Laura explained:
They were complaining about the reading. So I read to them. And I, you know, I, oh, and that’s another thing. I would sometimes read like the first page, and then I would say ‘now you guys are going read it.’ Either by themselves or with a group reading. And so, I don’t know, I feel like sometimes they’ll stop me if they don’t understand something and ask me questions reading aloud versus if they’re just reading to themselves they often don’t stop and say ‘hey what does this word mean, I don’t understand what it’s talking about’. I still have a lot of struggling readers as well, and so, there’s value in them just hearing these words in seeing these words while hearing me read it. And so, that’s why I often will do at least a small portion, even just the 1st column, and then have them do group reading. (Laura, Interview 5-24-12)

In addition to impacting teachers’ implementation decisions, five of the teacher participants reported student ability was an obstacle faced during story implementation. The following examples illustrate teachers’ concern with their perceptions of student ability:

I can’t really say that we encountered any issues, other than the fact that, again, the different levels of learning. Some students, you know, just simply because of the special needs probably weren’t quite at thorough with the answers. A lot of them found them more challenging, you know, more thought provoking. Where as the more motivated kids, you know, were I’ve got this, and didn’t really have much of an issue with it. (Rick, Interview 5-29-12)

You know, it was just a couple of things and I don't think that any of the wording was really too at all overwhelming for them. It was maybe just a word here or there for one or two kids. But I also have a lot of, so my classes have a lot of, a couple of my classes we have some ELLs. That, you know, this just natural that there are words that are still tough for them. I think that was, just trying to get their, get them into the footsteps of somebody at that time. It allowed them to really kind of think about and, you know, what were the religious ideas back then, what kind of science did they have back then, that kind of stuff. (Laura, Interview 5-24-12)

Well, with them, the questions help break them up, but I actually think that breaking [the stories] into smaller sections would be even better. So like, yeah, so this one has a page and a third of reading before the next question, and then the next question after that is 3 paragraphs…. An even breaking up of the stories, as far as length goes. So on some of the longer reading sections you can tell that some of the students who aren't as strong
of readers have a more difficult time on those. But the shorter once aren't that bad…. Yeah. I'd say that was one, was just breaking them up a little differently might be better in shorter pieces. (Will, Interview 5-10-12)

Perception of Constraints, Impact on Students, and Other Goals for Students

Although teachers at all three implementation levels commented on constraints such as time limitations, expectations of colleagues, student ability, and student resistance, teachers who implemented stories at a low level appeared to consider these factors as constraints they did not have the ability to change or overcome. Low-level implementers frequently discussed the constraints they faced during their post-implementation interviews, but did not indicate they had made any attempt to minimize the constraints. For example, when Vicki and Rick were first provided the short stories, they both commented that the stories were too long and students would not want to read them; instead of considering ways to reduce student resistance and help students learn to read longer material, they asked if they could use a jigsaw strategy or only have students read small sections of the stories. In the post-implementation interviews, Vicki and Rick still expressed that they could not effectively use the stories because their students were resistant or did not have the ability to read them and answer the questions. Vicki describes her frustration with student resistance:

Well, some of them didn’t want to do it… So, I think that’s part of, part of it. Like, I would love to be able to, you know, read through it together with the kids, but it just doesn’t, it’s not, you know, it’s impossible. (Vicki, Interview 5-29-12)

It’s a continual struggle to get them to, you know, and especially with the Bio kids. It’s really more of the hands on stuff that works better with them. Like when we got into the dissections and stuff, but you know, it’s the amount of the reading that kind of gets them turned off. (Vicki, Interview 5-29-12)
Conversely, higher-level implementers were more likely to view student ability and resistance as constraints they could overcome or minimize through their pedagogical decisions. The following examples from Jill, Karen, and Ken illustrate the view that student obstacles were viewed as minor and within their control to minimize. When asked about obstacles she faced implementing the stories, Jill explains that she found student resistance and students’ limited vocabulary to be relatively minor obstacles:

I mean, it was a minor obstacle. There were students that were, this is maybe more on my end, wondering why we had to know about these people in science class. But, like I said, if - when I addressed it, then they were ok with it. (Jill, Interview 12-21-12)

Sometimes there were just words that were challenging… But once I was aware that students struggled with that, then I would, you know, ask them what that word meant. And then we’d have a discussion about that. (Jill, Interview 12-21-12)

Karen describes how she modified her implementation to assist students with lower reading abilities make sense of the stories and how she would modify her implementation in the future to further increase her student engagement:

Reading in class so I knew they had actually read it and an intelligent and fruitful discussion could be had. Reading in pairs, as a reading strategy to hold them, not only accountable, but being in groups most students actually chose to discuss the questions. So, I thought that might be a strategy for interpretation of the story. Some students, because I didn’t want to alter the stories beyond the original structure you had provided or alter the questions, I had provided them with a modified version with - they received a reading where parts were already underlined. So, they got the same reading, just with additional underlines. (Karen, Interview 5-25-12)

I guess the obstacles that were there were likely due to how I chose to implement. There were two full days of reading, discussing, and writing. That is kind of a large cognitive load. And I had kids late in the second day that just kind of got lax and not engaged. Not a huge percentage, but enough that I think my choices about how I asked them to read and discuss and write. If I did it differently, I might have a lot more concentrated engagement for a short amount of time. Versus, two whole days plus a
full day of discussion afterwards. (Karen, Interview 5-25-12)

When Ken was asked why he chose to have a class discussion about reading strategies before giving students the stories, he said, “Just the fact that we don't read often and I wanted them to have some sort of strategy to attack this, this task that they have, having not done this very frequently” (Interview 5-14-12).

High and mid-level implementers frequently considered potential impacts on students and goals for their students that provide rationale for using the stories in the face of constraints. When asked how the stories impacted his students, Will did not feel he had sufficient evidence to comment. All other high and mid-level implementers reported that the stories promoted other goals they had for their students and that they saw increased participation from students who rarely participate in class discussions. Furthermore, all the high and mid-level implementers, except Will and Kaleb, perceived that the stories increased or reinforced students’ understanding of the science content and NOS concepts. Karen, Ken, Henry, and Jill also reported that the stories appeared to increased students’ interest in their class, the science content, and/or science careers. For example, when asked about his general impressions of the stories, Henry replied, “Students enjoy reading them, discussing them. Probably discussing them more than the reading. But I was surprised at how good the discussions were and how interested some kids were that normally were not interested in class” (Interview 6-25-12). Conversely, three of the five low implementers (Carol, Vicki, and Rick) perceived that many of their students were disengaged and likely only the high achievers were interested in the stories.

High and mid-level implementing teachers frequently noted the importance for students to improve their reading abilities, learn to read complex material, critically think,
or develop a deeper understanding of the NOS. The following examples from Laura, Ken, and Hillary illustrate their emphasis on using the stories to promote other goals for their students. Although Laura’s students complained about the length of the readings, she thought students’ learning to read more difficult material was important. Laura explains:

But, when they see, you know, small font and many multiple pages. That freaks them out because they’re used to… Here, read those 2 paragraphs, you know, which is like 16 words. So, you know, I think it's good getting them to read more, and like real reading. That’s super important. (Laura, Interview 5-24-12)

I mean, you know, they were initially overwhelmed by how long they are. But, it’s like really, make them any shorter you're going to lose a ton of information. It took a long time because they haven't, because they don't have a lot of reading stamina. And I don't know if you can fix that at all. You know what I mean? Other than just us keeping, you know, having them experience this. Because, the thing is, if you keep shortening everything, then you're right, they are never going to gain stamina. So, I get initially a lot of kickback from it, but they need it. (Laura, Interview 5-24-12)

Laura also perceived that using the stories promoted students’ development of critical thinking skills:

It really brought out some beautiful thinking and some very deep well-thought-out ideas when they were answering these questions. Like, to the point of amazement. My student teacher and I just look at each other, and we were like, wow, that's awesome. (Laura, Interview 5-24-12)

Ken perceived that his students were challenged by with the complexity of the readings, but believed this challenge beneficial for his students:

Students found the reading to be somewhat challenging especially General Chemistry students. Some of the vocabulary, and just more complicated sentence structure and stuff like that. And, but I still think it was appropriate. I mean, it's good to face those challenges and work through them together. (Ken, Interview 5-14-12)
General impressions were that the story is not only helped communicate how science is done, but also helped reinforce some of the content they were taught this year. I think the students need more opportunities for reading in science. I think they need more practice… It seemed like they got better the more we did. So I would be curious to see if I were to implement 5 or 6 of these, how would their reading science, their science reading skills improve over the course of the year. You know, that would be interesting to see. (Ken, Interview 5-14-12)

Hillary explained why developing more materials similar to the short stories is important even though she thought many students seemed intimidated by the length of the stories:

Really important, because we need more resources to go to, materials to work with. Where nature of science, but also, and I don’t know if this was a goal of the entire project, but it’s reading comprehension, and I didn’t, I actually didn’t fully grasp that until we did a project for this class. And so, emphasizing taking your time reading. So, that would be another goal, is that you need more things that emphasize reading comprehension and strategies for reading, things of this length. Like, I would say that even if the kids are intimidated, I would still use these stories, ‘cause regardless or not, they need to read. And they need to learn to take their time. That it’s not going to be just like that. And to understand what they’re reading. (Hillary, Interview 12-17-12)

*Impact of the Control-Treatment Design*

Control-Treatment teachers all expressed some frustration having to include control class periods because: (1) they saw benefit in using the stories and did not like that they could not use the stories with all their students, (2) the additional planning and not being able to keep their classes at the same pace, and (3) difficulty with assessing students when they had differing classroom experiences. Frustration was also expressed about the requirement to implement three short stories in the treatment sections.

Laura and Hillary both perceived significant student benefits from using the stories and disliked not being able to share that experience with all their students. The following excerpts from teacher interviews express this concern:
I wish I could use them in all my classes. That was really frustrating. Knowing how good things were going when I did them my in treatment classes, and knowing that I couldn't use them in my controls. That was like 'dang it'. Because they could've really helped some of the kids. (Laura, Interview 5-24-12)

I felt like mostly having the reading was really nice for having something we could all draw from. And so, getting those same ideas across in the control period when I didn’t have something to say, “Hey, lets look at this.” Or say, “Hey, let’s see what this guy did in this situation.” Was really, really hard. (Hillary, Interview 12-17-12)

Laura also expressed concern regarding assessing her students when not all students had the same classroom experiences:

You know, using these in all my classes, it really would've made testing easier. Because then I was like, the case of these guys got this knowledge, these guys got this knowledge, so I've got to figure out what I should test on. (Laura, Interview 5-24-12)

Several of the Control-Treatment teachers expressed frustration with the need for additional planning. Rick and Jessica describe the difficulties they faced having to plan for a separate control section:

Just something that would actually work in the book, you know. I didn’t what to research something or Google it. I wanted to keep something that everyone had the same copy of. So, looking for something that was, you know, convenient, convenient being the textbook, but yet worked from the standpoint that it meshed. (Rick, Interview 5-29-12)

It was just a time thing more than anything.... Trying to keep them matched and with the first one, or the 2nd one, me not being here for that, trying to figure out something that was going to take approximately the same amount of time. That was really the hardest thing, just juggling two things. So it ended up becoming a second prep versus just being one prep. And knowing, if kids were absent, which group did they belong to. (Jessica, Interview 5-29-12)

Hillary also noted that if she did not have to use a control group she would likely have spent more time on implementing the stories:
It impacted it mostly because I didn’t want the two classes to be in drastically different places. And I think that if I was using the reading in both of them, I would spend more time on it, because that way one class wasn’t way ahead of another and I could keep them in about the same place. Yeah, that was mostly it. It was just trying to keep them at about the same place. (Hillary, Interview 12-17-12)

Although Henry stated that having his class periods at different places in the curriculum was a difficulty he faced, he did not indicate this was a major obstacle. He stated:

Sometimes it off set the class so we weren’t on the exact same schedule. It’s, I mean, again, it’s a time frame thing. How am I going to fit everything in and bring everyone back to the same point. But, I don’t know. Just like any wrinkle at school, you just got to figure out a way to deal with it and do it and move done. You know, it’s just like a schedule change comes. Oh, we’re going to be on this schedule today. Ok, well I need to modify my day. (Henry, Interview 6-25-12)

Additional concern was expressed regarding the need to implement three stories. Vicki only implemented two stories because she did not feel she could make the Mendel story fit within the other constraints she had for the course. Rick said he ran out of time to do a third story in class, and thus simply sent a third story home as a homework assignment in his treatment class periods. As discussed previously, Jessica and Henry struggled to find a third story that would fit in their spring semester curricula, and eventually decided to use the Atomic Model story at the end of the semester as review for the final exam. Although Jessica expressed considerable concern over the struggle to implement a third story, Henry did not.

**Teachers’ Perceptions of Story Features and Resources for Implementation**

During the post-implementation interviews, teachers were asked what features of the short stories they liked or found helpful, what changes to the story features they would find beneficial for future implementation, and what other types of resources they
would find helpful for future implementation. Teachers’ responses to these questions are summarized below in Tables 16-18.

**Story Features Teachers Found Beneficial**

Features of the stories teachers reported as useful during their post-implementation interviews are summarized below in Table 16. All teachers, except Vicki and Rick, reported that they found the embedded questions in the stories useful. Seven of the teachers specifically indicated they liked that the questions divided up the reading into shorter segments. Additionally, Karen, Laura, Kaleb, and Jessica reported they found the pre-reading questions especially useful for preparing students for the reading.

Five teachers reported they found the bolded key point boxes useful, and three teachers specifically mentioned that the visuals (e.g., photographs, diagrams, and charts) were useful. Laura describes how the charts and graphs in the stories were particularly useful for helping students learn to interpret data, a goal in her department:

> The fact that they have charts and graphs in here's awesome. Because they see that so much now, and... one of the things that were doing actually now in our data teams, for the science department, is trying to find readings with charts and graphs. And so the they, and so it's kind of along the same lines as like an ACT. Where you can have a reading, you're going to see charts and graphs, going to see pictures, how does all that come into answer questions. And that, I mean it's really, it's beautiful in that way, because you had it all here. (Laura, Interview 5-24-12)

Ken, Henry, and Jill also specifically mentioned that they felt the reading level of the stories was accessible to their students.
Teachers’ suggestions for changing the short stories are summarized below in Table 17. All teacher participants indicated they would like a larger variety of stories so they could more easily select stories that fit within their curricula. Yet, four of the five low-level implementers (Carol, Beth, Vicki, and Rick) reported they would especially like shorter stories. When Beth was asked what length of story she thought appropriate for her students, she responded, “Three pages is pretty long to use in class” (Interview 5-24-12). Rick indicated he would likely only use stories if they were shorter, less difficult, and could be utilized without disrupting his flow of instruction:

I don’t know what age level the readings were geared for. I don’t know if they were for high school or college, I don’t know. I would say they were geared more for at least upper high school. And I’d find something that

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Questions</th>
<th>Divide the Reading</th>
<th>Pre-Reading Questions</th>
<th>Key Point Boxes</th>
<th>Visuals</th>
<th>Accessible Reading Level</th>
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<td>Rick</td>
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</table>
was maybe a little bit easier for the kids.... Some of it was pretty philosophical and there were probably some gaps there in student comprehension because they probably couldn’t quite figure out… where it was all going. (Rick, Interview 5-29-12)

I would look for something, maybe the reading wasn’t quite as intense, wasn’t quite as long. Something, so the flow of instruction could continue. (Rick, Interview 5-29-12)

Demonstrating their concern regarding story length, Carol jig-sawed the one story she implemented, and Rick and Vicki both inquired about jig-sawing the reading when they first saw the stories. Furthermore, when asked what changes to the stories they would find beneficial for future implementation, Carol and Vicki both expressed the desire to have access to the electronic document so they could pull out select portions and questions from the stories to use independently. During their interviews, Vicki and Carol stated:

I think if, because I have them in electronic copy, right?... Because, to be able to kind of section them a little bit, and kind of customize it a bit to what, to how I would use it. (Vicki, Interview 5-29-12)

A Word process document so I can take bits and pieces and put them together to fit where I need them to fit with the time. (Carol, Interview 5-25-12)

Another frequent suggestion was to address the difficult vocabulary and wording of some embedded questions. Although Rick thought the stories were just too difficult for his students, the other teachers making this comment (Karen, Henry, Jill, Laura, and Kaleb) specified specific vocabulary that was problematic. The words objective, subjective, and biased were frequently commented on during classroom observations and teacher interviews. Ken recommended creating stories at a variety of lengths and reading levels, while Kaleb and Jill both mentioned they would like to see stories that could be
readily used with their younger or lower level students.

Will, Henry, and Hillary all indicated a preference for increasing the number of embedded questions. Will encouraged including a wider range of NOS ideas in the embedded questions. Additionally, Will, Kaleb, and Vicki specifically suggested positioning the embedded questions to reduce and equalize the length of reading sections between questions. Will explains:

The questions help break them up, but I actually think that breaking [them] into smaller sections would be even better. An even breaking up of the stories, as far as length goes. So on some of the longer reading sections you can tell that some of the students who aren’t as strong of readers have a more difficult time on those. But the shorter ones aren’t that bad. Based on what I’ve seen, like, anything longer than a page on here, students sort of. I mean, it’s sad to say, but it’s, once they have to read more than a page [at a time] they start having a tough time. (Will, Interview 5-10-12)

Additional Resources Teachers would Find Beneficial for Future Implementation

When asked what additional resources they would find useful for future implementation of the stories (see Table 18), teachers at all implementation levels expressed interest in receiving additional ideas about how to implement the stories (e.g., implementation ideas from other teachers, reading strategies, possible related activities, and discussion questions). The most frequent requests were suggested reading strategies and additional ideas for story implementation from other teachers. Nine of the teachers, including five of the eight high and mid-level implementers, indicated information on additional reading strategies would be useful. For example, when asked what additional resources they would find beneficial for future implementation, Hillary and Ken stated:

Activities and reading strategies. I know we talked about that before, but having reading strategies to go along with them. And, probably more
discussion questions to follow up with the reading. (Hillary, Interview 12-17-12)

I would find [reading strategies] very useful. I would be very likely to use those, if they are in the form of student handouts or something like that. I would absolutely dispense those to my students. (Ken, Interview 5-14-12)

Eight of the thirteen teacher participants, including five of the eight high and mid-level implementers, reported they would like to know how other teachers had successfully implemented the stories. Karen and Vicki specifically mentioned the possibility of collaborating with other teachers, and Kaleb considered the possibility of viewing video of successful implementations. For example, when asked how the use of stories by additional teachers in her department might influence her interest in using similar stories in the future, Vicki stated,

I think it would be easier to, it would be less overwhelming, you know, if we each had some input or, you know, some activity we could do with it. More of us to come up with different ways to use it (Vicki, Interview 5-29-12).

The following teacher responses illustrate their desire for models of effective implementation:

Just any videos, or websites, or even links to activities we could do. Or ways that other teachers have used them that was successful. That’s probably the biggest one. How they used them. (Vicki, Interview 5-29-12)

It’d be nice to talk to other teachers who are also wanting to use them, and share suggestions on how they had found good ways of implementation. There may be other things that they’ve tried to couple with the stories. (Karen, Interview 5-25-12)

But, having some examples of how others implemented the stories. Just have maybe two or three examples of a framework, or a whiteboard series, or I don’t know. And just having some other ideas of what teachers have done. So that it’s been vetted. So they can say, ok I have this group of kids, this might be a better strategy to get at this particular group of kids. (Carol, Interview 5-25-12)
I guess maybe different ways of implementation. So examples of how the stories have been implemented to help out these teachers. So if teacher A has done these different discussions, teacher B has, you know some crazy thing that they did that worked really well. So, different ways to implement the stories. (Henry, Interview 6-25-12)

Six of the teacher participants, including four of the eight high and mid-level implementers, suggested including a bank of additional questions teachers could utilize during class discussions. The following teacher statements made during post-implementation interviews illustrate this request:

More stories. Potentially more questions embedded in the stories. Maybe not even embedded. Maybe just another, I mean it could be embedded, but other questions for the teachers to pose to the students or for the teachers to think about themselves. (Henry, Interview 6-25-12)

Maybe even a database of questions that could be correlated with different parts of the different stories. That would allow me to see if maybe there’s a trend. For example, if maybe I wanted to focus on… creativity for a quarter and make sure for every activity we do or every model building we do, I’ve got this bag of questions that I can address the idea of scientific creativity, as an example. Um… Maybe finding – I really like how the story built with the here’s what they did, here’s the evidence, here’s what they changed. And finding, maybe even a broader story of that for other models we’ve used. And, I’m thinking Biology and other areas, not just Chemistry. (Carol, Interview 5-25-12)

Additional resources that were suggested by fewer teachers included related activities that could be implemented with the stories, a website where teachers could have access to additional stories, articles or a website to support teachers’ understanding of the NOS and NOS misconceptions common among students, related videos or animations to illustrate ideas from the stories, and a bank of NOS exam questions. While both Jill and Vicki recommended including related videos or animations, they had very different rationales for those suggestions. Jill was concerned with providing illustrations of important science content in the stories that students’ struggled to understand:
It’d be kind of cool if there was, like, short videos. Even if it was just like kind of animated. Especially on that 1st reading [DNA Function] to kind of illustrate what was happening. You know, the mouse is injected, the mouse dies kind of thing. (Jill, Interview 12-21-12)

Conversely, Vicki’s concern was with student resistance and providing information in a format students would prefer rather than reading:

And maybe some video clips to go along with it to show. You know, ‘cause that’s the things that get them more interested, watching it. They’re so technology based right now that, you know. It’s got to be this grand display. (Vicki, Interview 5-29-12)

Like other high-level implementers, Ken is concerned with holding students’ accountable for their NOS learning on class assessments. However, he expressed concern with his ability to structure appropriate NOS exam questions:

It might be helpful to have an objective source of maybe exam questions that were appropriately worded. I sometimes worry that when I create my questions they're too open ended, but if I turn them into multiple-choice or too close-ended they can't give an adequate response. So that might be interesting. (Ken, Interview 5-14-12).
Table 17. Changes to the Stories Teachers Reported Would be Beneficial For Future Story Implementation

<table>
<thead>
<tr>
<th>Teacher</th>
<th>More Variety of Stories</th>
<th>Decrease Difficult Wording</th>
<th>Decreased Length</th>
<th>Variety of Reading Levels and Lengths</th>
<th>Even Out the Length of Reading Segments Between Questions</th>
<th>More Embedded Questions</th>
<th>Ability to Customize Stories &amp; Questions</th>
<th>Include More Reference to Scientists’ Personalities</th>
<th>Include More NOS Ideas</th>
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Table 18. Additional Resources Teachers Reported Would be Beneficial For Future Story Implementation

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Reading Strategies</th>
<th>Ideas for Implementation</th>
<th>Discussion Questions</th>
<th>Related Activities</th>
<th>Website Access</th>
<th>Resources to Support Teachers’ NOS Understanding</th>
<th>Related Videos/Animations</th>
<th>Exam Questions</th>
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Summary of Findings For Research Question 1

- Teacher participants’ story implementations varied drastically in their support for concept development, student accountability, and classroom cultures.

- Teachers’ understand NOS was a necessary but insufficient condition for effective story implementation. The lowest implementers had the lowest NOS understanding, but not all teachers with a high level of NOS understanding were high-level implementers of the stories.

- Teachers’ experience was not associated with implementation level. However, all the high-level implementers were at least in their third year teaching.

- Teachers reported their implementation decisions were impacted by concerns regarding: (1) course curricula; (2) student understanding and past experiences; (3) school constraints; (4) student ability and resistance; (5) learning goals for their students, and (6) perceptions of how the stories impacted students.

- Low-level story implementers expressed that constraints from student ability and student resistance were outside their control. Conversely, high-level implementers more frequently made implementation decisions to mitigate constraints from students’ ability and/or resistance.

- High and mid-level story implementers expressed their goals for students provided rationale for implementing the stories even when facing constraints.

- Teachers at all three levels of implementation expressed desire for teacher support resources providing suggestions for effective implementation of the stories.
Research Question 2: Impact of Stories on Students’ NOS Understanding

To address the second research question, separate Multiple Analyses of Covariance (MANCOVA) tests were performed for each Control-Treatment teacher’s students using SPSS version 20 to compare Treatment and Control students’ NOS understanding as measured on the VOSSI post assessments. VOSSI pre-assessment scores were included as a covariate to account for any pre-existing difference in Control and Treatment group students. When significant differences were detected with the MANCOVA analyses, subsequent univariate Analysis of Covariance (ANCOVA) were conducted to determine the significance of differences between Control and Treatment students’ performance on individual NOS components (Tabachnick & Fidell, 2007).

Reliability of the VOSSI Instrument

Initial analyses included calculating internal reliability indices for both the biology and chemistry student versions of the pre-VOSSI and post-VOSSI instruments. Tables 19 and 20 list the internal reliability statistics for each NOS component included on the chemistry student VOSSI and biology student VOSSI, respectively. For the Chemistry Student VOSSI, Chronbach’s alphas for the six NOS constructs ranged from 0.544 to 0.802. For the Biology Student VOSSI, Chronbach’s alphas for the six NOS constructs ranged from 0.588 to 0.796. Typically Cronbach’s alpha values above .70 are preferred for confidence that the items in a scale are measuring the same underlying construct and can be combined into a single scale (Pearson, 2010). However, Cronbach’s alpha is sensitive to the number of items in a scale; scales with fewer than ten items frequently produce Cronbach’s alpha values below .70 (Pearson, 2010).
Table 19. Internal reliability statistics for chemistry student VOSSI components

<table>
<thead>
<tr>
<th>Chemistry Student VOSSI NOS Construct</th>
<th>N</th>
<th>Cronbach’s α</th>
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<tbody>
<tr>
<td>Social and Cultural Influences on Science</td>
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<tr>
<td>Imagination and Creativity</td>
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<td>0.786</td>
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<tr>
<td>Social Interactions Among Scientists</td>
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<td>0.658</td>
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<tr>
<td>Time to Develop and Accept Ideas</td>
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<tr>
<td>Tentativeness of Scientific Knowledge</td>
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<td>Scientific Laws vs. Theories</td>
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<td>0.651</td>
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Table 20. Internal reliability statistics for biology student VOSSI components

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<th>Cronbach’s α</th>
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<td>Scientific Laws vs. Theories</td>
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<td>0.588</td>
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Differences Between Control and Treatment Students’ NOS Understanding.

For three of the Treatment-Control teachers, SPSS version 20 multivariate General Linear Modeling (GML) was used to conduct a multiple analysis of covariance (MANCOVA) to determine if any significant differences exist between Treatment students’ and Control students’ NOS understanding following implementation of the short stories (Tabachnick & Fidell, 2007). However, MANCOVA analyses were only conducted on the VOSSI results of Henry, Hillary, and Laura’s students. Regrettably, Rick and Vicki did not collect consent forms from their Control students and Jessica did not return post-VOSSI surveys for her Control students. Tables 21-23 provide a summary of the student VOSSI
statistics for the three remaining Control-Treatment teachers. The Biology Student VOSSI and the Chemistry Student VOSSI surveys contained different NOS constructs to assess NOS ideas most prominent in the stories; the constructs measured are listed in Tables 21-23.

Table 21. Descriptive statistics for Henry's Student VOSSI NOS components

<table>
<thead>
<tr>
<th>NOS Component</th>
<th>Control Pre (N = 28)</th>
<th>Treatment Pre (N = 49)</th>
<th>Control Post (N = 28)</th>
<th>Treatment Post (N = 49)</th>
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<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
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<tr>
<td>Social / Cultural Influences</td>
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<td>2.65</td>
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<td>Imagination and Creativity</td>
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<td>4.19</td>
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<td>Social Interactions</td>
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<td>Time</td>
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<td>2.78</td>
<td>14.73</td>
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<td>Tentativeness</td>
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<td>2.06</td>
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<tr>
<td>Laws vs. Theories</td>
<td>10.11</td>
<td>1.93</td>
<td>10.87</td>
<td>1.84</td>
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</table>

a. 8% of Treatment Students and 10% of Control Students are not included due to missing data points
b. Possible scores for each component range from a minimum of 4 up to a maximum of 20.

Table 22. Descriptive statistics for Hillary's Student VOSSI NOS components

<table>
<thead>
<tr>
<th>NOS Component</th>
<th>Control Pre (N = 13)</th>
<th>Treatment Pre (N = 12)</th>
<th>Control Post (N = 13)</th>
<th>Treatment Post (N = 12)</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>12.00</td>
<td>2.61</td>
<td>12.08</td>
<td>2.43</td>
</tr>
<tr>
<td>Imagination and Creativity</td>
<td>12.54</td>
<td>0.97</td>
<td>12.67</td>
<td>1.78</td>
</tr>
<tr>
<td>Social Interactions</td>
<td>11.77</td>
<td>1.59</td>
<td>11.92</td>
<td>2.10</td>
</tr>
<tr>
<td>Time</td>
<td>12.00</td>
<td>0.71</td>
<td>13.17</td>
<td>2.08</td>
</tr>
<tr>
<td>Tentativeness</td>
<td>14.92</td>
<td>1.71</td>
<td>13.00</td>
<td>1.41</td>
</tr>
</tbody>
</table>

a. 54% of Treatment Students and 48% of Control Students are not included due to missing data points
b. Possible scores for each component range from a minimum of 4 up to a maximum of 20.
Table 23. Descriptive statistics for Laura’s Student VOSSI NOS components

<table>
<thead>
<tr>
<th>NOS Component</th>
<th>Control Pre (N = 14)</th>
<th>Treatment Pre (N = 25)</th>
<th>Control Post (N = 14)</th>
<th>Treatment Post (N = 25)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Observation</td>
<td>15.57</td>
<td>1.87</td>
<td>15.24</td>
<td>2.57</td>
</tr>
<tr>
<td>Social / Cultural Influences</td>
<td>13.64</td>
<td>3.00</td>
<td>13.52</td>
<td>1.92</td>
</tr>
<tr>
<td>Imagination and Creativity</td>
<td>10.00</td>
<td>2.35</td>
<td>9.76</td>
<td>2.92</td>
</tr>
<tr>
<td>Methodologies</td>
<td>13.14</td>
<td>3.68</td>
<td>12.88</td>
<td>3.49</td>
</tr>
<tr>
<td>Time</td>
<td>15.57</td>
<td>2.98</td>
<td>13.96</td>
<td>2.39</td>
</tr>
<tr>
<td>Methodological Naturalism</td>
<td>12.21</td>
<td>2.36</td>
<td>12.56</td>
<td>1.85</td>
</tr>
</tbody>
</table>

a. 17% of Treatment Students and 36% of Control Students are not included due to missing data points.
b. Possible scores for each component range from a minimum of 4 up to a maximum of 20.

Results of the initial MANCOVA analyses indicate Henry’s Treatment Students had a significantly better NOS understanding than his Control Students (F = 0.6024, p = 0.000, Wilks’ Lambda = 0.639, eta squared = 0.361). No significant difference exists between Treatment and Control Students’ NOS understanding in Hillary’s classes (F = 0.842, p = 0.561, Wilks’ Lambda = 0.704, eta squared = 0.294) or in Laura’s classes (F = 1.477, p = 0.225, Wilks’ Lambda = 0.746, eta squared = 0.254). Table 24 contains the MANCOVA results for Henry’s, Hillary’s, and Laura’s, students. Unfortunately, both Hillary and Laura had many students with missing VOSSI survey data. 54 percent of Hillary’s Treatment Students and 48 percent of her Control Students had missing VOSSI data. 17 percent of Laura’s Treatment Students and 38 percent of her Control Students had missing VOSSI data. Thus, the results of the MANCOVA analyses for Hillary and Laura’s students may not accurately reflect the actual differences between the Control Students’ and Treatment Students’ NOS understanding.
Table 24. Summary of MANCOVA multivariate test results for VOSSI scores

<table>
<thead>
<tr>
<th>Teacher</th>
<th>N</th>
<th>Wilks’ Lambda</th>
<th>F</th>
<th>Sig.</th>
<th>Partial Eta Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Henry</td>
<td>Treatment 48</td>
<td>0.639</td>
<td>6.024**</td>
<td>0.000</td>
<td>0.361</td>
</tr>
<tr>
<td></td>
<td>Control 29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hillary</td>
<td>Treatment 12</td>
<td>0.704</td>
<td>0.842 (6,12)</td>
<td>0.561</td>
<td>0.294</td>
</tr>
<tr>
<td></td>
<td>Control 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laura</td>
<td>Treatment 25</td>
<td>0.746</td>
<td>1.477 (6,26)</td>
<td>0.225</td>
<td>0.254</td>
</tr>
<tr>
<td></td>
<td>Control 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** Significant at p < 0.01

Analysis of Henry’s Students’ Understanding of the 6 VOSSI Components

Table 25 presents ANCOVA results from subsequent univariate analyses of Henry’s students’ VOSSI scores for each of the six NOS components as separate dependent variables. To adjust for increases in type I error due to multiple testing in subsequent ANCOVA analyses, p values are commonly adjusted using Bonferroni corrections. Utilizing Bonferroni corrections, the p value for the six separate VOSSI components is adjusted to 0.0083. Both the Social/Cultural Influences component (F = 9.388, p = 0.003, partial eta squared = 0.120) and the Imagination and Creativity component (F = 27.273, p = 0.000, partial eta squared = 0.283) showed significant differences between control and treatment groups at this level. However, even among statisticians, no consensus exists at to when Bonferroni adjustments should be applied (Nakagawa, 2004; Perneger, 1998; Royall, 1997); Bonferroni corrections may increase the likelihood of type II error to unacceptable levels, such that “truly important differences are deemed non-significant” (Perneger, 1998, p.1236). Because this is a preliminary study designed to determine if the short stories have the potential to impact student’ NOS understanding, disregarding Bonferroni corrections and setting significance at
p < 0.05 may be appropriate. Under these less restrictive standards, the Laws and Theories component also resulted in significant differences (F = 6.476, p = 0.013, partial eta squared = 0.086). Results for the Social Interactions (F = 0.033, p = 0.856, partial eta squared = 0.000), Time for Development (F = 0.645, p = 0.424, partial eta squared = 0.009), and Tentativeness (F = 0.005, p = 0.942, partial eta squared = 0.005) components indicate no significant differences between groups.

Table 25. Subsequent univariate analyses of NOS components for Henry's students

<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 Influences on Science</td>
<td>9.388*</td>
<td>0.003</td>
<td>0.120</td>
</tr>
<tr>
<td>Imagination and Creativity in Science</td>
<td>27.273**</td>
<td>0.000</td>
<td>0.283</td>
</tr>
<tr>
<td>Social Interactions Among Scientists</td>
<td>0.033</td>
<td>0.856</td>
<td>0.000</td>
</tr>
<tr>
<td>Time for Development / Acceptance of Ideas</td>
<td>0.645</td>
<td>0.424</td>
<td>0.009</td>
</tr>
<tr>
<td>Tentativeness of Science Ideas</td>
<td>0.005</td>
<td>0.942</td>
<td>0.005</td>
</tr>
<tr>
<td>Scientific Laws and Theories</td>
<td>6.476*</td>
<td>0.013</td>
<td>0.086</td>
</tr>
</tbody>
</table>

* significant at p < 0.05  
** significant at p < 0.01

Summary of Findings for Research Question 2:

- In Laura’s and Hillary’s classes, no significant differences were found between Control Students’ and Treatment Students’ NOS understanding following implementation of the stories.
- Following implementation of the stories, Henry’s Treatment Students exhibited significantly better NOS understanding than his Control Students.
- Compared to Control Students in Henry’s classes, Treatment Students had a significantly better understanding of three of the six measured NOS constructs: (1) Social/Cultural
Influences on Science, (2) Imagination and Creativity in Science, and (3) Scientific Laws and Theories. No significant differences were observed for the three remaining NOS constructs: (1) Social Interactions Among Scientists, (2) Time for Development and Acceptance of Science Ideas, and (3) Tentativeness of Science Ideas.

**Research Question 3: Students’ Interest and Attitude Towards the Stories**

Following implementation of the stories, students completed *Interest and Attitude Survey 2* (Appendices J and K). Treatment students and Open-Use students were surveyed regarding their interest in the stories, their perceptions on how the stories impacted their views of science, and their preference for the stories versus other typical class readings. Table 26 summarizes students’ responses to these questions.
Table 26. Summary of student responses to *Interest and Attitude Survey 2* showing percentage of students choosing each response.

<table>
<thead>
<tr>
<th>Question 1. Overall, how interesting did you find this group of readings?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Students (N=546)</td>
<td>13</td>
<td>25</td>
<td>28</td>
<td>31</td>
<td>3</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>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Students (N=515)</td>
<td>6</td>
<td>10</td>
<td>47</td>
<td>33</td>
<td>4</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>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Students (N=513)</td>
<td>4</td>
<td>11</td>
<td>44</td>
<td>37</td>
<td>4</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 reading?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Students (N=513)</td>
<td>4</td>
<td>10</td>
<td>30</td>
<td>35</td>
<td>22</td>
</tr>
</tbody>
</table>
Table 26. continued

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?

<table>
<thead>
<tr>
<th>% of Students (N=513)</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>19</td>
<td>26</td>
<td>24</td>
<td>21</td>
</tr>
</tbody>
</table>

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 Students (N=610)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>7</td>
<td>30</td>
<td>44</td>
<td>13</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 Students (N=513)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>11</td>
<td>27</td>
<td>44</td>
<td>14</td>
</tr>
</tbody>
</table>

**Students’ Interest in and Perceptions of the Short Stories**

Interest ratings for the stories were on a five-point scale, ranging from extremely uninteresting (1) to extremely interesting (5). Most students did not rate the stories as interesting; only 34 percent of students rated the stories as somewhat interesting or extremely interesting, while 38 percent rated the stories as somewhat uninteresting or extremely uninteresting. However, a much larger percentage of students rated the stories as more interesting than their textbook or other typical class readings. 57 percent of students rated the
stories as somewhat more interesting or much more interesting than their typical class readings, while only 14 percent rated the stories as less interesting. When students were asked what percentage of typical class readings they would like to be replaced with similar short stories, only 10 percent of students wanted no class readings replaced with stories. 71 percent of students reported they would prefer 50 percent or more of their typical class readings replaced with short stories.

Question 4 asked students to compare their prior conceptions of doing science with how science was portrayed in the stories; 37 of responding students indicated the stories portrayed doing science as more interesting than they previously thought. Only 16 percent of students reported that the stories portrayed doing science as less interesting than they previously thought. Question 5 asked if the stories increased students’ interest in the science content related to the stories they read. 41 percent of students reported that the stories at least somewhat increased their interest in the related science content, while 15 percent reported that the stories decreased their interest in the content.

Question 8 asked students about the importance of learning about how science works and how science ideas are developed for high school science classes. 30 percent of responding students indicated this goal should be somewhat important, while 57 percent indicated the goal should be important or extremely important. Only 13 percent of students reported the goal should be of little or no importance. Additionally, most students responding to question 9 perceived that the stories at least somewhat helped them come to better understand how science works and how science ideas are developed (58 percent). 27 percent of students were neutral about whether or not the stories helped them meet this goal, and only 15 percent of students reported that the stories did not help them meet the goal.
What Students’ Liked and Disliked About the Short Stories

Treatment students’ and Open-Use students’ responses to extended answer questions on Interest and Attitude Survey 2 (Appendices J and K) were analyzed to identify common themes regarding what students reported liking and disliking about the historical short stories. Student responses were coded through reiterative rounds of open/initial coding and focus coding (Charmaz, 2006; Saldana, 2009). Codes were not exclusive as a single student response could refer to multiple things they liked or disliked about the stories; student responses were coded accordingly.

What Students Liked About the Short Stories

Students provided a variety responses regarding what they liked about the stories, including the eight following common categories: (1) Mentally Engaging, (2) Informative, (3) History of Science, (4) Reading Structure, (5) Helpful with Classwork, (6) Not Difficult, (7) Enjoyment of Science, and (8) Liked Nothing about the stories. Table 27, below, presents the percentage of student responses that fit in each category.

The most frequent category of student response (33%) referred to the stories as Mentally Engaging in someway (e.g., interesting, thought provoking, engaging, challenging, entertaining, or cool). For example, Karen’s student 36 wrote, “It made the reader think”, and Jessica’s treatment student 36 wrote, “They challenged me to think of new things and to learn what I didn't know.” Other student responses illustrating this category include:

I found the readings interesting because it explained the timeline of DNA study, which helped put things in perspective for me. I also like the questions because it helped me stop and consider what I had just read and its deeper meaning. (Karen, S 7)

I liked learning about those topics and they were pretty interesting to read
about. (Jill, S 38)

I was interested in the topic most of the time, I like knowing what goes on inside my body. I'm very intrigued by science in general. (Beth, S 29)

These readings could be very interesting and were full of knowledge. They could be fun to read because they were so full of facts and interesting. (Carol, S 50)

Table 27. What students reported liking about the short stories

<table>
<thead>
<tr>
<th>What Students Liked</th>
<th>Percentage of All Students (N = 540)</th>
<th>Percentage of Chemistry Students (N = 265)</th>
<th>Percentage of Biology Students (N = 275)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mentally Engaging</td>
<td>33</td>
<td>33</td>
<td>32</td>
</tr>
<tr>
<td>Informative</td>
<td>30</td>
<td>29</td>
<td>32</td>
</tr>
<tr>
<td>History of Science</td>
<td>30</td>
<td>29</td>
<td>32</td>
</tr>
<tr>
<td>Development of Ideas</td>
<td>21</td>
<td>28</td>
<td>15</td>
</tr>
<tr>
<td>Scientists as People</td>
<td>16</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>History in General</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Reading Structure</td>
<td>16</td>
<td>9</td>
<td>23</td>
</tr>
<tr>
<td>Organization</td>
<td>6</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Amount of Detail</td>
<td>5</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Embedded Questions</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Visuals</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Helped with Classwork</td>
<td>13</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Understanding</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Not Difficult</td>
<td>9</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Enjoy Science</td>
<td>8</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Liked Nothing</td>
<td>11</td>
<td>11</td>
<td>12</td>
</tr>
</tbody>
</table>

The next two most frequent categories (30% of responding students) include the Informative category and the History of Science category. Student responses indicating the
stories were informative, provided new information, or had many facts include: “You learned a lot of good information” (Henry, TS 40) and “I liked learning new facts” (Rick, TS 37).

Below are additional responses illustrating this category:

I liked that the readings were on things I don't know about. They had a lot of facts and stories about various science topics which I liked. (Jessica, TS 48)

These readings could be very interesting and were full of knowledge. They could be fun to read because they were so full of facts and interesting. (Carol, S 50)

These readings presented some interesting facts about how different scientific ideas came about. (Will, S 33)

Students frequently indicated they like some aspect of the history of science included in the stories. Responses in the History of Science category often fit into three subcategories; (1) Development of Science Ideas, (2) Scientists as People, and (3) a General Interest in History. For example, the response from Ken’s student 8 illustrates the General Interest in History subcategory, “I liked the historical part of the reading. I liked reading about historical advancements.” Karen’s student 104 response, “I have always wanted to know what real scientists were like” and Henry’s treatment student 18 response, “I liked the history involved and learning about the dudes behind the ideas”, both exemplify the interest in learning about Scientists as People subcategory. Other examples of the History of Science category include:

What I liked about the readings was how they explained the different experiments in detail to give us a better understanding of how their ideas came to be. It gave us students a new perspective on how these experiments were done and how they were successful or not successful. (Karen, S 75)

I think it is always interesting learning about history. Science is very interesting to me. DNA is a very complex thing and it is fun to learn about them. (Karen, S 86)
I liked not only learning about different science discoveries, but actually getting a little background information on the scientists. (Kaleb, S 4)

They gave descriptions on the experiments the scientists did, while also giving information on what the scientists were like, giving insight to their personality. (Kaleb, S 9)

The readings showed how sciences is developing and changing. The history was interesting since it showed how it was many scientists and not just one. (Will, S 72)

Liking some aspect of the Reading Structure was referenced in 16 percent of student responses; the most common aspects students reported liking include the Organization of the reading, Amount of Detail included, the Embedded Questions, and the included Visuals (e.g., photographs and diagrams). “I liked that the reading was simple and to the fact and that there were pictures you could use as a visual aid” (Jessica, TS 39), “I really liked how organized and easy to understand they were” (Kaleb, S 5), and “I like the challenge of the questions throughout the readings” (Henry, TS 35) are responses illustrating this category. Additional exemplars for this category include:

I liked how easy they were to follow. The “main idea” questions helped me better understand previous paragraphs I read. (Ken, S 24)

I like that the questions we had to answer went along with the page it was on. The questions went in order. The reading was easy and simple. And the info was in order and not scattered. (Jessica, TS 2)

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. (Henry, TS 6)

The information was interesting and I always learned many new things. I liked how the information was very detailed. (Kaleb, S 15)

13 percent of responding students indicated the stories Helped with Classwork in some way, and 5 percent of students specifically mentioned that the stories helped them
come to better understand some of the things we were learning.” Additional exemplars for this category include:

- It explained in details the things that was unclear in the book. An alternate source in learning. (Kaleb, S 8)

- 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. (Henry, TS 20)

- These readings go in depth on the subject and there are many interesting facts and other events. I learned many things from the reading. The readings also help in answering questions on the tests. (Laura, TS 21)

- What I liked about the readings was that they were straight to the point and had no unnecessary information. I thought it was very easy to comprehend the information. I really understood the experiments more, like the R strain one, more through the reading than spending days on [it] in class. The readings are very understandable. (Karen, S 8)

Nine percent of students responding indicated they found the stories easy to understand or Not Difficult, as illustrated by the above quote from Karen’s student 8. Jill’s student 6 comment, “They were very detailed so I was clearly able to understand them and what they were talking about” and Karen’s student 80 comment, “I was able to understand what was going on as I read. I also liked that the whole reading as a story. So I was able to be more interested in it than I would have been if they were facts” also provide examples of this category. Eight percent of students reported that they liked the stories because they Enjoy Science or learning about specific science content. Example student responses include, “Chemistry in general is interesting to me. Understanding how this world works and why does things is fascinating to me” (Carol, S 2), “I like learning about evolution” (Laura, TS 25), and “I’m very intrigued by science in general” (Beth, S 29). Sadly, 11 percent of
students responding reported they Liked Nothing about the stories.

What Students Disliked About the Short Stories

Student responses regarding what they disliked about the short stories were placed in nine primary categories: (1) Boring or Uninteresting, (2) Disliked the Structure, (3) Difficult To Understand, (4) Dislike Reading, (5) stories were Not Useful, (6) Disliked The History Of Science, (7) Dislike Science, (8) Disliked Everything about the stories, and (9) Disliked Nothing about the stories. Table 28, below, presents the percentage of student responses for each category.

The most common category of student responses (42 % of responding students) indicated they found the stories Boring Or Uninteresting. Examples of this category include: “They were boring and long. Not to my interest” (Laura, TS 1), “They were kind of boring to read, and did not keep my attention” (Vicki, S 6), and “They weren't interesting at all” (Beth, S 31). Jill’s student 6 wrote, “It was like reading out of a textbook. That is never really fun to read.”

The next most common category of responses (37% of responding students) indicated that students Disliked the Reading Structure. Most frequently, students reported they found the stories Too Long, Disliked the Embedded Questions, and thought there was Too Much Information in the stories. The following student comments illustrate this category:

They took a long time to get through because there was so much information to cover. (Jill, S 16)

I did not like how long they were and how much of it seemed like unnecessary info. (Kaleb, S 4)

The questions. It would have been easier if the questions weren't so hard. (Henry, TS 1)
The things I didn't like about the readings were some seemed to drag on. That could have been me though. They were overall good. (Henry, TS 26)

Table 28. What students reported disliking about the short stories

<table>
<thead>
<tr>
<th>What Students Disliked</th>
<th>Percentage of All Students (N = 531)</th>
<th>Percentage of Chemistry Students (N = 259)</th>
<th>Percentage of Biology Students (N = 272)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boring or Uninteresting</td>
<td>42</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>Disliked the Structure</td>
<td>37</td>
<td>34</td>
<td>39</td>
</tr>
<tr>
<td>Too Long</td>
<td>19</td>
<td>22</td>
<td>17</td>
</tr>
<tr>
<td>Disliked Questions</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Too Much Info</td>
<td>6</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Repetitive</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Organization</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Want More Detail</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Difficult to Understand</td>
<td>30</td>
<td>36</td>
<td>25</td>
</tr>
<tr>
<td>Dislike Reading</td>
<td>7</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Not Useful</td>
<td>5</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Disliked History of Science</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>People as Scientists</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Development of Ideas</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Dislike Science</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Disliked Everything</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Disliked Nothing</td>
<td>5</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

30 percent of students indicated they found the stories Difficult to Understand.

Examples illustrating this category include, “They were dry, boring, and hard to understand” (Jessica, TS 16) and “I thought the types of advancements were a bit boring. Also the texts were written for a very high level” (Ken, S 8). The following are additional exemplars for this category:

A few places in the reading were slightly confusing. Using "scientific words" that I was unsure of the meaning. Most of these spots I had to read over
several times to fully understand what the article was saying. (Jessica, TS 33)

Hard to understand for high schoolers. Too in-depth. Some we didn't apply to what we learned. (Will, S 12)

It was kind of complicated and we really had to pay attention in order to understand. (Chem 6, T22)

Seven percent of students reported they did not like the stories because they Dislike Reading in general. For example, Carol’s student 2 wrote, “I don't like reading.” Other exemplars for this category include:

I don't enjoy reading, so I didn't like reading the readings. (Carol, S 13)

I just do not like reading because I'm bad at comprehending so I didn't like having to write what I read about, I'd rather discuss it as a class. (Ken, S 42)

I just don't like reading in general. I'm a slow reader who has to read something slowly to make sure I understand everything. (Ken, S 2)

Additionally, five percent of students indicated they thought the short stories were Not Useful or pointless. Exemplars for this category include:

The readings on many of them didn't seem relevant to anything in my life and at times seemed pointless. (Carol, S 4)

I did not like reading about which scientists found what. That is unnecessary details and I thought it was a waste of my time! (Carol, S 41)

They didn't concern anything I really needed to know. They were giving me pointless info. (Henry, TS 36)

[I liked] nothing, they made you read things that will not help your grade in chemistry and when all you care about is your grade, then these became useless. (Jessica, TS 9)

In contrast to the 30 percent of students who reported liking the historical aspects of the short stories, only four percent of student responses indicated they Disliked History Of Science, learning about the Development of Science Ideas or learning about Scientists As
People. Student responses to this effect include the following:

They were boring and I really didn't like it at all. And we're supposed to be learning about chemistry not its history just the modern stuff. (Jessica, TS 57)

I did not like learning about the process each scientist took because I found learning about the scientist is more boring than learning about the actual process. It is also hard to stay focused when reading a large amount. (Kaleb, S 14)

I don't really enjoy reading about scientists that discovered the information. (Jill, S 27)

Too long, college reading, half of it is mostly about history, not biology. (Laura, TS 53)

Three percent of students reported disliking the stories because they dislike science. Two percent of students indicated they disliked everything about the short stories. However, five percent reported they Disliked Nothing about the stories. For example, Karen’s student 20 wrote, “I honestly don't think you need to make any changes because it was really great and fun to read”, and Henry’s treatment student 52 said, “There was nothing I did not like about the group readings.”

Summary of Findings for Research Question 3

• Although the majority of students did not find the historical short stories interesting, they did report the stories were more interesting than their textbook or other typical class readings. Additionally, 90 percent of responding students indicated they would like similar stories to replace at least some of their typical class readings.

• 37 percent of students indicated the stories portrayed doing science as more interesting than they previously thought, while only 16 percent reported doing science was portrayed as less interesting than they thought.
• 41 percent of students reported the stories increased their interest in the related science content, while 15 percent reported a decreased interest in the content.

• The majority of responding students (57%) reported understanding how science works and science ideas are developed should at least be an important or extremely important goal for high school science classes, while only 13 percent reported it should not be a goal at all. Additionally, a majority of students (58%) perceived the stories at least somewhat helped them meet this goal.

• In their written responses regarding what they liked about the stories, students most frequently reported: the stories were mentally engaging or interesting (33%), the stories were informative (30%); they liked learning about the history of science (30%); the stories helped them with their classwork (13%); the stories were not difficult (9%); and the stories increased their understanding of the science content (5%).

• In their written responses regarding what they liked about the stories, students most frequently reported: the stories were boring or uninteresting (42%); the stories were difficult to understand (30%); the stories were too long (19%); they disliked the embedded questions (9%); they dislike reading (7%); the stories were not useful (5%); and they disliked learning about the history of science (4%).

Research Question 4:
Factors Correlated with Students’ Interest in the Stories

Reliability of Interest and Attitude Survey Multi-Item Indices

Interest and Attitude Surveys 1 and 2 (Appendices H, J, K, and L) included three multi-item indices to assess factors possibly associated with students’ interest in the NOS short stories. These indices included a seven-item index to assess students’ attitude towards
reading, a ten-item index to assess how congruent students’ perceptions of an effective science learning environment are with reform-based teaching practices, and an eight-item index assessing whether students attribute their academic success and failure to factors within or beyond their control. All items in the indices were Likert questions asking students to rank their agreement with each statement on a five-point scale (completely disagree, somewhat disagree, neutral, somewhat agree, completely agree). Several items in each index were reverse coded such that they provided a consistent measure of each construct. For the reading attitude index, a higher score (5) is consistent with a positive attitude towards reading and a low score (1) is consistent with a negative attitude towards reading. For the effective science learning environment index, a high score (5) is consistent with a more reform-based view of science learning and a low score (1) is consistent with a more traditional view of learning. For the attribution index, a high score (5) is consistent with attributing academic successes/failures to factors within the students control and influenced by effort. A low score (1) on the attribution index is consistent with attributing academic successes/failures to factors outside of the students’ control (e.g. luck, fixed intelligence, and teacher decisions). Appendix I lists the specific items for each of the three indices and their coding.

After reverse-coding items, scale reliability tests were conducted with SPSS for each of the three indices. Items with low inter-item correlation values were removed from each scale prior to conducting statistical tests with student interest data. Items removed from each index are indicated in Appendix I. Table 29 lists Cronbach’s α and mean inter-item correlations for the three indices on Interest and Attitude Survey 2 after eliminating items with poor inter-item reliability. One item was removed from the reading attitude index,
resulting in a six-item index with Cronbach’s alpha of 0.860 and mean inter-item correlation of 0.500. Three items were removed from the science learning environment index, resulting in a seven-item index with Cronbach’s alpha of 0.731 and mean inter-item correlation of 0.279. Two items were removed from the attribution index, resulting in a six-item index with Cronbach’s alpha of 0.600 and mean inter-item correlation of 0.201.

Typically Cronbach’s alpha values above .70 are preferred for confidence that the items in the scale are measuring the same underlying construct and can be combined into a single scale (Pearson, 2010). By this recommendation, the internal reliability of the Reading Attitude Index and the Science Learning Environment Index are sufficient. However, Cronbach’s alpha is sensitive to the number of items in a scale; scales with fewer than ten items frequently produce Cronbach’s alpha values below .70 (Pearson, 2010). Mean inter-item correlation values may be a more appropriate measure of internal reliability for scales with fewer than ten items; inter-item correlations between .2 and .4 provide justification for combining less than ten items into a single scale (Briggs & Cheek, 1986; Pearson, 2010). Using these recommendations, the mean inter-item correlations provide justification for all three of the multi-item indices used in this study.

Table 29. Internal Reliability Statistics for Indices on Interest and Attitude Survey 2

<table>
<thead>
<tr>
<th>Index</th>
<th>N</th>
<th>Cronbach’s α</th>
<th>Mean Inter-Item Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-item Reading Attitude Index</td>
<td>613</td>
<td>0.860</td>
<td>0.510</td>
</tr>
<tr>
<td>7-item Science Learning Environment Index</td>
<td>610</td>
<td>0.731</td>
<td>0.279</td>
</tr>
<tr>
<td>6-item Attribution Index</td>
<td>610</td>
<td>0.600</td>
<td>0.201</td>
</tr>
</tbody>
</table>
Data for the three indices from *Interest and Attitude Survey 1* were only used to calculate test-retest reliability scores. Table 30, below, presents the test-retest reliability results for the three indices. Test (Interest and Attitude Survey 1) and retest (Interest and Attitude Survey 2) scores were correlated to determine test-retest reliability for the three indices. Correlation coefficients of 0.7 or above are typically considered sufficient (Pearson, 2010). Only the Reading Attitude Index met this criterion with a correlation coefficient of 0.763. The correlation coefficient was 0.619 for the Science Learning Environment Index and 0.601 for the Attribution Index. These lower correlation values may be indicative of classroom experiences that impacted students’ views of effective science learning and attributions during the semester they participated in the study.

<table>
<thead>
<tr>
<th>Index</th>
<th>N</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-item Reading Attitude Index</td>
<td>576</td>
<td>0.763</td>
</tr>
<tr>
<td>7-item Science Learning Environment Index</td>
<td>571</td>
<td>0.619</td>
</tr>
<tr>
<td>6-item Attribution Index</td>
<td>569</td>
<td>0.601</td>
</tr>
</tbody>
</table>

**Factors Correlated with Students’ Interest in the Short Stories**

Students’ responses to *Interest and Attitude Survey 2* were analyzed to determine which factors, if any, were correlated with students’ interest in the historical short stories. Table 31, below, lists the Pearson’s product moment correlation coefficients for each factor. Of particular interest were potential correlations between students’ interest in the short stories and the three multi-item indices. Analysis revealed students’ scores for all three indices were positively correlated with their interest in the stories. A moderate positive correlation (0.30 <
A small positive correlation \(0.1 < r \leq 0.3\) exists between students’ interest in the stories and their Reading Attitude Index scores \((r = 0.259)\).

### Table 31. Correlations with students’ interest in the short stories

<table>
<thead>
<tr>
<th>Factor</th>
<th>N</th>
<th>Pearson’s Correlation</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Science Learning Environment Index</td>
<td>505</td>
<td>0.437**</td>
<td>.000</td>
</tr>
<tr>
<td>Attribution Index</td>
<td>505</td>
<td>0.318**</td>
<td>.000</td>
</tr>
<tr>
<td>Reading Attitude Index</td>
<td>507</td>
<td>0.259**</td>
<td>.000</td>
</tr>
<tr>
<td>Stories Promoted the NOS Goal</td>
<td>507</td>
<td>0.493**</td>
<td>.000</td>
</tr>
<tr>
<td>Interest in a Science Related Career</td>
<td>545</td>
<td>0.295**</td>
<td>.000</td>
</tr>
<tr>
<td>Importance of NOS Goal</td>
<td>506</td>
<td>0.027</td>
<td>.540</td>
</tr>
</tbody>
</table>

** * significant at p < 0.01

Other factors students rated on Interest and Attitude Survey 2 were also analyzed for potential correlations with students’ interest in the stories. A medium positive correlation exists between students’ interest in the stories and their perception that the stories promoted NOS \((r = 0.493)\). A small positive correlation exists between students’ interest in the stories and their interest in science-related careers \((r = 0.295)\). Interestingly, even through students’ interest in the stories is correlated with their perception of that the stories promoted their understanding of NOS, no correlation exists with their perceived importance of a NOS goal for high school science classes.
Summary of Findings For Research Question 4

- A moderate positive correlation exists between students’ reported interest in the stories and their views of an effective science learning environment ($r = 0.437$), attributions of academic successes/failures ($r = 0.318$), and perception of whether the stories promoted their understanding of how science works ($r = 0.493$).

- A small positive correlation exists between students’ reported interest in the stories and their attitude towards reading and their interest in a science-related career ($r = 0.295$).

- No correlation exists between students’ reported interest in the short stories and their perception of the importance of a NOS goal for high school science class ($r = 0.027$).
CHAPTER 5: DISCUSSION AND CONCLUSIONS

Study Overview

This study investigated the use of historical short stories about the development and acceptance of science ideas as NOS instruction in secondary science classes. Specifically, the study sought to determine:

- How secondary science teachers implemented historical short stories;
- Factors secondary science teachers claim impact their implementation of the historical short stories;
- The impact of the stories on students’ NOS understanding;
- Students’ interest and attitude towards the stories; and
- Factors potentially correlated with students’ interest in the stories.

Research Question 1: Factors Associated with Teachers’ Implementation of the Stories

Summary of Findings for Research Question 1

- Teacher participants’ story implementations varied drastically in their support for concept development, student accountability, and classroom cultures.
- Teachers’ understand NOS was a necessary but insufficient condition for effective story implementation.
- Whether teachers’ experience is associated with implementation level is unclear. However, all the high-level implementers were at least in their third year teaching.
- Teachers reported their implementation decisions were impacted by concerns regarding: (1) course curricula; (2) student understanding and past experiences; (3) school
constraints; (4) student ability and resistance; (5) learning goals for their students, and (6) perceptions of how the stories impacted students.

- Low-level story implementers expressed that constraints from student ability and student resistance were outside their control. Conversely, high-level implementers more frequently made implementation decisions to mitigate constraints from students’ ability and/or resistance.
- High and mid-level story implementers expressed their goals for students provided rationale for implementing the stories even when facing constraints.
- Teachers at all three levels of implementation expressed desire for teacher support resources providing suggestions for effective implementation of the stories.

Discussion of Research Question 1

*Teachers’ Experience*

Whether teacher participants’ level of story implementation is associated with their years of teaching experience is unclear from the data gathered for this study. High-level implementers were in their third through fifth year of teaching. Mid-level implementers were in their first through fourth year of teaching. Low-level implementers ranged from fifth year teachers to one in her 25th year. Notably, all the high-level implementers were at least in their third year of teaching. A bell-shaped relationship between teaching experience and implementation may exist, but this study contains insufficient data points to make this determination. Perhaps effective implementation of the short stories requires more pedagogical skill than most novice teachers have yet developed. Supporting this view, the two first-year teachers in this study reported they were still struggling with classroom
management and effectively planning and implementing content instruction; such struggles impacted their ability to implement the stories to as extensively as they would like.

While Jill and Hillary were both first year teachers, they were both mid-level implementers with Jill the highest mid-level implementer and Hillary the lowest mid-level implementer. Jill’s more extensive implementation was likely related to the significant support she received from Karen, a high-level story implementer. Jill and Karen developed a close working relationship during Jill’s student teaching; during Jill’s participation in the study, she and Karen taught in adjoining classrooms and frequently planned lessons together. Karen and Jill’s collaborative planning included Jill’s implementation of the short stories; their decisions regarding implementation also took into account Karen’s experiences with the stories during her participation in the study the previous school year. Jill’s frequent collaboration with a more experienced and like-minded colleague likely permitted her to implement the stories and improve her teaching practice to a level she would unlikely reach on her own as a novice teacher. Such an outcome from this specific collaboration is congruent with Vygotsky’s model of social learning (1978, 1986) in which collaborations with more capable peers push less adept peers to develop more complex understandings than they are capable of on their own.

**NOS Understanding**

Results of this study reflect prior research indicating NOS understanding is a necessary but insufficient condition for effective NOS instruction (Abd-El-Khalick et al., 1998; Abd-El-Khalick & Lederman, 2000; Herman et al., 2013b; Lederman, 1992). Results of this study indicate at least a moderate level of NOS understanding is associated with
effective implementation of the short stories. The three teachers with the lowest implementation scores (Rick, Vicki, and Beth) were also the only three teachers exhibiting fully naïve views of some NOS constructs measured by the VOSSI. However, as demonstrated by Carol and Kaleb, moderate to high levels of NOS understanding alone are insufficient to predict effective implementation of the stories. Although Kaleb had the second highest NOS understanding score, he was the in the lower half of the mid-level implementers. While Carol’s NOS understanding score was higher than Henry (a high-level implementer), Carol was a low-level implementer. Thus, factors besides NOS understanding impacted their implementation decisions.

Interestingly, eight participants had higher NOS understanding scores than Henry, who was a high-level implementer. While Henry exhibited no fully naïve NOS views prior to participation in the study, the majority of his views were transitional. These results raise the issue of what other factors may have influenced Henry’s implementation decisions that resulted in effective implementation practices. Perhaps his views of effective pedagogy, commitment to reform-based teaching, and/or perceived importance of NOS education influenced his decision to spend considerable effort and class time effectively implementing the stories. Such a view is congruent with Herman, Clough and Olson’s (2013a) finding that teachers’ use of general reform-based science teaching practices (GRBSTPs) is associated with their NOS implementation level. Herman et al. (2013a) explain:

GRBSTPs include the use of questions that effectively assist students in meaning-making, scaffolding them from their initial thinking to desired understandings. Teachers who have developed this cognitively demanding teaching practice are in a much better position to ask questions that effectively draw students’ attention to NOS ideas in a manner that has them meaningfully think about those ideas. Teachers who generally struggle with questioning will likely also struggle to effectively teach the NOS. This is because they will be far less proficient at uncovering students’ thinking regarding the NOS, less
effective at asking questions that overtly draw students’ attention to NOS ideas in a manner that demands meaningful thinking and reflection, and less able to effectively scaffold students from their initial NOS ideas and reasoning to more thoughtful, defensible, and robust NOS understanding. (p. 17-18)

That Henry spent considerable time reading the stories and preparing for class discussion was evident from classroom observations and his discussions with the researcher. Perhaps the stories supported Henry’s further development of NOS understanding during the study.

Notably, all the high and mid-level story implementers attended the same teacher preparation program that emphasized both understanding NOS and effective NOS instruction. Among the low-level implementers, only Carol had formal education regarding NOS. However, Carol’s NOS coursework focused primarily on understanding NOS, not effective NOS instruction. These results indicate that valuing NOS instruction and understanding effective NOS instruction may be key factors associated with extensive implementation of the short stories.

Perceptions of and Reactions to Constraints

All teachers in the study indicated they faced constraints from the school environment (e.g., time limitations, course curricula, pressure from colleagues, student ability, and student resistance). Time, student resistance, student ability, and course curricula were the most frequently mentioned constraints to story implementation. However, high and low-level story implementers often reacted very differently to the constraints they perceived.

Teacher participants who implemented the stories at a low-level frequently appeared to view student resistance and ability as obstacles to implementation that were outside of their control; they often cited the length and difficulty of the stories as obstacles to extensively implementing the stories with their participating students. Low-level
implementers frequently mentioned they thought if they had more motivated students or students of a higher ability they would be able to have better discussions about the stories and/or students would be more interested in the stories. Teachers who implemented stories at a low level often complained about the length of the readings, both because of student resistance and the time required for implementation. Three of the five low-level implementers participated as Control-Treatment teachers and had agreed to implement three of the short stories. However, Vicki only implemented two of the stories and Rick simply gave a third story to students as a homework assignment that was never discussed in class; both cited time restrictions as the reason they could not adequately implement three stories in their classes. Jessica did implement three stories, but also cited time limitations and her continued absences from class as reasons for not implementing the stories well. The other two low-level implementers, Carol and Beth, were Open-Use teachers and only asked to implement a minimum of one story. Carol, citing time restrictions and her absences from class, only partially implemented a single story.

High and mid-level story implementers also cited institutional constraints, but implemented the stories in a manner that attempted to mitigate those constraints. In particular, high-level implementers more frequently reported how they did or would in the future make implementation decisions to reduce student resistance or assist students with lower reading abilities. Time was also a significant constraint to the high and mid-level implementers, but the concern was primarily with the amount of class time needed to effectively implement and discuss the stories. High and mid-level implementers frequently used between two and three class periods implementing each story; they often commented that implementation of the stories took longer than they expected and may have limited the
number of stories they could implement in their classes. However, all the high and mid-level teachers still expressed value in using the stories. High and mid-level implementers also frequently indicated they felt the stories had additional value, beyond teaching NOS, such as promoting other student goals (e.g., developing reading and critical thinking skills, increasing students’ interest in science and science careers, and improved understanding of science content). The value high and mid-level implementers placed on the short stories is demonstrated by their enthusiasm and willingness to implement the stories. All three of the Control-Treatment teachers who implemented at a high or medium level (Hillary, Laura, and Henry) fully implemented three stories. Additionally, all the Open-Use teachers who implemented at a high or medium level (Will, Karen, Ken, Jill, and Kaleb) implemented two or three stories even though they were only required to implement one. Again, the teacher preparation program the high and mid-level implementers attended may have played a significant role in their perception that the short stories were valuable for meeting multiple goals they had for their student.

School curricula also greatly influenced teachers’ implementation decisions. All teacher participants reported they selected stories for implementation based on their fit with the science content they were teaching and all teachers indicated they would like a wider variety of stories to select from for future implementation. However, low-level implementers more frequently mentioned that they had a hard time selecting stories that they thought would fit well with their science curricula than did high and mid-level implementers. Rick, the lowest implementer and teacher with the lowest NOS understanding score, went so far as to claim he felt none of the stories fit well with his curricula even though he taught units on evolution, genetics, and ecology the semester he participated. Conversely, high and mid-
level implementers more frequently mentioned they thought the stories improved their students’ understanding of, interest in, or ability to remember the related science content. Although the stories are highly contextualized within content frequently taught in their courses, perhaps the low-level implementers still view the heavily NOS-laden stories as separate from their content and something additional to teach rather than a resource to support their content instruction.

An additional consideration is whether the teacher preparation program all the high and mid-level implementers attended was essential for directing their attention to the relationship between NOS understanding and students’ interest in and understanding of science content. None of the low-level implementers had formal education regarding effective NOS instruction, and may therefore be less likely to recognize the value of contextualized NOS instruction in promoting understanding and interest in the science content. Further research needs to be conducted to determine if professional development opportunities are sufficient for improving low-implementers perceptions of the stories and implementation decisions when they have not had previous formal education regarding NOS and effective NOS instruction.

*Lack of Modeling for Effective Implementation*

All the teacher participants, except for Will (the highest rated implementer) and Rick (the lowest rated implementer), indicated they would find beneficial additional resources that assist in story implementation (i.e., implementation ideas from other teachers, collaboration with other teachers, reading strategies, and further discussion questions). The widespread request for implementation guidance, even among the high and mid-level implementers, may
indicate a general discomfort with NOS-specific PCK and/or effectively using non-textbook readings. Because NOS is rarely taught in an accurate and effective manner (Abd-El-Khalick, Bell, & Lederman, 1998; Bell, Lederman, & Abd-El-Khalick, 1997; Capps & Crawford, 2013; Hodson, 1993; King, 199; Lederman, 1999), few teachers will have observed the occurrence of such instruction in secondary science classrooms. Although teachers may have exposure to modeling of effective NOS instruction (as is the case with all the high and mid-level implementers in this study) and content-area reading strategies during methods classes, perhaps teachers are resistant regarding their ability to transfer knowledge from these experiences into the context of a secondary classroom. Perhaps increased exposure to modeling of accurate and effective NOS instruction and the effective use of content-area reading strategies occurring with secondary science students would decrease teachers’ concerns regarding implementation of the short stories.

Research Question 2: Impact of Stories on Students’ NOS Understanding

Summary of Findings for Research Question 2

- In Laura’s and Hillary’s classes, no significant differences were found between Control Students’ and Treatment Students’ NOS understanding following implementation of the stories.

- Following implementation of the stories, Henry’s Treatment Students exhibited significantly better NOS understanding than his Control Students.

- Compared to Control Students in Henry’s classes, Treatment Students had a significantly better understanding of three of the six measured NOS constructs: (1) Social/Cultural Influences on Science, (2) Imagination and Creativity in Science, and (3) Scientific Laws
and Theories. No significant differences were observed for the three remaining NOS constructs: (1) Social Interactions Among Scientists, (2) Time for Development and Acceptance of Science Ideas, and (3) Tentativeness of Science Ideas.

Discussion of Research Question 2

Although analyses of Laura’s Biology students and Hillary’s Chemistry students indicate no significant differences in the NOS understanding of students in their treatment and control sections, both had many missing student VOSSI surveys significantly reducing the sample size used for analyses. Therefore the sample of students from Laura’s and Hillary’s classes used in the MANCOVA analyses may not be representative of their actual student population. Additionally, of the three teachers, only Henry was a high-level story implementer; Hillary and Laura were both mid-level implementers. Thus, whether the lack of significant differences between control and treatment students’ NOS understanding in Laura’s and Hillary’s classes is a result of poor sampling or teachers’ implementation of the stories is unknown.

Although Henry’s Treatment Students exhibited a better understanding of NOS than his Control Students following implementation of the stories, significant differences were only observed for three of the six NOS constructs measured on the Chemistry Student VOSSI. No significant differences were observed for Social Interactions Among Scientists, Time for Development and Acceptance of Science Ideas, and Tentativeness of Science Ideas. This difference may be explained by the particular stories Henry chose to implement. Among the four stories Henry implemented between his two courses (Atomic Model, Conservation of Mass, Heat, and Temperature), the role of creativity and imagination in
science, the impact of society and culture on science, and the role of laws and theories were most frequently made explicit in the embedded key point boxes and questions. Social interactions among scientists were explicitly addressed, but in these particular stories scientists building off of the prior work of others is more clearly portrayed than collaborative interactions. That the development and acceptance of ideas take significant time and that science ideas are tentative is evident throughout all the stories; however, they are only rarely addressed explicitly in the embedded key point boxes and questions. Addressing these particular NOS constructs more explicitly in the stories may be necessary to draw students’ attention to and prompt classroom discussion of these ideas.

The results of the analyses comparing Control Students’ and Treatment Students’ VOSSI scores following implementation of three historical short stories indicates that the stories can be used to positively impact students’ NOS understanding. However, the limited sample size from Hillary’s and Laura’s classes prevents the researcher from making judgments about why the stories positively impacted the student’s NOS understanding for some teachers’ students but not others. Perhaps story implementation at a high level of effectiveness is necessary for improving students’ NOS understanding; however, this cannot be determined from the available data.

*Problems with the Control-Treatment Design*

The quasi-experimental control-treatment design was included in this study to permit investigation of the impact of the short stories on students’ NOS understanding while controlling for individual teachers’ pedagogy and NOS instruction. However, use of such a design may have unfortunate unintended consequences. Of the six Control-Treatment
teachers in this study, only Henry indicated he had no serious concerns with the requirements of the control-treatment design. Yet, even Henry mentioned that he frequently had to consider how he was going to get his class periods aligned when they were not using stories in the treatment classes. Comments made by the other five Control-Treatment teachers indicate the study design may have negatively impacted their implementation of the stories in their classes.

Control teachers frequently indicated concern about keeping all their class periods at the same point in the curriculum and disliked the additional planning required by including control class periods. Some indicated if they were using the short stories in all their classes they may have spent more time implementing and discussing the stories, because they would better be able to keep all their class periods aligned and would not have to find additional work for the control periods. Additionally, teachers were concerned that their students were not all getting the same classroom experiences and some felt they could not assess students over the NOS ideas in the stories when not all students were exposed to the stories. Control-Treatment teachers also frequently expressed concern and frustration with the need to implement a minimum of three short stories.

Such negative responses among Control-Treatment teacher participants raises the concern that such a design may not be the best option for determining the impact of story implementation on students’ NOS understanding. Teachers might more fully implement the stories if they were not concerned with keeping their control and treatment periods in alignment. Additionally, the frustration experienced by Treatment-Control teachers may result may disincline them towards participation in future research projects. Other design options may need to be considered for future research.
Research Question 3: Students’ Interest and Attitude Towards the Stories

Summary of Findings for Question 3

- Although the majority of students did not find the historical short stories interesting, they did report the stories were more interesting than their textbook or other typical class readings. Additionally, 90 percent of responding students indicated they would like similar stories to replace at least some of their typical class readings.

- 37 percent of students indicated the stories portrayed doing science as more interesting than they previously thought, while only 16 percent reported doing science was portrayed as less interesting than they thought.

- 41 percent of students reported the stories increased their interest in the related science content, while 15 percent reported a decreased interest in the content.

- The majority of responding students (57%) reported understanding how science works and science ideas are developed should at least be an important or extremely important goal for high school science classes, while only 13 percent reported it should not be a goal at all. Additionally, a majority of students (58%) perceived the stories at least somewhat helped them meet this goal.

- In their written responses regarding what they liked about the stories, students most frequently reported: the stories were mentally engaging or interesting (33%), the stories were informative (30%); they liked learning about the history of science (30%); the stories helped them with their classwork (13%); the stories were not difficult (9%); and the stories increased their understanding of the science content (5%).

- In their written responses regarding what they liked about the stories, students most frequently reported: the stories were boring or uninteresting (42%); the stories were
difficult to understand (30%); the stories were too long (19%); they disliked the embedded questions (9%); they dislike reading (7%); the stories were not useful (5%); and they disliked learning about the history of science (4%).

Discussion of Question 3

That 41% of responding students report the stories increased their interest in the science content coincides with many of the high and mid-level teachers’ perception that students were more interested in content and increased class participation. However, further analysis is needed to determine if students’ interest in and perceptions of the stories is related to their teachers’ story implementation practices. Perhaps students in classes where the stories were implemented at a higher level and included extensive class discussion are more likely to have an interest in the stories and report they improved their interest in the science content.

That 33 percent of responding students described finding the stories interesting or mentally engaging and 30 percent reported they enjoyed learning about the history of science lends support to prior research that indicates historical narratives effectively humanize and may increase many students’ interest in science (Martin & Brouwer, 1991). That 42 percent of responding students described the stories as boring or uninteresting may reflect a general response to school work as 90 percent also reported they would prefer replacing some of their typical class readings with these types of stories. Perhaps students’ reporting that the stories are boring reflects students’ expectation that educational activities should be fun or at least not cognitively demanding, a view perpetuated by children’s television shows and educational video games (Postman, 1985). Interestingly, among the students reporting that
the stories were useful for classwork, five percent specifically mentioned thinking the stories improved their understanding of the science content in class. Since several high and mid-level implementing teachers also reported they perceived the stories helped students’ understand and/or remember the content, specifically surveying secondary students about their perceptions of whether the stories impacted their content understanding may be useful in future research.

**Question 4: Factors Correlated with Students’ Interest in the Short Stories**

**Summary of Findings for Question 4**

- A moderate positive correlation exists between students’ reported interest in the stories and their views of an effective science learning environment ($r = 0.437$), attributions of academic successes/failures ($r = 0.318$), and perception of whether the stories promoted their understanding of how science works ($r = 0.493$).

- A small positive correlation exists between students’ reported interest in the stories and their attitude towards reading and their interest in a science-related career ($r = 0.295$).

- No correlation exists between students’ reported interest in the short stories and their perception of the importance of a NOS goal for high school science class ($r = 0.027$).

**Discussion of Question 4**

Students who expressed interest in the stories were more likely to hold views regarding effective science learning environments more congruent with reforms-based teaching practices, attribute their academic successes/failures to factors within their control (e.g., effort and practice), have a positive attitude towards reading, and report being more
interested in science-related careers. Perhaps efforts to assist students in understanding the value of deep and robust learning (as opposed to mere recall), what is required for such learning, and the important role and cognitive demands of reading for comprehension would together result in students valuing the stories to a greater extent.

**Implications**

1) Developers of similar NOS short stories should rethink story length.

Teacher participants in this study were frequently concerned about the length of the short stories and the amount of class time needed for implementation. Some teachers reported that they would be more likely to use the stories or use the stories more frequently if they were shorter. Therefore, designers of similar short stories, if their goal is to promote more widespread story implementation, should consider making shorter stories or providing stories at various lengths. Creating stories of various lengths may provide resources teachers:

a. are willing to use with students they do not feel have the ability or disposition to read longer stories,

b. can use with higher ability students or to provide students with more lengthy reading experiences, and

c. perceive they can more frequently utilize during their instruction.

2) Significant professional development opportunities will likely be required for most secondary science teachers to effectively implement the short stories.

All the high and mid-level implementers in this study graduated from a teacher preparation program that extensively promotes teachers’ NOS understanding and effective
NOS pedagogy and has been shown to have significant long-term impact on teachers’ NOS implementation (Herman et al., 2013b). Most secondary science teachers have not had such extensive education in NOS or effective NOS instruction; many teachers have had no formal NOS education. Thus, that many science teachers would be able to implement the stories as a moderate or high level is unlikely. Additionally, even many of the high and mid-level implementers from this study reported suggestions for effective implementation would be beneficial. To promote effective implementation of the short stories, professional development activities are likely needed to provide opportunities for:

a. improving teachers’ NOS understanding,

b. teachers to develop a compelling rationale for NOS instruction and implementation of the stories,

c. modeling of both effective NOS instruction and implementation of the stories,

d. collaboration with other like-minded teachers to share implementation ideas and discuss ways to mitigate potential implementation constraints, and

e. developing teachers’ NOS-specific PCK.

3) To promote implementation of NOS resources in secondary science instruction, designers must consider how classroom teachers perceive NOS resources.

Consideration of how teachers will likely perceive NOS resources is essential. Teachers are less likely to utilize resources they perceive will require extensive class time or do not clearly support their science curricula. When selecting stories for implementation, the primary concern for all teachers in this study was how well the stories meshed with their curricula. Teachers are unlikely to implement resources they do not perceive will support the
science content they teach. Additionally, many teachers in this study indicated short stories ranging between four and seven pages in length were too long for their students or required significant class time to implement. Thus, resources such as extensive historical case studies are unlikely to be utilized except by a small percentage of highly motivated teachers.

4) Designers of NOS resources for inclusion in secondary science instruction should include support materials for teachers.

Support resources may help teachers feel comfortable enough with the NOS resources to utilize them and increases the likelihood the NOS resources will be implemented effectively. Such teacher support resources might include:

a. suggestions for effective implementation,

b. explanations about how the resources can be inserted into and support their content instruction,

c. models of effective implementation (e.g., videos),

d. clear and compelling rationales for implementing the resource, and

e. explanations of key NOS concepts and examples from the history of science reflecting those NOS ideas.

5) Secondary science teacher education programs should include significant opportunities for preservice teachers to observe modeling of NOS instruction in the context of the secondary science classroom.

As demonstrated in previous research (Herman et al. 2013b), teacher education programs including a significant NOS education component can have a lasting impact on
teachers’ NOS understanding and implementation. However, for most teachers to be willing and comfortable implementing short stories similar to the ones in this study, they likely need opportunities to build their NOS understanding, significant rationales for teaching NOS, and observe models of effective NOS instruction. Teacher preparation programs should include significant opportunities for preservice science teachers to observe modeling of effective NOS instruction, including effective scaffolding of students’ thinking towards understanding complex NOS concepts, to begin developing preservice teachers’ NOS PCK and confidence in their ability to make effective NOS instructional decisions.

Observing effective NOS instruction by the methods instructor in the context of the preservice classroom alone may not provide sufficient modeling for secondary teachers to feel comfortable with their ability to effectively implement NOS resources such as the short stories in this study; observing models of effective NOS instruction in multiple contexts, especially including examples in secondary science classrooms with a variety of student abilities, might assist in promoting preservice teachers’ development of NOS PCK and comfort implementing NOS materials in their classrooms. Opportunities for preservice teachers to collaborate on evaluating available NOS resources, design lesson plans for implementing selected resources, potentially implement their lesson plans during a practicum or student teaching experience, and evaluate their implementation may also serve to increase preservice teachers’ NOS PCK.
Recommendation for Further Study

1) Teacher participants in this study were restricted by the need for minimum implementation requirement. All teachers were asked to, at a minimum, have students read the entire story and answer all the embedded questions for each story implemented. Additionally, Control-Treatment teachers were expected to implement a minimum of three stories and Open-Use teachers were expected to implement at least one story in its entirety. To better understand teachers’ implementation decisions and the factors influencing their decisions and selection of stories to implement, further research is needed that does not require teachers to implement at least one story, stories be implemented in their entirety, or students to answer all the embedded questions.

2) Although many teacher participants in this study indicated they would like access to a wider variety of stories, stories that fit better with their curricula, and/or less lengthy stories, further study is needed to determine if providing such resources actually results in secondary teachers implementing more stories in their classrooms.

3) Most teachers in this study reported they would find supplemental resources with suggestions for effective story implementation, reading strategies, and/or NOS discussion questions to utilize with the stories beneficial. Further research should be conducted to determine the impact supplemental teacher support resources and/or professional development opportunities have on both secondary science teachers’ implementation of historical short stories, students’ perceptions of the stories, and the impact on students’ NOS understanding.
4) That only the teachers in this study who implemented the stories at a high or medium level of effectiveness reported an increase in students’ class participation indicates that teachers’ implementation decisions may impact students’ perceptions of and interest in the stories. Additionally, of the three Control-Treatment teachers who returned sufficient student survey data for analyzing the impact of the stories on students’ NOS understanding, only the teacher who implemented the stories at a high level had significant differences between Control and Treatment students’ NOS understanding. Further research is needed to more clearly understand the impact of teachers’ implementation decisions on students’ interest in the historical short stories, perceptions of the stories, participation in class, and NOS understanding.

5) Several of the high and mid-level story implementers in this study reported they perceived utilization of the stories improved students’ interest in the related science content, understanding of the science content, ability to remember the science content, interest in class, and interest in science-related careers. Further study could illuminate the impact stories similar to those used in this study have on students’ interest in or understanding of science content, interest and participation in class, and interest in science careers.

6) Additional research could also further illuminate the relationships that exist between students’ interest and attitudes towards the stories and their views of effective science learning, attitudes towards reading, reading ability, and attributions of academic success. Further research might include investigating the potential impacts changing students’
views of learning, attributions, or reading attitudes has on students’ interest and attitudes towards the stories. Conversely, further research could be conducted to investigate the potential the stories have for changing students’ views of learning and attributions.


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APPENDIX A. BIOLOGY STORIES

Early Efforts to Understand the Earth’s Age: Naturalists and Chronologists

Pre-reading Questions:

1. How old do you think the Earth might be? What factors may have influenced your views about the age of the Earth?
2. Many people think science and religion must be at odds. What are your current views about the relationship between science and religion?

Advances in science are too often wrongly portrayed as the work of one person battling in the name of modern science against the darkness of ignorance and narrow-minded religion. Early attempts to understand the Earth’s age illustrates how scientific understanding changes and refutes the commonplace “science versus religion” perception. This historical episode also illustrates that many individuals, over long periods of time and in strange ways, contributed to our current knowledge of the Earth’s age. Examining the evidence and arguments put forward for the Earth’s age will help you better understand how science works and the important science idea that the Earth is very old.

The earliest known efforts to determine the Earth’s age came from people who, by modern standards, would not be considered ‘geologists’. Around 350 BC, the Greek philosopher Aristotle suggested that the Earth and the universe were eternal—they had always existed and would forever exist. Jewish and Christian philosophy, on the other hand, argued that the Earth was created, and this view became widely held in the Western world. Many scholars were unconcerned with these speculations and were simply content to say the Earth was old! on the scale of a few thousand years. Given that at that time in history few people lived beyond fifty years, several thousand years seemed like a very long time. During this time, theologians (those who study religion) and those we would today call ‘scientists’ demonstrated a complete lack of interest in serious study of the Earth’s age.

Beginning about 1650, interest in the age of the Earth was rekindled, but for different reasons. This was the time of the Renaissance and the Reformation throughout Europe. Theologians and other scholars increasingly retranslated Biblical, Greek, and other writings. In addition to correcting bad translations, some scholars began to raise questions about some Biblical stories such as the Genesis account of creation and Noah’s Flood. At this same time, people of all faiths and nationalities traveled—mostly across Europe—to better understand the world beneath their feet. Trading ships also returned from the Americas and Asia bringing exotic news reports. As humans analyzed writings and explored the Earth in new ways, some interpreted the evidence as supporting a young Earth, while others put forth evidence suggesting the Earth was undeniably old.

One approach to understanding the Earth’s age was to analyze chronologies (the order of events) found in texts that included Biblical scripture. This approach involved estimating the lifetimes of historical figures and then placing them in order according to ancestry. Using this approach with the Bible had its limitations as much of it is simply a genealogical list of who begat whom. So chronologists turned to other records of mankind’s existence, such as non-religious books and royal lineages. Reports from those having traveled to many parts of the world posed problems to the chronologies. The Chinese and Egyptians seemed to have much richer, longer histories than those of the Europeans. Lack of reliable records frustrated chronologists. Like all researchers, they had to make a judgment about the accuracy of old and new information. They decided that this conflicting new evidence was unreliable and dismissed it, trusting their own written records instead.

3. Why might chronologists have preferred to rely on their own written records rather than those from other cultures? In what ways could records from other sources be valuable to scientists?

Chronology illustrates how inquiry about the natural world must be considered within the culture and timeframe it occurred. In the late 1600s, chronology was respected for its rigorous collection of data and precise conclusions. In this sense, it possessed characteristics that ‘modern’ science values. Today, chronologists’ efforts to understand the age of the Earth are often unfairly ridiculed. This is because some modern Creationists, in declaring James Ussher’s date of October 23, 4004 BC to be the exact day of creation, have distorted the historical context in which those chronologists worked. Understanding the context of early work regarding the age of
the Earth requires the important understanding that the chronologists did not force the Earth to be young. The dominant culture already told chronologists that the Earth was young. They simply found a method to defend their culture’s viewpoint.

Naturalism was a second way of determining the age of the Earth. Naturalism reflected a new way of thinking about and investigating the natural world. This new way of thinking emerged over a long period of time and was influenced by many individuals. This period of time (1550 to 1730) is often called the Scientific Revolution, because of the significance this emerging new way of thinking would have for science and all of society. Astronomers like Copernicus argued that the sun was at the center of the solar system. Doctors like William Harvey argued for the circulation of blood in the human body. And physicists like Isaac Newton argued that the world should be understood through the interaction of forces and matter.

The whole Newtonian system put forth two very important considerations for geologists: (1) the world should be explained in terms of natural events and not through supernatural intervention; and (2) the history of the Earth might not completely overlap with the history of humans. The idea that the Earth may have existed prior to humans populating its surface was very unsettling to seventeenth century scholars.

4. Why might the idea of an Earth existing prior to a human population be unsettling for scholars in the 1600s?

This complex and changing cultural backdrop is the context in which the first ‘true’ geologists worked. Some skepticism regarding using chronology to date the Earth had always existed. Those who opposed that approach now looked to evidence the chronologists had dismissed! the natural world. A new class of ‘naturalists’ argued that investigating the rocks and oceans were the best way to understand the Earth’s history. But both the old and the new ways of thinking influenced their approaches to understanding the age of the Earth and the judgments they made regarding evidence.

These naturalists were gentlemen of ‘proper’ society, spending their leisure time enthusiastically inspecting the nooks and crannies of the Earth. Erasmus Darwin (Charles Darwin’s grandfather) was known for climbing into the gullies and cracks of the English countryside wearing his powdered wig, breeches, and topcoat. In 1787 the Frenchman Horace-Bénédict de Saussure led a team of men to the top of Mount Blanc, the highest point in the Alps, carrying mercury barometers and other equipment to test the air.

Perhaps most important to understanding the age of the Earth, naturalists like Nicolas Steno studied strata (layers of rock and soil) and put forward the idea that the layers had been laid in order of the oldest at the bottom and most recent on the top (Figure 1). Embedded in these layers, Steno and others noticed preserved shapes of animal bones – fossils – that nobody had ever seen before. This discovery would drive a whole new generation of naturalists to study the Earth’s age to explain how the fossils got there.

Determining the age of the Earth was also needed to develop an explanation that would account for how physical processes work to shape the Earth over time. Two very different explanations existed. One used Biblical events to explain a short timescale. The other looked at natural events to determine a much longer time scale. In some cases the short timescale is associated with catastrophism (the idea that massive Earthquakes, floods, and other events unlike those experienced today shaped the Earth). The longer timescale is associated with uniformitarianism - this explanation of the Earth claimed that forces presently acting on the Earth are the same as those that have acted in the past. Both approaches had their supporters.
within the scientific community, and both made reference to evidence of the natural world to support their thinking. The work of Jean-André de Luc (Figure 2) and James Hutton (Figure 3) illustrates these two approaches, but they are only two of the many individuals in both camps.

Figure 2. Jean-André de Luc

Jean-André de Luc was born in Geneva, Switzerland, and would later move to England and travel most of Europe. He was the first person to use the word ‘geology.’ While not adhering to a literal interpretation of the Bible, he wanted to explain the world in accordance with Scripture. Pointing to a set of marine fossils he found in the Swiss highlands, he questioned how aquatic life could be fossilized 7,000 feet above sea level in a landlocked region. He thought, around 1780, the best explanation was that at one point the Earth had been entirely flooded. Very gradually, the water levels lessened and at the same time, the continents had risen from the bottom of the ocean. After a couple thousand years, the world would look like it does now and humans would populate its surface. De Luc didn’t think Noah fit all of the world’s creatures into the ark, but he certainly thought a recent catastrophic flood shaped the world’s landmass.

De Luc wasn’t alone in his arguments, but he was original in his methods. Unlike other scholars, he wanted his work to be understood by regular people unfamiliar with geology. Noting the oldest rocks had no fossils, he turned to the younger rocks of more recent origin and their fossils. He interpreted this to mean that at one time animals and vegetation unlike those seen in modern times populated the Earth. However, in the late 1700s geologists had yet to find human fossils. De Luc and other naturalists interpreted this evidence to mean that the Earth existed before humans walked its surface. If so, then the age of humans was very recent compared to the age of the Earth.

About the same time, across the English Channel in Britain, James Hutton also traveled the countryside looking at exposed rock layers. Hutton is often called the ‘father of geology,’ but that does a gross injustice to the many other individuals working to understand the Earth. At the same time Hutton traversed Britain, countless other naturalists traveled the world. In many cases, they were hunting minerals to be used for industry. In other cases they were trying to explain the Earth.

Figure 3. James Hutton
Hutton was most well known for his 1795 book, *Theory of the Earth*, which argued for a world that had “no vestige of a beginning, no prospect of an end.” As a background to this scientific proposition, Hutton should be seen as a man of his time. Trained as a doctor and familiar with the new ways of thinking about the natural world, he accepted the Newtonian explanations of gravity, light, and heat. He agreed that these were the forces of nature that caused the seasons and other natural phenomena. He was also a deist, a new expression at the time, which meant that he believed God created and designed the world in a nearly mechanical way, such that after creation God never needed to intervene. In this view the Newtonian laws commanded over a land that was set up for human life.

Hutton’s friends included fellow scholars and members of the Scottish Enlightenment who provided an environment that nurtured progressive ideas. Among the influential figures in the Scottish Enlightenment were intellectual icons such as David Hume (philosopher), Adam Smith (*The Wealth of Nations*), Joseph Black (discoverer of carbon dioxide), and James Watt (inventor of the steam engine). Hutton counted all of these men among his friends, but Joseph Black, with whom he shared a love of chemistry, was his closest friend. Hutton and Black brought their understanding of chemistry to bear on the geological problems that Hutton was considering.

5. Consider how scientists’ many associations with others likely influence their thinking. Many people dislike the thought of a science career, seeing it as a solitary undertaking. How does this story illustrate that science is a social endeavor?

Hutton traveled extensively, observing exposed rocks and strata found in quarries and cliffs. The most popular story of Hutton is his trip in 1788 to the east coast of Scotland. As he looked up at the cliff face, he saw an ‘unconformity’ in the rocks (Figure 4). At the bottom of the cliff was gray micaeous greywacke. However, instead of lying horizontal, as they were accustomed to seeing in quarry walls, the rock beds were standing straight up. Above that was another large exposure of layered rocks, this time lying horizontally and red in color.

Hutton explained what they were looking at to his companions. This unconformity, he said, demonstrated the cyclical process of nature. The greywacke that was standing vertically at the bottom of the cliff face had originally been laid down as horizontal deposits, which was the only way sediments formed. After an enormous amount of time and the application of subterranean heat, they were transformed into rock. Then, the intensity of the heat was such that it caused the horizontal strata to buckle and fold and rise above sea level, resulting in the vertical formation that they were seeing. The tops of the buckled rocks immediately began eroding and after a time, the land was once again submerged under water. After the buckled rocks were once again submerged deeply under water, new sediments started piling on top of them. This time, the strata were formed from red-colored grains from different rocks on the Earth’s surface. Subterranean heat and pressure once again acted to form the sediment into rocks and raised it above sea level again, but this time with less force, since the strata didn’t buckle, but remained horizontal. He knew this idea to be similar to volcanoes, which he saw to be a sort of natural ‘safety-valve’ for the Earth. When pressure got too high, volcanoes released magma, moving interior matter to the Earth’s surface.

Through these cycles, Hutton, a deist looking for a natural explanation, reasoned how the Earth regulated and preserved itself over time. Knowing that human history failed to record any drastic erosion, he argued that the processes must take place over a very long time, indescribable to humans. This indefinite
timescale, practically an eternity, drew cheers and criticism, but then so did every other theory of the Earth. Hutton’s main contribution to the history of geology was to propose that very small changes happened over a very long time, which would become the backbone of the uniformitarian argument.

6. Many textbooks and teachers will talk about what data shows or what data tells us. How does Hutton’s and other scientists’ need to convince others of the meaning of observations illustrate that data doesn’t show or tell scientists what to think?

The early theories of the Earth’s age depended on many individuals of many beliefs from many countries. Of these early geologists, Hutton is today often seen as the ‘winner’. However, during his career he often fared little better than other naturalists in defending his ideas of the Earth. While he made significant contributions to our understanding of the Earth, science textbooks typically give him excessive credit for today’s accepted theory of the Earth. This episode in the history of science should be remembered as a time when very different kinds of science battled for acceptance. Each group gathered evidence and argued, using their own methods, for their particular conclusions. Understanding the Earth’s age, like the development of all scientific ideas, was influenced by social factors and clearly required the talents and efforts of more than one person.

Note that evidence from the natural world is emerging that overwhelmingly supports a very old Earth. Those attempting to use chronology to determine the age of the Earth faced more and more problems, and eventually no reputable scientists took such efforts seriously. Yet, people of faith were found in both the chronologists and naturalists camps.

7. How does this story illustrate that efforts to understand the age of the Earth should not be depicted as science versus religion?
A Very Deep Question: Just How Old is the Earth?

Pre-reading Questions:
1. Scientists currently accept the age of the Earth to be approximately 4.5 billion years old. How might they have become confident in this age?
2. In what ways might the interactions between scientists impact the development of scientific ideas?

Early efforts to understand the Earth’s age cannot be categorized fairly as a battle between science and religion. Rather, those early efforts reflected two different approaches to collecting and interpreting evidence. The chronologists’ approach was to carefully analyze historical texts of all sorts, including the Bible, to estimate the lifetimes of historical figures, and then determine the Earth’s age by placing them in order according to ancestry. The naturalists’ approach was to carefully study the natural world, referring to it as “the Book of Nature”, to understand the Earth’s history. People of faith were found in both of these groups.

The naturalists argued that the Earth is old, but how old remained a mystery. Many naturalists, including James Hutton (Figure 1), showed no interest in plotting a chronology of geological history, and even explicitly rejected that task. Chronologists, on the other hand, sought to determine temporal sequence - the sequence of events through time - arguing that ‘what happened when’ mattered. Even if determining precise dates was not possible, getting events in the right order was important to them. Most scholars became convinced throughout the nineteenth century that the naturalists were correct in their assertion that the Earth had a deep history. Many of them began to wonder if the Earth’s age and other geological events could ever be determined with precision.

The first generation of geologists included men like James Hutton who were independently wealthy and spent their free time practicing geology. The following generations of geologists made their living doing geological research in the field, reporting it to their colleagues, and teaching it in universities. Professional societies increased greatly in the nineteenth century, and they provided a place for scholars to share ideas with other intellectuals. In 1807, the Geological Society of London began as a dinner club at a pricey tavern in order to keep away men from lower society. In 1825, it opened its doors somewhat, and admitted any man with an interest in geology. Reflecting the gender role norms in society that existed at that time, women were forbidden. The geological society aimed to understand the Earth and concentrate solely on geological matters. However, this sole focus did not last long. Politicians sought geological evidence to help locate valuable coal. Moreover, Charles Darwin’s mechanism for biological evolution - natural selection! - was in need of geological evidence supporting an Earth that was at least hundreds of millions years old. Motivated by an interest in the Earth itself, but also by the importance of geology in many fields of study, geologists sought to understand the Earth’s structure, its features, and the very difficult problem of its timescale.

In the 1850s many methods were being used to determine the timing of geological events. Three were particularly popular—stratigraphy, fossils, and sedimentation. At the time, none of these methods could be used to establish exact ages of the Earth, but they were used to determine the order that geological events had occurred. Stratigraphy studies the order of rock layering, or strata (Figure 2), and it remains a staple of modern geology. As geologists studied these rocks, they found remnants of what appeared to be plants and animals embedded in the strata. But not until the late 1700s did anybody seriously think they were fossils of long-dead, and possibly extinct, animals. In the 1850s some thought that the placement of these fossils within the strata could be used to determine the Earth’s age.
Others thought that the process of sedimentation would provide the only reliable estimate of geological events. Sediment forms as rocks wore away from rain, wind and floods. Grains of sand and silt would be sent to settle in lower lying areas such as valleys, rivers, and oceans. Some geologists thought they could measure this flow of sediment and calculate how long it would take to make some of the enormous rock formations.

3. John Phillips, in 1860, used the idea of sedimentation to estimate the Earth’s age. Based on the rate of sedimentation he observed occurring today, he assumed that approximately one foot of land eroded into the ocean every 1,330 years. He speculated that geologic columns would have a maximum height of 72,000 feet.

Using his approach and numbers, what would Phillips calculate as the age of the Earth?

This approach relied upon uniformitarianism (the idea held by many geologists that forces presently acting on the Earth are the same as those that have acted in the past). Thus, the uniformitarian view holds that the rates of sedimentation processes occurring today have occurred at the same rate in the past. Shortly after 1860, a variety of approaches relying on sedimentation had been used to provide an approximate age of the Earth, and values ranged from 38 to 300 million years.

William Thomson (better known as Lord Kelvin, the namesake of the Kelvin temperature scale), argued that he could approximate the Earth’s age by estimating the amount of heat it lost over time. As a physicist, Kelvin (Figure 3) had no formal training in geology. However, he made several contributions to our scientific understanding of heat. Kelvin thought, for example, when ice cubes are placed into a glass of water, energy in the form of heat moves from the water to the ice. The water loses heat and cools. The ice gains the heat and melts. This meant that the total amount of energy could not be lost (or created), but just transferred to the air, the glass, the table, or something else. He thought this transfer of energy applied to the sun and the Earth, and could be used to estimate the Earth’s age.

Kelvin’s approach was in opposition to the sedimentary technique used by geologists. The basis of his argument was that in every interaction, energy must be transferred. This would be the case for the Earth.

However, in 1850, scientists had no evidence that anything had been adding energy to the Earth. Kelvin took this to mean the Earth had been losing energy since its birth. He then collected data on temperatures inside caves and volcanoes to determine the Earth’s interior heat. He compared this to the surface temperature and estimated how long it would take the Earth to cool to its current temperature. At first he calculated about 100 million years, but this calculated number fell as he considered other variables and additional information. By 1900 Kelvin placed the Earth’s age at 24 million years old. Despite the many uncertainties in his calculations, Kelvin maintained that his approach...
clearly refuted theories that had put forth an Earth that is hundreds of millions of years old.

Kelvin’s conclusion raised concerns about the viability of uniformitarianism because his calculated time frame was far shorter than uniformitarianism would require. However, the Earth’s age was not as important to Kelvin as emphasizing that geological theory must be consistent with well-established physical principles. Kelvin argued that geologists, particularly those advocating uniformitarianism, had neglected the principles of thermodynamics in their speculations. Kelvin also denied catastrophism, maintaining that geological speculation must be physically and philosophically sound. Kelvin thought that scientific laws reflected regularity in nature. For Kelvin, the universe was mechanical and worked on physical relationships.

But geologists were not arguing against a mechanical universe that worked on physical relationships. John Joly’s work provides, perhaps, the best example of the geologists’ reliance on these ideas. He and other geologists were using different data, and their calculations based on this data indicated a much older Earth. Joly (Figure 4) applied the technique of sediment analysis to the salt content of the oceans. He assumed the oceans began as entirely fresh water, and that the ocean had slowly acquired its current salt levels through erosion of rocks. The result of Joly’s calculation was that it would take 90 million years to reach the ocean’s current salt level. By 1899, he and many other geologists had reached a similar conclusion — the Earth was approximately 100 million years old.

At the turn of the century, then, two “scientifically” calculated estimates of the Earth’s age had two very different results. Kelvin measured the loss of heat by the Earth and arrived at 24 million years, while the geologists had measured the buildup of sediment and concluded that the Earth was 100 million years old. Each of these methods made sense, and few scientists were willing to change their minds.

Figure 4. John Joly

Many students today choose not to pursue science careers, thinking that science is a dull and unimaginative process.

4. Using the historical example from this story, explain how both the methods scientists use and the sense they make of data illustrate that science is a creative endeavor.

The next method for determining the Earth’s age would come from investigations that began near the turn of the 20th century. In 1896, Henri Becquerel noticed that wrapped photographic plates placed in a drawer with a mineral called “pitchblende” become exposed. He interpreted this to mean that the mineral was emitting something that caused the exposure of the photographic plates. Additionally, the emission had similar penetrating properties to X-rays (the name given to a phenomena investigated by Wilhelm Röntgen just one year earlier). A new element — uranium — was isolated from the pitchblende, and it was determined to be responsible for the penetrating rays.

In 1898, Pierre and Marie Curie (Figure 5) announced they had isolated two new elements — radium and polonium — and called the energy they gave off ‘radioactivity.’ This newly observed phenomenon, radiation, would soon play the key role in the fifty-year struggle to determine the Earth’s age. The processes responsible for radioactivity would not be understood for another 20 years. However, in 1903, Pierre Curie and his student announced that as radium gave off energy, it also gave off heat; enough heat was released that one gram of radium could melt a gram of ice over the course of a day. Then Rutherford and his student realized that if radium gave off heat in the lab, it must also do this in its natural habitat — the Earth. They calculated that as little as five parts in ten billion of radium would heat the Earth enough to keep it sustainable far longer than Kelvin’s estimate of 24 million years.
School science is divided into subjects, but that is not how science truly works. Note how geology, chemistry and physics are all tied together in understanding the Earth's age.

Moreover, the work in these areas had significant implications for work in biology. Charles Darwin understood that natural selection (his proposed mechanism for biological evolution) would only work if life had existed on Earth for at least hundreds of millions of years. Thus, work regarding the Earth's age crossed many scientific disciplines.

Kelvin refused to accept that radiation actually gave off energy as had been reported. Kelvin remained firm in his view that the Earth was 24 million years old, and this produced some awkward situations. At one conference, Rutherford (Figure 5) was set to give a lecture that would essentially discredit Kelvin's theory. As Rutherford took the stage, he saw Kelvin sleeping in the back. Momentarily relieved that the famous physicist may not hear his speech, Rutherford began. To his horror, Kelvin awoke as he began talking on radiation. Rutherford would later recall that, "I saw the old bird sit up, open an eye and cock a baleful glance at me!" Rutherford's point was not to mock Kelvin, but to say that he had found a new way of estimating the age of the Earth.

Most physicists and geologists soon recognized that this newly understood natural phenomenon was a likely solution to the previously irreconcilable difference between the physical and geological estimates of the Earth's age.

Using Rutherford's ideas, Bertram Boltwood pioneered a method of radiometric dating in 1907. If one knew the time it took for a radioactive parent element to decay into a daughter element, then measuring the ratios of each element in a sample and calculating how long it would take to get the observed ratios was a simple matter. This method sent estimates of the Earth's age skyrocketing as high as two billion years. However, many samples also came back with a date of 400 million years.

This wide range of values could not be explained until 1913 when scientists began to understand that there are different forms of the same element (called isotopes). Carbon, for example, has three isotopes. Most all carbon on Earth is in the form of carbon-12. However, tiny amounts of carbon-13 and carbon-14 exist. While the chemical properties of a radioactive element's isotopes are the same (i.e. Carbon 12, 13, and 14 chemically behave the same), its radioactive properties can vary drastically.

In the case of Boltwood, he tried to measure the decay rate from uranium to lead. Decay rate is measured in a 'half-life' (the time it takes half the parent element to decay). The more abundant uranium-238 decays to lead-206 with a half-life of 4.5 billion years. Meanwhile, the rare uranium-235 decays to lead-207 with a half-life of 700 million years. Until the development of mass spectrometers in the 1930s, it was very difficult for scientists to determine which isotope they were using. However, once understood, this radiometric dating would play a key role in our current understanding of the Earth's age.

As radioactivity and its implications for geological dating became better understood, scientists acted in new ways to determine the Earth's age. Rutherford and Joly teamed up in 1913 to study a particular kind of mark left by radioactive decay in rocks. Interestingly, although Joly argued that sedimentation was a uniform process throughout history, he never accepted that radioactive decay was uniform. He tried, unsuccessfully, to reconcile the 100 million year estimate of the Earth's age calculated using his salinity dating process, with results that came from radioactive decay calculations.

Arthur Holmes was, perhaps, the first geologist to fully grasp the implications of modern physics. Holmes was willing to try all the new methods to
get the two fields working with each other. He was a lifelong geologist who had traveled the world working for mining and oil companies. Holmes would eventually settle into a professorship and act as a diplomat between scientists. His work, using the now well established regularity of radioactive decay, produced an age of the Earth that was approximately 2 billion years old.

5. Scientists are rarely pleased with ideas that do not cohere. Why do you think that scientists want their ideas to fit together, even if those ideas come from different science disciplines?

By the 1950s, most scientists were convinced the Earth was very old. However, this required over a century of work that began in the 1850s. Many more decades of work, and hard-earned new knowledge from various scientific disciplines, was required to provide convincing evidence that our Earth is several billion years old.

Today, the phrase ‘deep time’ is often used when referring to the enormous and difficult to grasp age of the Earth. The modern estimate of the Earth’s age was determined by uranium-lead radioactive dating of Earth materials and meteorites from the asteroid belt (thought to have formed at approximately the same time as Earth). Currently, scientists estimate the Earth is about 4.5 billion years. Science textbooks often cite that number. However, textbooks hide the extensive debate that took place regarding how knowledge of the Earth should be sought, how data should be interpreted, and how knowledge from various scientific disciplines is expected to fit together. In doing so, textbooks distort how science works, and make science careers appear far less than the creative and interesting profession than it is.

Scientists currently accept the age of the Earth to be about 4.5 billion years old. No one scientists can be attributed with determining the age of the Earth – it required the work of many creative and determined individuals.

6. How does this story illustrate the many ways scientists interact during the development of scientific ideas?
Charles Darwin: A Gentle Revolutionary

Pre-reading questions:
1. Most everyone recognizes the name of Charles Darwin. What have you heard or what do you think you already know about Darwin and his scientific work related to evolution?

Charles Darwin’s near legendary status has made him seem larger than life, but few people accurately understand the events in his life, his motives, and his contributions to our understanding of biology. Born in 1809, Charles Darwin (Figure 1) had a family history of interest and work in science. His grandfather had been a successful physician and naturalist. His father had also been a successful physician. Following in his father’s and grandfather’s footsteps, Charles planned on also being a doctor. In 1825 he enrolled at Edinburgh University to obtain his medical degree. However, like many students today, he found the lectures boring, and he was unable to stomach working with human cadavers in his anatomy classes.

Figure 1. Water-color portrait of Charles Darwin painted by George Richmond in the late 1830s.

From Origins, Richard Leakey and Roger Lewin

A career as a doctor was not for Charles. He and his father decided that Darwin should become a clergyman. In 1827 Charles moved to Cambridge University where those aspiring to join the clergy took the same challenging classes as those studying to be scientists. While at Cambridge, Darwin met scientists who contributed to Darwin’s attitude and efforts toward investigating nature. They encouraged a balance of observation and experiment. Thus, along with being well versed in religious studies, Darwin became a keen observer and important researcher in the fields that we now call geology (the study of the earth’s structure and its history) and zoology (the study of animals). Although Cambridge infused Darwin with a scientific spirit, he again found the classes boring and livened his days by gathering and inspecting beetles he found in the courtyards. He wrote:

But no pursuit at Cambridge was followed with nearly so much eagerness or gave me so much pleasure as collecting beetles. It was the mere passion for collecting, for I did not dissect them, and rarely compared their external characters with published descriptions, but got them named anyhow. I will give a proof of my zeal: one day, on tearing off some old bark, I saw two rare beetles, and seized one in each hand; then I saw a third and new kind, which I could not bear to lose, so that I popped the one which I held in my right hand into my mouth. Alas! it ejected some intensely acid fluid, which burnt my tongue so that I was forced to spit the beetle out, which was lost, as was the third one.

While you might think gathering beetles an odd form of amusement, in Darwin’s time many sources of amusement we rely on today were unavailable. There were no televisions, radios, or movies to entertain Darwin. The study of natural history was often a popular form of entertainment.

Perhaps most important during his time in Cambridge, Darwin met and befriended one of the top geologists of the day, Adam Sedgwick. President of the newly formed Geological Society of London, Sedgwick took the young Darwin on geological expeditions to Wales. At the time, Sedgwick promoted a then popular position in geology called ‘catastrophism,’ which argued that landscapes such as mountains, canyons and lakes formed swiftly through epic hurricanes, earthquakes or floods. Darwin had his reservations about this idea, but nonetheless developed a passion for studying the natural world.

After a geological trip to Wales with Sedgwick, Darwin found an irresistible job opportunity waiting for him. Captain FitzRoy of the H.M.S. Beagle was about to set sail in order to survey territory in South America (Figure 2). Fearing the
daily drudgery of interacting with sailors below
his social status, the captain had been looking for
a scholarly gentleman to engage in intelligent
conversation. Darwin accepted the offer, and the
ship set sail on December 27, 1831. Darwin was
a young man, interested in the natural world,
who was offered an adventurous opportunity to
explore the world. Consider how you might jump
at such an opportunity!

At this time, discussions of evolution had been
ongoing for over a century by the time the
Beagle sailed. For example, the French botanist
Jean-Baptiste Lamarck had written about the
evolution of species in the late-1700s and early-
1800s. Lamarck, like many naturalists at that
time, thought that life spontaneously generated.
This ‘natural’ creation could only be responsible
for very simple life forms, so he argued that once
generated they began climbing up the ‘ladder of
life’ toward advanced life forms. The most
advanced forms, humans, were considered to
have progressed the farthest, and thus were
considered the oldest beings on the ladder.
Simpler species had been more recently
generated. One of Lamarck’s more lasting
contributions to the idea of evolution was the
concept of adaptability. He thought that an
organ or limb would become stronger or more
pronounced with more use—for example, the
more a giraffe stretched its neck for food, the
longer it would become. Disuse would result in an
organ or limb becoming smaller. He also thought
these sorts of changes were passed to offspring.
Lamarck’s mechanism of use and disuse for how
species adapt has since been rejected.

Later, in 1844, Robert Chambers also put forth a
popular evolutionary idea. In his book Chambers
combined astronomy, geology, theology, and
biology to advocate that life forms advanced
according to a divine law. God, the maker of the
universal laws, had worked them out such that
species followed a set progression. Chambers
was not a scientist, but he read all the up to date
works on evolution and developed a very
influential argument that many in the public took
as the best explanation of evolution.

Note that ideas regarding the evolution of
species did not originate with Darwin. Moreover,
people, like Darwin, who believed in God, were
often promoting ideas regarding the evolution of
species.

2. Summarize both Lamarck’s and Chamber’s
views on how species evolve and how these
two ideas differ from each other.

Darwin would have read all of these works—one
could not be a naturalist in his day without being
familiar with Lamarck and Chambers’ writings.
However, on this expedition Darwin made two
important observations. The first had to do with
geology. In England, Sedgwick had trained
Darwin’s eye to see geological formations as
happening all at once. However, Darwin couldn’t
accept this view once he viewed the rugged and
varied landscapes of South America. Before
leaving England, Darwin had acquired a copy of
the geologist Charles Lyell’s new book Principles
of Geology, which would become a classic
throughout science. Lyell rejected catastrophism
and argued that things like mountains and rivers
did not form all at once, but gradually over time.
As the Beagle passed through Brazil, Darwin noted his approval of Lyell's ideas. The solid rock that Darwin observed was granite, which geologists believed formed under great pressure, such as under the ocean. Darwin couldn't conceive of the granite being produced under an ocean and then exploding up all at once. Instead, he thought it more likely that such a large landscape had been slowly built up over time. He made many more of these geological observations. They were very important because he began to apply this idea of gradual change to his second important group of observations he made on the trip - living organisms.

As the Beagle skirted the South American coast and pulled in at major ports, Darwin collected and categorized insects, crustaceans, flowers, and made observations of the larger mammals. Once collected, he packed up specimen and left them at port for the next ship to Cambridge. When he returned home, Darwin practically had a library of foreign specimens to examine.

Perhaps the most famous example of his work as a naturalist was conducted on the Galapagos Islands. Arriving in September 1835, Darwin had by now become very interested in the types of creatures inhabiting the islands near land. He noticed that of the birds on the Galapagos, most of the short flying birds (like finches) were entirely unique to the islands. Other birds, like seagulls, could fly further - between the islands and the mainland. This stirred Darwin's imagination. If organisms were uniquely created for their particular climate, then why would island animals be so similar to land animals even if they had completely different climates? In a famous example, Darwin compared the Galapagos finches to the mainland finches of Chile, finding them to be pretty much the same except for variations in their beak. The landscapes, however, were entirely different—the Galapagos were volcanic islands, while Chile was a mountainous region. Darwin couldn't figure out why, if these species were supposedly created especially for the climate of the Galapagos, they would be so similar to the mainland birds.

Darwin then pushed the question one step further. Why would two very distant locations with very similar environments, such as Africa and South America, have completely different flora and fauna? Darwin began questioning the idea that each species had been uniquely created for its particular environment. He doubted the view that every small island in the ocean would have received a special visit from a Creator.

Rather, Darwin saw more reasonable the idea that organisms had not been created on the islands, but instead were somehow transported there from the mainland, and then began the slow changes that developed them into different species. This change from one species to another became a staple of Darwin’s evolutionary theory.

Upon returning to Cambridge in 1837 from his trip on the Beagle, Darwin began the lengthy process of reviewing all the specimens he had collected and published his Voyage of the Beagle. A significant influence on Darwin’s thinking was an essay he read. Roughly 40 years earlier, the clergyman Thomas Malthus had published an essay stating that mankind’s population would, if uninhibited, increase exponentially. Because resources are limited, a struggle for existence would result.

Darwin was struck by Malthus’ phrase “struggle for existence”, and he made a creative leap in applying it to the problem of species adaptation and divergence into new species. Darwin applied the term “struggle for existence” to species fighting for limited resources. Perhaps some species might have an adaptive advantage over others, and that would partially explain why so much variety existed. The importance of his insight is illustrated by his own words:

In October 1838! I happened to read for amusement “Malthus on Population,” and being well prepared to appreciate the struggle for existence which everywhere goes on from long-continued observation of the habits of animals and plants, it at once struck me that under these circumstances favourable variations would tend to be preserved, and unfavourable ones to be destroyed. The result of this would be the formation of new species.

After his return on the Beagle, Darwin began suffering from a chronic stomach ailment and frayed nerves, perhaps caused by a sickness he picked up in South America. In 1842 he moved to the countryside for a more quiet and calm life. That same year, Darwin wrote a sketch of his thoughts in case he was to die. He had no intention of publishing his thoughts at this time.
He spent nearly twenty more years analyzing his collections, conducting further studies, and discussing ideas with others to gain overwhelming evidence for his ideas.

In 1844, Darwin made a first draft of his evolutionary theory. In that essay Darwin argues that small changes in local populations would, in time, accumulate and result in an organism becoming incompatible with its ancestors. Speciation (the forming of a new species) would be gradual with no clear cut-off point. This idea accounted for the trouble naturalists often had determining separate species. However, he didn’t want anybody to see the essay because he had not figured out a mechanism responsible for adaptation. While Lamarck and Chambers thought adaptation followed some sort of set plan, Darwin felt that this didn’t make sense—a ladder of progression might explain why species changed, but it couldn’t explain why they “diverged” (branched off from each other) or why so many varied species existed.

Scientists are human beings and part of society. Like all humans, their work is influenced by the culture in which they exist.

4. What cultural factors were influencing other scientists’ thinking that adaptation must follow some sort of plan?

Darwin’s ongoing work included studying pigeon breeding, the geographical distribution of organisms, and barnacles. Darwin knew that animal breeders carefully paired males and females possessing desired traits to emphasize those traits in the offspring. Darwin knew, of course, that humans were artificially selecting and breeding animals for desired traits. This provided an analogy for how nature, given far more time, might select for traits and result in organisms adapted to their environment. Darwin reasoned that the random variation from which breeders select their traits must also exist in nature. This natural selection is comparable to artificial selection. However, natural selection is far more pervasive and creative than artificial selection because it acts continually on every feature in every generation.

Darwin had collected a wide variety of barnacles (small crustaceans known for clinging to ship hulls). Popular ideas regarding evolution accounted for wide variation in ‘advanced’ life forms like birds or apes or humans, but it would not be expected in the ‘primitive’ barnacles. Nonetheless, there was variation and Darwin wanted to understand what caused it. He felt that studying variation in the crustaceans could help him understand why all species undergo change. After years of study and reflection, in November, 1854 he outlined his principle of divergence that stated divergence and eventual speciation would occur in locations where competition for resources was intense.

Darwin had no “eureka” moment where he suddenly put all the pieces together. Rather, his thinking continually developed and many ideas had to be modified while others abandoned. Around 1854, his thinking was as follows. First, he thought that species did not ‘progress’ up a ladder, but instead randomly ‘diverged’ from each other. What this meant was that nature had no plan for how a species would develop, and that species would naturally split off into different types instead of moving toward a predetermined goal. Second, he realized that the pressure causing this divergence was the competition for resources. Darwin accepted that long ago God created one or more very primitive life forms. Those original life forms then had the tendency to expand and search for resources, and changes in the environment drove adaptation. One could not easily see these changes because life forms did not continuously change—they only did so when environmental factors, such as climate change or access to resources, prompted an adaptation. Furthermore, many of these transition species did not appear in the fossil record because fossilization rarely occurs in the first place.

5. How might the work of Lamarck, Lyle, and Malthus have each influenced Darwin’s ideas?

For Darwin, another challenge loomed on the horizon—convincing scientists that his ideas had merit. Fearing the readers of the Victorian age would ruin his life by labeling him a ‘materialist’ or an ‘atheist,’ he had withheld from publishing his ideas. However, he had long been forging friendships with scientists dissatisfied over the older evolutionary theories.

In June 1858, Alfred Russel Wallace wrote Darwin a letter presenting ideas very similar to Darwin’s and seeking Darwin’s assessment prior to publishing them. Until this point Darwin had never felt rushed to present his work. Now with
Wallace closing in, he acted. Concerned about honesty, he first informed Charles Lyell and another mutual friend of Wallace's letter. After convening a group of scientists to compare Darwin and Wallace's notes, Darwin was given his rightful priority in the matter. That August, the *Journal of the Proceedings of the Linnean Society of London* published a paper by Darwin alongside Wallace's. While Wallace had only recently come to his idea and had very little support for it, Darwin raced to his pen and paper and wrote *On the Origin of Species* practically from memory. In the *Origin*, he drew upon extensive research he had conducted during the past twenty years. In the closing days of November 1859, the first printing of his *On the Origin of Species* appeared in London's bookstores. Darwin's work was rewarded with a first-day sell-out of 1250 copies, a very large printing for the time.

Note that Darwin's theory explaining the evolution of species does not address the origin of life. The title of his book refers to how the diversity of species arose, not how life first arose.

Charles Darwin was a complex man who put a lifetime of work into his theory of evolution. Many scientists and public officials gradually accepted Darwin's ideas on evolution, but Darwin's primary mechanism, natural selection, was widely rejected by scientists for many years. Many scientists refused to abandon the idea that evolution progressed toward some proper end. As with most all advancement in science, change was slow and no single piece of evidence brought about our current understanding of evolution. Darwin's *Origin* lead to a scientific debate that continued for decades. Once published, his theory of evolution by natural selection wouldn't be considered a true landmark of science until geneticists infused natural selection into their work on heredity in the 1930s. During the past 100 years, overwhelming evidence has continued to support Darwin's most fundamental ideas regarding biological evolution.

Darwin's ideas sparked debate and did not instantly convince his scientific peers. This is typical of newly proposed ideas in science, and is not at all unique to biological evolution.

Darwin's theology at any given time in his work is much debated. While he was never an atheist, Darwin's religiosity had faded by the time of his death in 1882 due to his witnessing the painful and early deaths of his daughters. However, believing that ultimately some higher power must be in charge, Darwin died an agnostic. Recognizing his significant contributions to science, the powers of the time, including the Church, made sure he was buried in London at Westminster Abbey. Charles Darwin was buried next to another icon in science, Sir Isaac Newton.

Figure 3. Charles Darwin in 1868, age 59

Photograph by Julia Margaret Cameron

Many people wrongly think that scientists follow a rigid step-by-step scientific method when doing research. This misconception wrongly leads to another misconception that the value of a scientific claim can only be made through a controlled experiment. Many of the most well established scientific ideas are built on observational science and defy investigation by means of a controlled experiment.

6. How might the public's adherence to these two significant misconceptions cause them to reject biological evolution?

Science explains events in the universe without reference to the supernatural. Individual scientists often have a deep personal faith in a supernatural being, but when doing science, they must provide natural rather than supernatural explanations for phenomena. This approach has provided useful scientific explanations for phenomena that in the past were attributed solely to supernatural intervention.

7. How would permitting supernatural explanations in science interfere with the quest to develop explanations humans can understand and use?
Today we know that the blueprint for life lies in the nucleus of every cell in the human body. Often referred to as simply DNA, its full name is deoxyribonucleic acid. It looks like a twisted ladder, called a double helix. The steps are made of four nitrogen bases—adenine, thymine, cytosine, and guanine. They are more commonly referred to by their abbreviations A, T, C, and G. Each of the bases has a complementary partner. T pairs with A, and C pairs with G. Every step in the DNA ladder is made of these pairs, stacked in different orders to build the genes that are the genetic code for an organism.

We now know a lot about DNA, but it’s been a long journey to develop that understanding. James Watson and Francis Crick are the two names usually associated with determining the structure of DNA in 1953. They and Maurice Wilkins received the Nobel Prize in 1962 for that work. But efforts to understand the genetic material and the structure of DNA involved many more people over a long period of time.

The story of nucleic acids began in Germany in 1869. Friedrich Miescher (Figure 1) had just finished medical school. However, he opted to go into cell chemistry rather than become a physician. He thought pus, the stuff that oozes out of wounds, might be useful in understanding proteins. Miescher expected the nuclei of these pus cells would have a certain protein, but after investigation realized a different substance was also in the nucleus. Moreover, he found it in cells throughout the body. It was definitely not a protein. Since it came from nuclei of cells, he called it nuclein (we now use the term nucleic acids to refer to molecules such as DNA and RNA). However, Miescher did not recognize the importance of nuclein in heredity; he thought it just stored phosphorous in the body.

In the late 1800s, scientists had many difficulties determining what portion of the cell related to heredity. Scientists would not get a better grasp on the processes behind heredity until the 1900s. By 1900, scientists had begun to identify some portions of the structure of nuclein. Nuclein contained sugars (ribose and deoxyribose), phosphate, and the four nitrogen bases. However, the scientist Phoebus Levene proposed that the four bases were always present in equal amounts (an idea we now know is false). This convinced many in the larger scientific community that nucleic acids were too simple to account for the variability noted in organisms. Thus, they could not be the genetic material. Proteins, however, are made up of twenty-three possible amino acids and did appear to possess the variability expected in genetic material. Thus, many scientists continued their investigations of proteins.

In 1914 a staining procedure that was specific for DNA was developed. With this stain the presence or absence of DNA in cells could be determined by viewing stained cells through a high-powered microscope. Further staining work was interpreted as indicating that all cells (except egg and sperm cells) in a particular animal or plant contained the same amount of DNA. You might think that this would sway scientists toward considering DNA as the genetic material, but that was not the case. DNA just didn’t appear to have the necessary complexity that could produce the immense variations of life. Moreover, proteins were also determined to be in cell nuclei, and they possess the complexity that scientists expected the genetic material to have.

Fourteen years later in 1928, bacteriologist Fred Griffith (Figure 3) was studying the disease-causing capability of two strains of a bacteria that causes pneumonia. One strain had a smooth coat (S-strain) on its surface. When the S strain was...
injected in mice, the mice developed pneumonia and died. The other strain, called ‘rough’ (R-strain), did not have a smooth surface. When the R-strain was injected in mice, the mice did not develop pneumonia. Griffith then used heat to kill the disease causing S-strain and injected them into mice. The mice did not develop pneumonia. But when he mixed heat-killed S-strain bacteria with live R-strain bacteria (both harmless by themselves) and injected the mixture into mice, the mice developed pneumonia and died. Autopsy of the mice showed they were full of S-strain bacteria (Figure 2).

Griffith reasoned that material in the heat-killed S-strain that caused the smooth coat was transferred to the live R-strain. Once transferred, the material transformed the live R-strain bacteria into live S-strain bacteria that could cause pneumonia. But he did not know what this material was. More than a decade of work was required to isolate the material responsible for the transformation first observed by Griffith.

Techniques to destroy various compounds found in bacteria were developed and Oswald Avery, Colin MacLeod and Maclyn McCarty applied these to solve the puzzle. One-by-one different components of the S-strain bacteria were destroyed prior to mixing them with live R-strain bacteria. Transformation always occurred except when the S-strain bacteria were treated with an enzyme that destroyed DNA. In 1944 Avery, MacLeod and McCarty announced that DNA carried the genetic information responsible for transforming the R-strain bacteria to the disease-causing S-strain bacteria.

While more and more scientists began to accept that DNA played at least some role in heredity, other scientists remained skeptical. Many scientists still felt that further experimental work was needed to show that all genes are composed of DNA.

In 1952 Alfred Hershey and Martha Chase (Figure 4) published further evidence in favor of DNA being the genetic material. In their tests they permitted bacteriophages (viruses that attack bacteria) to infect E. coli bacteria. The bacteriophage they used in their work was known to be essentially DNA with a protein coat. These bacteriophages land on bacteria and bore a hole through the cell surface. The virus injects something into the bacterium that instructs the bacterium to produce more viruses. But scientists did not know if that something was DNA or protein.

The key to Hershey and Chase’s experimental work was that proteins have sulfur in their structure, but no phosphorous. DNA contains phosphorous, but no sulfur. Before infecting the E. coli, they went through a process that ensured

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**Figure 2. Griffith’s Experiment with smooth and rough coated pneumonia causing bacteria**

<table>
<thead>
<tr>
<th>Rough Strain (Non-Virulent)</th>
<th>Smooth Strain (Virulent)</th>
<th>Heat-Killed Smooth Strain</th>
<th>Rough Strain &amp; Heat-Killed Smooth Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouse Lives</td>
<td>Mouse Dies</td>
<td>Mouse Lives</td>
<td>Mouse Dies</td>
</tr>
</tbody>
</table>

*Image obtained from Wikimedia Commons, author Madprime*

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*Note that data does not tell scientists what to think. Scientists must interpret and make sense of their data.*

### 2. What sense would you make of Griffith’s results?

Griffith reasoned that material in the heat-killed S-strain that caused the smooth coat was transferred to the live R-strain. Once transferred, the material transformed the live R-strain bacteria into live S-strain bacteria that could cause pneumonia. But he did not know what this material was. More than a decade of work was required to isolate the material responsible for the transformation first observed by Griffith.
the bacteriophages would be labeled with radioactive phosphorous (\(^{32}\text{P}\)) and radioactive sulfur (\(^{35}\text{S}\)). This would permit them to track whether the virus inserted protein, DNA, or both inside the bacterium. The sample of E. coli was determined to contain \(^{32}\text{P}\) and a very small amount of \(^{35}\text{S}\) that was deemed insignificant. This was interpreted by Hershey and Chase as indicating that DNA, and not protein, plays a role in heredity. While this work convinced many scientists that DNA was the genetic material, still not all agreed.

**Table 1. Nitrogen base percentages in organisms.**

<table>
<thead>
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<th></th>
<th>A</th>
<th>T</th>
<th>C</th>
<th>G</th>
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</thead>
<tbody>
<tr>
<td>Human</td>
<td>30.9%</td>
<td>29.4%</td>
<td>19.8%</td>
<td>19.9%</td>
</tr>
<tr>
<td>Salmon</td>
<td>29.7%</td>
<td>29.1%</td>
<td>20.4%</td>
<td>20.8%</td>
</tr>
<tr>
<td>Sheep</td>
<td>29.3%</td>
<td>28.3%</td>
<td>21.0%</td>
<td>21.4%</td>
</tr>
<tr>
<td>Turtle</td>
<td>29.7%</td>
<td>27.9%</td>
<td>21.3%</td>
<td>22.0%</td>
</tr>
<tr>
<td>Yeast</td>
<td>31.3%</td>
<td>32.9%</td>
<td>17.1%</td>
<td>18.7%</td>
</tr>
<tr>
<td>E. coli</td>
<td>24.7%</td>
<td>23.6%</td>
<td>25.7%</td>
<td>26.0%</td>
</tr>
</tbody>
</table>


**4.** Scientists work under the assumption that nature is organized and can be understood. Chargaff reported that the amount A and T appeared in 1:1 ratios and the amount of C and G appeared in 1:1 ratios regardless of the organism. However, a look at Chargaff’s data in Table 1 reveals no exact 1:1 ratios.

What does this indicate about the roles of creativity and interpretation in science?

**Figure 5. Erwin Chargaff**

Source: American Philosophical Society

**5.** Summarize the contributions the following scientists made towards our understanding that DNA is the genetic material passed from parents to offspring and/or our understanding of the structure of DNA:

- a. Miescher
- b. Fred Griffith
- c. Avery, MacLeod and McCarty
- d. Hershey and Chase
- e. Chargaff

Meanwhile, Erwin Chargaff (Figure 5) had always been skeptical of the hypothesis put forward by Levene that the four nitrogen bases were always found in equal amounts. He struggled throughout the 1940s to determine the base ratios of a variety of organisms. By 1948, he had proposed the idea that DNA from different organisms had different nucleotide ratios. That is, they had different percentages of the four nitrogen bases. However, the percentage of A in any organism equals the percentage of T, and the percentage of G in any organism equals the percentage of C (See Table 1). The idea that the amount of A=T and C=G became known as Chargaff’s rule.
Pre-reading questions:
1. Scientists are very confident in our current understanding of the structure and function of DNA. However, this was not always the case. Once they were convinced DNA was the genetic material, how do you think scientists might have determined the structure of DNA?

Today we know that the blueprint for life lies in the nucleus of every cell in the human body. We now know a lot about DNA, but it’s been a long journey to develop that understanding. James Watson and Francis Crick (Figure 4) are the two names usually associated with determining the structure of DNA in 1953. They and Maurice Wilkins (Figure 4) received the Nobel Prize in 1962 for that work. But efforts to understand the genetic material and the structure of DNA involved many more people over a long period of time. Part one of this story focused on how scientists determined DNA, and not protein, was the genetic material found in the nuclei of cells which is responsible for inheritance of traits. Part two of this story will focus on how scientists determined the structure of the DNA molecule and how it specifically carries and transmits genetic information.

Work to understand the actual structure of DNA and how it passes traits from parents to offspring occurred primarily after 1950. At the time, the most modern technique available to scientists to collect information on the three-dimensional structure of molecules was called X-ray diffraction. Molecules, like DNA, were exposed to X-rays for up to 100 hours to produce an image hinting at the physical structure (Figures 1 and 2). X-ray diffraction gives patterns of light and dark marks that must be interpreted. Much skill was required to acquire good X-ray diffraction pictures and interpret them. Maurice Wilkins and Rosalind Franklin (Figure 4) of the University College in London had these skills and had already been collecting such data when James Watson and Francis Crick began their quest to determine DNA’s structure.

The young James Watson (Figure 4) graduated college at age 19, finished his doctorate at Indiana University at age 22, and then went to Europe to do post-doctorate work. Shy and quiet with a huge smile across his thin frame, Watson eventually attended a conference in Naples where he watched a presentation by Maurice Wilkins. Although Watson found Wilkins dry and unenthusiastic, the pictures of X-ray diffraction Watson saw at the conference inspired him to work on DNA.

Watson then moved to work at the University of Cambridge, England. There he shared an office with Francis Crick (Figure 4), who “talked louder and faster than anyone else,” and could understand the most complex concepts almost instantly. Although Crick was fifteen years older than Watson, he had yet to finish his doctoral thesis. Cricks’ laughter echoing through the halls was vastly different than Watson’s calmness. The two got along well despite their differences of personality.

Watson and Crick feared they might tread on the work of other DNA researchers, although they freely asked for help. Rosalind Franklin specialized in X-ray diffraction and gathered the data most valuable to Watson and Crick. Watson, however, did not get along with Franklin. This reflected difference in personalities, but also the sexism toward women in and out of science during that time period. Despite this animosity, she was a brilliant scientist who lived a vibrant life and sought her just recognition.

In the late 1940s, Linus Pauling from Caltech in the United States proposed amino acids were shaped in an alpha helix, and thought the same shape might apply to DNA. Wilkins and Franklin had X-ray diffraction evidence for a helical
structure, but they didn’t know whether it could be a single, double, or triple helix. Watson and Crick entered this debate and struggled for two years because of their lack of familiarity with the field. While paying attention to the X-ray diffraction work being done, they took a different approach. They would attack the DNA structure problem through model building. In Watson’s words, Pauling had not determined the alpha helix only by looking at X-ray diffraction pictures:

! the essential trick, instead, was to ask which atoms like to sit next to each other. In place of pencil and paper, the main working tools were a set of molecular models superficially resembling the toys of preschool children.

Using this approach, they first proposed a triple helix with three sugar-phosphate backbones in the middle and the nitrogen bases sticking out. Confident in their model, they called Wilkins and asked him to come down to give his view. He, Franklin, and two others arrived the next day to see Watson and Crick’s model. After observing the model and listening for a short while, Franklin and Wilkins made clear why the model could not work. Watson and Crick were embarrassed and their work stalled.

A major advance came when Rosalind Franklin developed a new way to image DNA. Prior X-ray diffraction was done on a “crystalline” form of DNA, called its “A form.” Franklin determined that if she put the DNA in an environment of 70-90% humidity, the DNA opened up a bit. She called this the “B form.” When the B form was subjected to X-ray diffraction, the resulting image was interpreted as clearly indicating a helical structure (Figure 2). Knowing the value of her discovery, she wanted to keep it quiet. However, Watson visited Franklin to chat about helical structures. They got into an argument and she ran him out of the room. Watson took this to mean she detested the helix, although Franklin’s personal notes indicate she was in favor of a helix. The tense situation was interrupted by Wilkins appearing at the doorway. All too familiar with his own tensions working with Franklin, Wilkins began opening up to Watson and briefly showed him the new B form data, called photograph 51. Watson instantly interpreted the photo as clear evidence for a helix and raced back to Cambridge. Franklin, however, did not know that Wilkins had shown Watson her photo.

At this same time Linus Pauling had also been working on determining the DNA structure using models. He proposed a model that had several features similar to Watson and Crick’s failed triple helix. When Watson and Crick learned that Pauling was on the hunt for the DNA structure, they devoted all their efforts to beating him to the goal. By this time they had decided that the DNA sugar-phosphate backbone belonged on the outside, but they were uncertain whether it should be a double or triple helix. On the hunch that in biology, things tend to come in pairs, Watson began playing with two backbone models.

Watson spent considerable time trying to make a “like-with-like” (i.e. C paired with C, G with G, T with T, and A with A) double stranded DNA structure work. However, he acknowledged that the difference in size between the bases meant the molecule would be very irregular in width. Crick also noted that Watson’s “like-with-like” idea did not account for Chargaff’s rule (a DNA molecule will have equal amounts of T and A, while G and C are also found in equal amounts). Interestingly, Watson claimed to have a “lukewarm” attitude towards Chargaff’s experimental data. Although Watson continued to work with his “like-with-like” idea, he eventually began entertaining other possibilities.

Figure 2. Photo 51 x-ray diffraction of wet DNA B form double helix taken by Rosalind Franklin and Raymond Gosling on Friday, May 2nd, 1952.

Note that Watson did not give up easily on his earlier idea despite evidence against it.
2. Why might Watson – or other scientists – not easily give up on an idea despite evidence against it?

3. What does this example illustrate about individual scientist’s objectivity?

On February 21, 1953, Watson showed up early to his office. He began trying different arrangements of nitrogen base pairs beginning with his ‘like-with-like’ idea. Admitting that was fruitless, he began trying other possibilities. Watson suddenly became aware that an adenine-thymine pair was identical in shape to a guanine-cytosine pair. He later wrote:

> my morale skyrocketed, for I suspected that we now had the answer to the riddle of why the number of purine \([A \text{ and } G]\) residues exactly equaled the number of pyrimidine \([T \text{ and } C]\) residues. Chargaff’s rule then suddenly stood out as a consequence of a double-helical structure for DNA.

4. Earlier Watson spoke poorly of scientists who did not accept the evidence for DNA being the genetic material. Yet Watson was resistant to accept Chargaff’s experimental evidence.

   a. Why do you think Watson changed his mind about Chargaff’s work?

   b. How does this story illustrate that scientific data does not tell scientists what to think?

When Crick showed up to the office later that morning, Watson excitedly shared his insight. Crick and other colleagues approved of the new configurations. In the days ahead, Watson and Crick began building a detailed model of their proposed structure to ensure its details would account for the available data. They wanted to let Wilkins and Franklin know of their model, but delayed in calling. They remembered the disaster sixteen months earlier when they had prematurely asked Wilkins to come see their failed triple helix. Watson and Crick painstakingly completed the demonstration model (Figure 3), ensuring the bond angles and distances accurately accounted for the available data. When finished, they had a colleague call Wilkins and ask him to come see the DNA model that Watson and Crick had devised.

Wilkins quickly noted key features of the structure and liked the model. Before leaving, he said that he would compare the diffraction pattern predicted by the model to the X-ray diffraction data he and Franklin had collected. Two days later he called saying his and Franklin’s data strongly supported a double helix. Shortly afterwards they all submitted articles to the journal *Nature* to announce to the world their structure.

**Figure 3. Watson and Crick working on their model of the structure of DNA**

Major scientific insights often take much time to be accepted by the scientific community. However, the significance of the double helix was accepted relatively quickly. In 1962, the Nobel Prize in Biology was awarded to James Watson, Francis Crick, and Maurice Wilkins. Rosalind Franklin would have assuredly also received a
Nobel, but she tragically died of ovarian cancer in 1958. This was likely due to the extensive exposure to X-rays she received while performing her X-ray diffraction work. The Nobel Prize is not awarded after death. Unfortunately, Franklin’s contributions are often overlooked. Watson characterized Franklin poorly in his popular 1968 book *The Double Helix*. Even Wilkins and Crick protested its publication. Other research and published books have more accurately depicted Franklin and her outstanding scientific work. But when the determination of the DNA structure is mentioned, still too often all credit appears to go to Watson, Crick, and sometimes Wilkins.

The story of the blueprint of life has now spanned over 140 years, and research in this area is accelerating. As we learn more, new questions arise. But the early history of DNA shows us that this is nothing new. Scientists worked for almost a hundred years to determine the genetic material, the structure of DNA, and how DNA replicates. Much has been learned since the awarding of the Nobel Prize for this work in 1962, and yet many challenges remain. Watson and Crick may be the most well remembered scientists who worked on the structure of DNA, but they couldn’t have succeeded without a large supporting cast.

**Figure 4.** Four of the scientists typically credited with the determining the structure of DNA

![Figure 4](http://www.ba-education.com/for/science/dnadiscovery.html)
The Realization of Global Warming

Pre-reading Question:
Politicians and the media often portray global warming as a controversial issue debated by scientists.

1. What are your current views about the scientific evidence supporting global warming?
2. How do you decide whether or not an idea or evidence is scientific?

Perhaps better than any other issue, global warming shows how scientific data and its interpretations affect all of society. Most politicians will state their view on climate change, and as such we tend to think of it as a political issue. Phrases like ‘greenhouse effect,’ ‘ozone hole,’ and ‘carbon cycle’ are so politicized that their scientific value sometimes seems to depend on whether the speaker is a Republican or Democrat. Many Americans have lost track of the argument among all this political jargon and choose to go on with their lives as normal. Others have become ‘green,’ or more aware of the environment. So what exactly does it mean to be aware of global warming? To scientists, awareness of global warming has been a long journey requiring years of data collection and interpretation. What follows is a short glimpse into how scientists determined that the Earth is warming.

Before jumping into the story, it’s best to know how global warming stands among scientists today. First, 140 years of data and reconstructions of the last 1,000 years of weather patterns make clear that the Earth is warmer now than it has been in the last 1000 years. The question now is just how much of a role humankind plays in this warming. Are we its sole cause, plunging the Earth into a climate catastrophe? Or are we adding to an already natural warming trend that will result in significant but tolerable weather change? Or, as many critics of global warming claim, are scientists just refusing to admit that our emissions are being deposited away into the natural carbon ‘sinks’ (ocean bottoms and terrestrial vegetation) and that life will go on as normal? Here is where the term ‘global warming’ becomes tricky. Depending on who’s talking, it can mean all of the above. With so many different uses of the term, it’s pretty easy to just give up and label global warming as non-scientific.

But that would be mistaken. Global warming research is very scientific. Something helpful to keep in mind here is that ‘global warming’ is a buzzword that represents a lot of scientific ideas about climate change. The science is complex. Many computer models have the Earth warming in the range of 0.5°C to 6°C, but this is just a global average, and it would not be distributed evenly throughout the world. Many scientists agree that some regions of the Earth will become colder. However, with the rest of the world experiencing higher temperatures, many disasters could arise. Glaciers could melt into the ocean, forever losing their supply of fresh water and significantly raising ocean levels. Life cycles of plants and animals could be disrupted, and growing seasons might be disrupted by irregular weather cycles. All of this is well supported science, but it can easily be taken out of context to be seen as non-scientific. Clearly, a lot of confusion exists in the public’s mind over global warming.

The effects of global warming are potentially catastrophic for some components of the biosphere. So understanding it and its causes is crucial. Global warming is tied to the greenhouse effect. Around 1830, Fourier came to the conclusion that the Earth’s atmosphere holds in heat, much like glass in greenhouse that provides ideal growing habitats for plants year-round. If the Earth had no atmosphere, its surface temperature (heated only by the direct radiation of the sun) would be around 0°C — the freezing point of water.

The greenhouse effect depends on the types of gases making up the atmosphere. Nitrogen (N₂) and oxygen (O₂) gases make up close to 99% of the Earth’s atmosphere. In the late 1850s the noted British physicist John Tyndall analyzed the gases of the Earth’s atmosphere one by one. Tyndall determined nitrogen and oxygen do not trap the heat radiation reflected from the Earth’s surface. However, he determined that three gases in the Earth’s atmosphere do hold in heat. These greenhouse gases are water vapor (H₂O), carbon dioxide (CO₂), and ozone (O₃). These three greenhouse gases trap a portion of the heat radiation reflected from Earth’s surface.

On Venus, CO₂ makes up 96% of its atmosphere and is responsible for temperatures over 400°C. On Earth, the greenhouse gases make up less than 1% of our atmosphere and maintain an average temperature of 14°C. Tyndall had the insight that if the amount of CO₂ in our
atmosphere dropped even a little, the change could cool the planet. He also suggested this might be a possible explanation for ice ages. Interestingly, he does not appear to have considered the consequences of rising CO$_2$ levels. At the time, his explanation worked to describe one way in which surface temperature was maintained on the Earth’s surface. But nobody considered that booming industry could one day change our climate.

Given what scientists now know about the greenhouse effect, it might seem like anybody studying the environment should have immediately realized that the Earth must be affected by man-made pollution. The story, however, isn’t that simple. Most of the evidence of global warming comes in bits and pieces, relying on determined (and often obsessive) researchers going to the ends of the Earth to study the most unusual ecosystems. They came from many different disciplines — oceanography, geophysics, astronomy, physics, chemistry, and others. Once they collected their data, the hardest journey lay ahead of them. What did the numbers mean? Were humans making things worse? And at what point should scientists warn the public and politicians?

Like most science ideas, global warming was not “discovered” in a single instance or a single experiment. The idea developed and has been supported by research over a long period of time.

Svante Arrhenius (Figure 1), a Swedish scientist, received one of the first Nobel prizes in chemistry. In 1896 he argued that the Earth’s climate could be alternating between ‘ice ages’ and warming periods based on changes in CO$_2$ levels in the atmosphere. For example, a period of intense volcanic activity would put a lot of CO$_2$ into the atmosphere and cause a warming. If these volcanoes then went dormant for a long enough time, the planet could cool and cause an ice age. But Arrhenius went further. He wrote in April, 1896 that “We are evaporating our coal mines into the air.” He noted that human activity was adding large quantities of CO$_2$ to the air and must be causing “a change in the transparency of the atmosphere.”

Very few scientists specialized in climatology (the science studying climate) in the early 1900s, and those that did often did so as a hobby. To those who kept an eye on the sky, CO$_2$ was no more important than any other gas that made up the atmosphere. Then, in 1938, Guy Stewart Callendar went before the Royal Meteorological Society to present his argument that contemporary calculations of carbon dioxide in the atmosphere happened to be higher than those in the previous century. This rise in CO$_2$, he said, could be the cause of warming on the Earth. Perhaps modern industry had contributed to this rise with its belching smoke stacks and mechanized vehicles. Far from being a climatologist, Callendar was a steam engineer, and he relied on old, simple information. His ideas were heard by the Society, but not well received.

During World War II, the state of climatology changed almost overnight. Historian Spencer Weart describes what it was like before the war: “Climatology could hardly be scientific when meteorology itself was more art than science. The best attempts to use physics and mathematics to describe weather — or even simple, regular features of the planet’s atmosphere like the trade winds — had gotten nowhere.” American entrance into World War II on two sides of the globe placed a huge importance on knowing and predicting weather patterns. Money poured into research directed at better understanding and predicting weather. Military Generals fantasized about one day controlling the weather, seeding clouds from airplanes, and bringing rain down upon enemies at just the right time. Of course, this never happened, but the intense research into the Earth’s climate did greatly improve understanding of the atmosphere and weather.
In the mid-1950s, two researchers began studying CO\textsubscript{2} levels in the atmosphere. David Keeling (Figure 2), a post-doctoral student at Caltech, had been measuring CO\textsubscript{2} levels in various areas of the country. An outdoors lover, Keeling had decided against working in a chemistry lab in favor of working in a developing field called geochemistry. From May to September of 1955 he collected CO\textsubscript{2} samples while camping with his wife and newborn son at sites in the Western United States. While camping at Yosemite, they ran into problems with hungry deer. One night he heard noise outside the tent.

I rummaged around, grabbed my flashlight, looked out, and the flashlight was just like a policeman’s apprehending a suspect. Two big eyes, looking right at me! It was that darn mule deer (or another just like it) and he had my research notebook between his teeth. And as soon as I got him started he ran off into the woods with the notebook.

Keeling rushed out of the tent and amazingly found his notebook, the pages showing the teeth marks of the deer.

Note that scientists choose a particular field of study because of their academic interests, but also because of what they find personally enjoyable. Many people reject a career involving science, wrongly thinking that all scientists work solely in a laboratory. In actuality, scientists work in all sorts of settings.

By 1958 Keeling had collected and analyzed an enormous amount of data and determined that an invisible CO\textsubscript{2} cycle exists. The cycle occurs over the entire planet during the course of a year. Plants and other photosynthetic organisms take in CO\textsubscript{2} from the atmosphere during photosynthesis. Thus, as the amount of photosynthesis increases, the Earth’s CO\textsubscript{2} levels drop. Most photosynthesis occurs during the growing season — from around April through October, peaking in June. So the Earth’s CO\textsubscript{2} levels rise and fall during the year (see the annual cycle in Figure 4 below).

Meanwhile, Gilbert Plass (Figure 3) had been working close by at Lockheed Martin. He had been researching heat-seeking missiles when he took up studying the absorption of CO\textsubscript{2}. After running his calculations through the company computer, in 1956, he claimed that human activity could raise temperatures by 1.1°C every century. Hearing of each other’s work, Keeling and Plass teamed up and studied the absorption of CO\textsubscript{2} by ocean water. What they determined was that the ocean did absorb some carbon and send it to the bottom, but only 1/10 as much as previously thought. The rest of the carbon had to go somewhere else.

‘Carbon sinks,’ are where carbon is naturally processed or stored away. For example, ocean water will absorb some carbon. Over a very long time of cycling, the carbon will be sent to the depths of the ocean, where it will not contribute to global warming. Another carbon sink is the world’s photosynthetic organisms. Plants take in CO\textsubscript{2} through the process of photosynthesis. However, plants can take in only so much CO\textsubscript{2}. So, if output of CO\textsubscript{2} is great enough, it will overpower the natural ‘carbon cycle’ and remain in the atmosphere trapping heat. The science of the 1950s had brought this possibility to the table—the industry so loved by mankind might be overloading the carbon cycle and raising the CO\textsubscript{2} levels of the atmosphere.
Meanwhile, the problem of ice ages still had not been solved. By now, Swedish researchers were drilling into ice cores and carefully removing pollen samples. These pollen samples reveal what kinds of plants lived in an area at particular times in Earth’s history. Other researchers were dating tree fragments from ice sheets. All of the researchers’ calculations continued to indicate a 20,000 year cycle of warming and cooling. However, nobody could figure out just how this could happen.

Note that many different sources of evidence are being collected by different researchers. Yet they are independently interpreting their data to mean the Earth has approximately 20,000 year cycles of warming and cooling. Confidence in this idea grows every time researchers independently come to the same idea with different sources of evidence.

However, without a well-supported theory to explain this 20,000 year cycle, scientists are not satisfied. This illustrates the importance of theories in science. Theories provide an explanation for regularities in the natural world.

By 1965, enough scientists had been concerned about the situation that they met in Boulder, Colorado, at the National Center for Atmospheric Research. They titled their meeting “Causes of Climate Change.” The group concluded that the Earth’s climate was not self-stabilizing — external influences (such as humans) could cause significant changes. Meanwhile, David Keeling continued collecting CO₂ samples. After plotting his data, Keeling determined that while the Earth’s CO₂ levels rise and fall each year in an ongoing cycle, the overall trend is higher levels of carbon dioxide each year. This is called a Keeling curve (Figure 4).

While climatology boomed from an influx of researchers and money, it perhaps best benefited from new digital computers. These computers did the dirty work of crunching thousands of numbers and forecasting models. However, these computers also accidentally gave a great insight to climatologists. Researchers realized that if they cut digits from the numbers — say plugging in .002 instead of .0024959 — the computer would produce very different forecasts than if they had used the full number. At first researchers thought this meant that they needed to have the most accurate data possible to prevent error. Then something very important dawned on them. What if these very small changes actually represented just how narrowly balanced the environment was? What if all that was required to change the environment over time was a very small change in CO₂ levels? These small changes, they realized, could account for the speedy changes between ice ages.

**Figure 4. An example of a Keeling Curve measuring atmospheric CO₂**

Image created by Robert A. Rohde / Global Warming Art.

4. Scientists use many different methods to understand the natural world and work in many different types of places. How has this story illustrated that scientific work is not limited to controlled experiments or always conducted in a laboratory?

Going into the 1970s, fuel resources were being used at a faster rate than ever seen before — putting even more CO₂ in the atmosphere. In 1972, the entire world felt a significant change in the climate. Droughts ravaged Africa starving millions of people. The Soviet Union couldn’t harvest its crops. The monsoons missed India. The media demanded answers — the only people who seemed to have them were the climatologists. The scientists were unsure of what to say, but many of them felt pressed to say that the climate could change in as little as 100 years. Citizens reacted, and the first Earth Day was held. National governments were pressed to ban chlorofluorcarbons, an ingredient in aerosol cans discovered to be one of the worst greenhouse gases.

Meanwhile, scientists found themselves struggling. Suddenly reporters and politicians wanted concrete answers they didn’t have.
Tension between various countries made exchanging data difficult. Money still came, but the funds were earmarked for short-term weather prediction — the kind seen on television. Few people were concerned about the long-term. Even scientists didn’t know what could happen in the next hundred or thousand years.

By the 1980s, global warming had become a topic on public opinion polls. One-third of the American population had heard of the ‘controversial’ idea. Still, it was hard to come by an accurate prediction of long-term weather trends — many things appeared to impact weather. Despite the seeming impossibility of forecasting long-term weather trends, they still had some stand-bys to rely on. For example, tornado and hurricane season came at the same time every year. Despite all the complexities, scientists felt some trends must hold. In 1980, Jim Hansen determined a trend that nobody wanted to hear — over the 20th century, global temperatures had risen by an average of 0.2°C. Furthermore, scientists came to realize a harrowing fact — greenhouse warming could be hidden by ocean warming until the CO₂ levels were so high climate change was inevitable.

In 1986, the Climatic Research Unit at the British University of East Anglia compiled all the data on Earth’s surface temperature they could get and concluded that the three warmest years on record had all come in the 1980s. Previous research had focused primarily on CO₂. New research made clear that methane was actually twenty-times worse. The main sources of natural methane was undrained rice paddies and cattle. Researchers soon realized that the levels of methane in the atmosphere had climbed by 11% in the 1980s alone.

Then scientists realized another feedback process that could happen. If ice sheets melted to reveal swampy environments, the release of methane would increase warming and thereby release more methane. The cycle could repeat as Earth continued to warm releasing even more methane. Indeed, the environment did seem precariously balanced.

It’s clear that global warming wasn’t just ‘discovered’ one day, but put together piece by piece over a very long time. There is no question that the Earth is warming, because it’s within its natural cycle to warm. The question is how much of this warming can be attributed to humans, and whether it is harmful or reversible. After over a hundred years of accumulated evidence, virtually every Earth scientist agrees that humans are adding CO₂, methane, and other greenhouse gases to the atmosphere at a dangerous level — a level which might not be reversible. This is an important fact to remember as global warming is taken up by politicians in the coming years.
Pre-reading Question:
1. In what ways, if any, do you think creativity plays a role in scientific work?

In the summer of 1878, Abbot Gregor Mendel (Figure 1) was visited in his monastery by the horticulturist C.W. Eichling, who was working for a French seed company. While touring Central Europe, Eichling had been urged to visit Mendel’s collection of pea plants at his monastery in the town of Brno (which is in what is now called the Czech Republic). During Eichling’s visit, Mendel showed him the grounds, his beehives, and of course his beds of pea plants. The plants, Mendel admitted, had been crafted to suit the monastery’s food needs. The beds featured 25 varieties, many of them a “hybrid” (the offspring of two different types of peas) of wild-grown plants mixed with the local sugar-pod types.

Eichling wondered how this monk could really claim to possess custom-made plants. Mendel responded, “It is just a little trick, but there is a long story connected with it which would take too long to tell.” The Abbott then continued the tour of his monastery, ignoring Eichling’s requests for the rest of the story. When Eichling left, he asked a customer why Mendel had been so reluctant to reveal his story, and was told that no one believed Mendel’s experiments were more than the work of a “charming putterer.”

At the age of 56, almost five years had passed since Mendel did his scientific work with pea plants. Having become so preoccupied with the daily operations of a large monastery, Mendel could only spend rare free hours in his garden. About 20 years later, this “charming putterer” would be recognized for developing two ideas that we now accept as fundamental laws of inheritance. He is now often referred to as the father of modern genetics.

2. In 1878, why would Eichling have doubted that the monastery could possess pea plants developed specifically for their needs?

In 1822, Johann Mendel was born in a small village (also in what is now the Czech Republic). He lived a peasant’s life for many years. In grade school he was pointed out as a gifted child, and sent off to a boarding school in a German speaking town.

His parents could barely afford the bill, and his occasional gifts from home came in the form of bread loaves. To pay for housing, Mendel tutored other students. Mendel earned top grades in school. However, he was unable to secure a job as a full-time teacher following graduation. Thus, he returned home and spent a year on his parents’ farm. In 1841 he was accepted to the University of Olomouc, in a Czech speaking town. The decision to attend University was tough for Mendel—in addition to hardly speaking a word of Czech, his father had been injured and the family farm was in real danger of collapsing. Still, Mendel chose to continue his education.

At the university, Mendel pursued a degree that included work in mathematics, physics, philosophy, and ethics. He developed good relationships with his professors and again earned top marks. After his two year degree, his life went into a very different direction than he had expected. When Mendel had decided to leave the family farm, his sister took charge. While he was away at school, his sister married and her new husband gained control of the farm. The contract handing over control of the farm to Mendel’s new brother-in-law stipulated that Johann would receive a handsome annual sum of money in return for entering the priesthood. Luckily for Johann, his physics professor had been a member of an Augustinian Monastery. In 1843, with his good grades and his teacher’s reference, Johann was accepted at the Augustinian Monastery in Brno. At the monastery he would be named “Gregor”. As long as he performed his clerical duties, he was free to study whatever he wished.
Life at the Monastery provided time for Mendel to study and, years later, to investigate the heredity of pea plants. The word “scholar” comes from the Latin word “schoole” 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.

The popular image of monastery life is painted such that monks are quiet, reserved creatures that pray the whole day and interact little with the outside world. This was not the case at Brno. Mendel’s duties involved visits with the sick and poor and attending regular church services. Furthermore, the Brno monastery had an extensive collection of rocks, minerals, and plants collected by monks while on their travels. Most important, the monastery had an excellent library, stocked with books of all types. Mendel used these resources extensively, hoping to earn a certificate and become a full-time teacher.

Although praised for his classroom teaching, Mendel couldn’t pass the very tough certification exams mostly because he limited his studies to what was on hand at the monastery. By 1851, Mendel had resigned himself to being a substitute teacher in a monastery. However, later that year the natural history teacher at Brno Technical School took ill, and Mendel stepped in. He taught over a hundred students a day and did so well that he was hired on full-time. When the Abbot of the monastery later learned that Mendel hadn’t passed the certification exams, he decided to send Mendel to the University of Vienna to sharpen his education.

Mendel’s work at Vienna was incredibly important for his future. Specifically, he was exposed to ideas involving mathematical probability. This encounter with probability likely influenced Mendel’s interpretation of his later experiments with pea plants. In addition, Mendel’s education included a broad range of coursework including botany (the scientific study of plants) and zoology (the scientific study of animals). He finished his degree and returned to the monastery, immediately beginning his work on peas.

At the time Mendel began his scientific work and investigations into heredity were done with animals. Plants were not used in hybridization experiments until the 1700s. This was likely due to the difficulty natural scientists had in accepting that plants sexually reproduced. Linnaeus, a devout Christian, was willing to accept that God’s creatures could breed and make new species. He noted that plants also had sexes, and that when two different kinds of plants produced a new offspring (or ‘hybrid’), it was good enough to be considered a new species. The notion that humans could artificially create new species came as a shock to eighteenth-century naturalists. Nature was supposed to be orderly and harmonious, but if humans could indeed make a new species whenever desired by simply crossbreeding existing species, chaos would follow. So at the time Mendel began his work, scientists were thinking about inheritance and were considering the idea that new species might result from reproduction and breeding. However, precisely how characteristics were transferred from parents to offspring remained a complete mystery.

Scientists are human beings and part of society. Like all humans, their work is influenced by the culture in which they exist.

3. What may have been some commonly accepted ideas in society that made it difficult to accept that humans could create new species of life through selective crossbreeding?

What inspired Mendel and others to begin investigating how heredity occurred was prior work regarding the fertility of hybrids. Almost 100 years earlier, around 1760, Joseph Koelreuter, a German, began mating hybrids with other hybrids. He filled all the space he could spare with potted plants acquired from all corners of the globe, even obtaining seeds from Linnaeus. Koelreuter made two important observations. The first was that not all hybrids could produce offspring. The second was that when hybrids were mated, many offspring looked like the parents, but some appeared to be a new species. How could one set of parents create identical offspring and a new species all at once? Koelreuter provided the following explanation: in nature, species remain unchanged and parents
give birth to offspring like themselves, but when humans interfere is when the ‘unnatural’ crosses (new species) appear.

While Koelreuter’s explanation is no longer accepted, his work was important because it questioned one of the major ideas regarding heredity at the time, called “preformation.” Preformation stated that an exact miniature of the parent existed inside sperm cells or egg cells. Therefore, exact blueprints were passed on in each generation. The idea of preformation had survived to Koelreuter’s day even though the microscope had been invented almost one-hundred years earlier. Despite failure to see miniature replicas of parents in the sex cells, the preformation idea lived on because it could explain why so many species had more or less identical offspring.

After making many observations and measurements of his hybrid plants, Koelreuter argued that his results could only occur if both the male and female were involved in heredity. Mendel had extensively read Koelreuter’s work, and it influenced the way he thought about heredity. Franz Unger, a professor at Vienna, was yet another influence on Mendel’s thinking. Unger rejected the idea that species were unchanging. In contrast to Koelreuter, Unger proposed that new variations arise even in natural populations – without interference from humans.

So at the time Mendel graduated from the University of Vienna, his thinking regarding heredity was influenced by the following ideas: 1) new ‘species’ can appear in the form of hybrids, 2) great difficulty existed in explaining why these hybrids gave rise to new hybrids, and 3) whatever the mechanism of heredity, it involved both the male and the female.

In the summer of 1856, in between clerical duties and teaching, Mendel began his research on pea plants (Figure 3) of the genus *Pisum*. He favored these plants for their purity and easily observed characteristics. Mendel’s experiments followed from an idea that no one had previously considered. Mendel idea was to predict “the number of different forms that would result from the random fertilization of two kinds of ‘egg cells’ by two kinds of pollen grains.” In other words, Mendel assumed there were different forms of what he called “factors” for each trait in an organism. For example – there would be a “factor” that causes long stems and a different “factor” causing short stems. He suspected that the factors responsible for different forms of a trait would not occur together in the same sex cell (sperm or egg). One sex cell could only contain one of these factors at a time, not both. Mendel did not know what these factors were, but his idea has observable consequences as illustrated in figure 2.

**Figure 2. Ratio of offspring expected from the random cross of two kinds of egg cells and two kinds of pollen grains (which contain the male sex cells).**

<table>
<thead>
<tr>
<th>T pollen</th>
<th>t pollen</th>
<th>T egg</th>
<th>t egg</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>TT</td>
<td>Tall offspring</td>
<td>Tall offspring</td>
</tr>
<tr>
<td>Tt</td>
<td>tt</td>
<td>Tall offspring</td>
<td>Short offspring</td>
</tr>
</tbody>
</table>

If equal numbers of two kinds of egg cells - one for tall stems (T), the other for short stem length (t) - were randomly fertilized by two kinds of pollen grains - one for tall stems (T), the other for short stem length (t), and if tall stem length was dominant to short stem length, then we could predict the resulting ratio of offspring would be 3 tall to every 1 short plant. These predictions are what Mendel set out to test.

**Figure 3. Gregor Mendel working in his garden**
Mendel used varieties of the genus *Pisum* that he had tested for purity of type. That is, through self-fertilization crosses (allowing pollen from a plant to fertilize an egg from the same plant), he determined that particular plants were "true-breeding" (only contained one factor) for certain traits. He then began strategically making crosses between plants. But rather than simply observing what resulted (as earlier researchers had done), he counted the number of each kind of offspring resulting from his crosses.

4. In what ways did Mendel’s thinking show a gradual progression from prior ideas about heredity?

In what ways was his thinking also a break from those prior ideas?

The simplest illustration of Mendel’s work is his crosses between short and long stem pea plants. Beginning with true-breeding long stem length plants (6-7 feet high) and true-breeding dwarf plants (3/4 to 1 ! feet high), he crossed them together. The offspring that resulted from the crossbreeding (called the F₁ generation) were all tall. Mendel did not know what in the sex cells caused pea plants to have long or short stems, but proposed that whatever caused the plants to have long stems somehow overpowered whatever caused pea plants to have short stems. That is, the long stem factor was dominant and dwarfness (which did not show up in this F₁ generation) was caused by a recessive factor.

The tall hybrid plants from the F₁ generation were then self-fertilized, to create the next or F₂ generation. When the F₂ offspring matured, most were tall, but some were short. This was just what others had observed, but unlike previous explanations for this phenomenon, Mendel was interested in how the number of each compared.

Upon counting the members of the F₂ offspring, Mendel interpreted the numbers as exhibiting a constant ratio—averaging three talls to one short, or a 3:1 ratio. Table 1 below contains Mendel’s published numbers of tall and short F₂ offspring as well as the results of the same type of crosses with other characteristics that Mendel conducted in pea plants.

Note that the numbers do not reflect a perfect 3:1 ratio. While some crosses gave results that were almost exactly that ratio, other results were further from it. Moreover, Mendel’s published paper made reference to additional crosses he performed, but whose numerical results were not reported. The results in Table 1 were selected by Mendel for presenting, and they were likely chosen because they best illustrate his proposed ideas regarding heredity.

Historians Fairbanks and Rytting write that when Mendel noted that one of his crosses yielded results he thought were not in line with the predicted ratio, “he repeated the experiment and obtained results that were more acceptable to him.” Some ambiguity (uncertainty) is part of all scientific work, and those who do research must make judgments to make sense of that ambiguity. Viteslav Orel, a biographer of Mendel, wrote:

In generalizing that the segregation ratio was 3:1, Mendel! pointed out that this figure was only apparent when a large number of observations was involved. Where the number of observations was small, quite different results might be obtained; by way of example he stated that in one plant he found 43 round seeds and only two [rough] ones. The other extreme of random occurrence was a plant which yielded 20 seeds with the dominant yellow color and 19 with the recessive green color.

### Table 1. Mendel’s F₂ experimental results

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Number of F₂ Offspring</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed shape</td>
<td>Round ........5,474</td>
<td>Angular ......1,850</td>
</tr>
<tr>
<td>Cotyledon color</td>
<td>Yellow ........6,022</td>
<td>Green.........2,001</td>
</tr>
<tr>
<td>Seed coat color</td>
<td>Colored ........705</td>
<td>White .........224</td>
</tr>
<tr>
<td>Pod shape</td>
<td>Inflated ........882</td>
<td>Constricted ....299</td>
</tr>
<tr>
<td>Pod color</td>
<td>Green ...........428</td>
<td>Yellow ..........152</td>
</tr>
<tr>
<td>Flower position</td>
<td>Axial ...........651</td>
<td>Terminal ......207</td>
</tr>
<tr>
<td>Stem length</td>
<td>Tall .................787</td>
<td>Short ..........277</td>
</tr>
<tr>
<td>Total</td>
<td>Dominant...14,949</td>
<td>Recessive...5,010</td>
</tr>
</tbody>
</table>
Mendel wasn’t fudging his data. Scientists must make sense of data, and this requires making judgments when interpreting data. Data doesn’t tell scientists what to think. Over time, the wider scientific community will decide to what extent an individual scientist’s decisions hold up to scrutiny; this reduces, but does not eliminate, the amount of subjectivity in science.

5. How does Mendel’s work illustrate that observation and data analysis is not objective, but is subjective and influenced by their expectations and their perception of the world?

6. Many students today choose not to pursue science careers, thinking that science does not require creativity. How does Mendel’s original idea, approach to testing that idea, and his analysis of data illustrate that science is a creative endeavor?

Mendel’s extensive empirical research (research based on experiments) into plant hybridization provided evidence supporting his idea that factors for particular traits are transmitted individually in sex cells (what we today refer to as the law of segregation). Mendel also reported that when he crossed plants that were hybrids of two or three different traits, those traits assort independently of one another – the inheritance of one trait does not influence the inheritance of a different trait - (what we today refer to as the law of independent assortment). His work illustrated how the development of hybrids could be accounted for by the segregated transfer of factors from parent to offspring. Of course, Mendel had no idea what these factors were or how they were passed from parents to offspring. But his experimental work did not support the preformationist idea that the entire organism was transferred to an offspring).

In 1868, Gregor Mendel was appointed Abbot of the Brno Monastery. Overtaken by the daily work of maintaining a monastic order, Mendel quit his pea experiments and slowly withdrew from scientific circles. On his death in 1884, the local paper wrote, "His death deprives the poor of a benefactor, and mankind at large of a man of the noblest character, one who was a warm friend, a promoter of the natural sciences, and an exemplary priest.”

Mendel’s biographer Orel asserts that important contributions made to science by the pea plant experiments were: 1) The application of mathematics in research into heredity and 2) clarifying the role of fertilization in the transmission of parental traits to offspring. However, Mendel’s research did not immediately revolutionize thinking regarding heredity, and only a few scientists really took Mendel’s research to heart.

In 1900, Mendel's work was ‘rediscovered.’ While it had never really been lost, his results resonated with some vocal scientists. They hailed him as being the discoverer of what they now called ‘genes,’ the microscopic objects thought to be responsible for transmitting information from parent to offspring. This idea angered one biologist, T.H. Morgan so much that in 1910 he set out working with fruit flies to disprove Mendel’s ideas. However, after much research, Morgan changed his mind, realizing that certain characteristics in fruit flies were indeed transmitted as individual units and linked by gender. Over the next thirty years as the field of genetics developed, the name Mendel continuously appeared as its founder.

Mendel’s ideas involved:
- some “factors” determining particular traits in life forms.
- the application of mathematics and probability to life forms.

7. Why might scientists in Mendel’s time have found each of these ideas difficult to accept?

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APPENDIX B. CHEMISTRY STORIES

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

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).

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. \( \frac{85}{15} = 5.66 \)

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

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 (A₂B or AB₃).

   \[ A + B = A₂B \text{ or } AB₃ \]

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 (H₂O).

Figure 3. Dalton’s Drawings of Atoms and Molecules

Source: *Dalton’s A New System of Chemical Philosophy, 1808*

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 $H_2$ rather than $H$, and water’s formula became $H_2O$.

**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.

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 (\( \text{H}^+ \)), 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?

**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.

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**

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
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?

People often wrongly think of scientific ideas as being “discovered” — arising at some specific time from startling or new experimental evidence collected by a solitary scientist. This unfortunate view drives many talented individuals away from science, thinking that it lacks the creativity and collaboration most people enjoy in a career. The story behind how our scientific understanding developed regarding what happens to mass during a chemical reaction dispels these and other common myths about scientists and scientific work.

Our story begins with the work of the influential Greek philosopher Aristotle (384-322 BC). Aristotelian natural philosophy, which remained the dominant way of thinking about the world through the Scientific Revolution of the 17th century, was based not on experimentation but on observations and logic. For Aristotelian natural philosophers, that matter could not be created out of nothing or vanish without a trace was simply logical.

After the Scientific Revolution, many practitioners of the new science of chemistry continued to accept the Aristotelian idea that matter could not be created or destroyed, and used this idea as a guiding principle of their work. For example, the Scottish chemist Joseph Black (1728–1799) weighed the reactants and products in chemical reactions. Any difference between the two he attributed to experimental error.

But in the 18th 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.

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.

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.

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.

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.

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 Priestly, 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 Reflexions 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 1990, 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?
The origins of entropy: How culture influences scientific progress.

Pre-reading Questions:

1. In what ways might culture and society influence what science ideas are investigated or accepted by the scientific community?

In the late 18th and early 19th centuries, the Industrial Revolution was in full swing in England. Many new types of heat engines were invented. These new machines offered increased power and efficiency and could produce large amounts of goods cheaply. With these new machines came new questions about their nature: why did the steam engine, the water wheel, or any other machine work? And why were certain engines more efficient than others? The desire for more mechanical knowledge often stemmed from a fear of falling behind. For instance, French engineers saw the advanced skills and technologies of the English and worried that France was falling behind in industrial know-how. The Industrial Revolution brought on an obsession with increased power and efficiency of machines.

This obsession with power and efficiency would drive investigation in science, particularly the field of thermodynamics - the study of the operations of heat. Two ideas dominated early 19th century debates concerning the nature of heat. Some scientists argued that heat, or "caloric", was like a fluid that was transferred from one object to another. Others argued in favor of the dynamical theory of heat, which stated that heat was the motion of microscopic particles.

Although such discussion of heat was important for the emerging fields of thermodynamics and mathematical physics, investigation of heat was mostly driven by engineering and industrial concern with the efficiency of steam engines. While the entropy concept (second law of thermodynamics) would become a generalized principle of nature, its origins lay in the concerns of a small community of scientists and engineers about the operations of heat in engines. To understand the origin of these ideas, we must revisit the Industrial Revolution of the early 1800s.

The arrival of new, high-pressure steam engines around 1800 spurred many new questions about engine principles. This high-pressure system operated with pressures exceeding atmospheric pressure, increasing the power of the engines. Engineers were particularly interested in the principles of the 'expansive' processes in this engine. In older engines, steam was constantly injected into the cylinder in order to compress the piston. In the 'expansive' models, less steam was injected. Instead, the steam was allowed to expand in the cylinder, thus doing the same work with less steam.

Despite the variety of engine designs and the new innovations, there was no 'complete theory' on why these engines worked. This was a problem Sadi Carnot (Figure 1) would highlight in 1824. This involved concepts potentially useful for the practical concerns of working engineers and industrialists: mechanical 'work' and 'efficiency.' The term 'work' represented a 'quantity of action' equal to the product of force and distance.

Along with this concern for work output came the engineers' concern with an engine's efficiency. The efficiency of an engine is the ratio of the input of heat and output of work. Without a conversion factor between heat and work, it was difficult to measure an engine's efficiency. Many who studied engine efficiency studied the water wheel (Figure 2) because its efficiency was easier to quantify than that of the steam engine. Water
wheel efficiency was calculated by observing the speed of incoming water, the size of the wheel, and the work produced. Carnot would reference water wheels in his later works on engine efficiency. Eventually, the problem of inefficiency would be mathematized and conceptualized in the Second Law of Thermodynamics and the notion of entropy.

Figure 2. Burden Iron Works Water Wheel, Troy, NY

Obtained from Library of Congress Historic American Engineering Record

Sadi Carnot cared little for the seemingly ceaseless debates over the microscopic causes of heat. Was heat a material substance (caloric)? Or was it the product of the motion of microscopic particles? Though Carnot sided with the first option, he was not overly concerned with this question. Nonetheless, Carnot shared concerns about the practical problems of steam engines. What preoccupied Carnot were questions about measurable macroscopic quantities, like pressure, temperature, heat, and work.

Like other French engineers, Carnot was concerned that France was falling behind British industry. He believed that the ‘haphazard’ nature of improvements to heat engines was due to the lack of systematic knowledge about the engine’s inner workings. Carnot thought that if one understood the underlying theory of steam engines, then one could systematically make improvements to engine work output and efficiency. Carnot’s goal was to create a complete theory of heat engines using general principals regardless of the particular substance being used in the engine.

Carnot produced a number of important insights. First, while a heat source was clearly important for the operation of the engine, the presence of a cold source was just as important. What caused the production of useful mechanical work was the movement of heat from the heat source to colder surroundings. Carnot often used the analogy of water wheels to explain his ideas. Because he accepted the caloric theory of heat, he imagined that heat flow from hot to cold sources was similar to the flowing of water through a water wheel from ‘high’ to ‘low’. Just as water was ‘conserved’ and not consumed in the water wheel, so too was caloric conserved. Thus, one source of inefficiency was any movement of heat without the production of work. Carnot claimed that the waste of heat was like the wasted motion of water in a water wheel. If water fell without spinning a wheel, or if the water didn’t optimally interact with a wheel’s buckets, motion would be wasted and thus work output would be inefficient. Similarly, if heat were transferred to the surroundings without doing work, engine efficiency would be reduced.

The implications for the second law of thermodynamics lay in Carnot’s key insight: an engine’s maximum efficiency only depends on the difference in temperature between heat source and heat sink. Carnot therefore determined that which substance in an engine was doing the work didn’t matter at all. Whether steam, air, or some yet undetermined mechanism, the limits of efficiency were the same. With these understandings, Carnot imagined an ideal ‘perfect’ engine, an engine that was reversible. By running the engine backwards, work could be used to transfer heat from the surroundings to the heat source. Carnot used the idealized “Carnot cycle” to describe the operations of a reversible engine. An ideal, reversible engine also assumed no friction. The reversible engine was the ‘limit’ to an engine’s productivity and efficiency. The reversible engine, though theoretical and not practically achievable, was the best possible engine, and thus a target to for which to shoot.

Carnot’s work was largely unnoticed, possibly due to his position between the domains of physics and engineering. Carnot’s ideas also relied on the caloric theory of heat, a position that was becoming unpopular. Part of the reason for the decline of the caloric theory was the work of James Joule, an amateur gentleman scientist and a friend of William Thomson’s (Lord Kelvin).
Joule (Figure 3) was in favor of the dynamical theory of heat, which claimed that heat was just a form of motion. Because work could produce motion, Joule thought that heat could be transformed into work and vice versa.

Figure 3. James Joule

Public Domain Image

Joule was the son of a Manchester brewer. He initially had little status in the scientific institutions of his day. Joule, supported only by his own means and interests, was an amateur scholar with no academic affiliations. Joule began experimental research on the relationship between heat and work in 1843. At this time, Joule was interested in the heat produced by fluid friction.

In Joule’s investigation, a paddle-wheel was attached to a system of weights; when the weights were raised and dropped, the paddle-wheel agitated a tank of water (Figures 4 and 5). Using precise thermometers and skills obtained from his brewing background, Joule measured the slight changes in temperature of the water due to this mechanical agitation. Comparing this measure of heat produced by the paddle-wheel to the work done by the machine, Joule was able to calculate the “mechanical equivalent of heat.” Joule published “On the Mechanical Equivalent of Heat,” in 1850 detailing the conversion factor between heat and work. This connection between the motion of the paddle-wheel and the heat of the water further convinced Joule that heat was a form of motion; Joule cited his own experiments as evidence for the dynamical theory of heat.

Figure 4. Joule’s Heat Apparatus

Public Domain Image

Figure 5. Joule’s Heat Apparatus


2. Joule began his work in 1843, but did not publish his work until 1850. Many people think science is a quick process and that scientists develop ideas quickly. Using Joule and other examples from this story, why do you think science ideas often take years or even decades to develop and become accepted.

Because of the skills and precise instruments required for such experiments, many of Joule’s contemporaries couldn’t replicate his experiments. Joule’s status as an outsider to the community didn’t help either. Joule’s findings needed help to acquire credibility, and Joule received this aid from William Thomson (Figure 6). Thomson, a professor at Glasgow University, was the dominant figure in British science in the second half of the 1800s. He worked on many topics, including heat, electricity, and magnetism. He also did work on the first transatlantic telegraph. Thus Thomson’s support for Joule’s

Notice Joule’s background in brewing provided him with tools and knowledge with which he could investigate his ideas regarding heat and work. Scientists, like everyone else, draw on their prior knowledge and experience when approaching new problems.
theories was crucial for their credibility among the scientific elite. Though Thomson couldn’t repeat Joule’s experiments exactly, he decided that a larger apparatus was needed to clearly exhibit Joule’s claims. Thomson upped the scale of the paddle-wheel experiment, using large weights and wheels. Thomson nearly boiled water with this set up, exhibiting Joule’s effects on a large scale.

We often think of scientists accepting ideas based solely on empirical evidence. Yet, Joule had evidence, but his ideas and conclusions were not initially accepted. Factors such as his reputation and unavailability of technology limited others’ willingness to accept his ideas. While we would like to think scientists are objective decision makers, they cannot avoid bias.

3. Explain what types of things might cause scientists to be biased.

Though Thomson supported the conversion of mechanical work into heat, as well as the conversion factor, he wasn’t sure about the opposite conversion of heat into work. This was due to his loyalty to the results and arguments of Sadi Carnot. Thomson’s work on the absolute temperature scale, the Kelvin scale, was constructed using Carnot’s ideas. Thomson thus didn’t want to abandon Carnot’s work. Yet, supporting Joule’s work seemed to clash with his support for Carnot’s. Carnot’s work, as detailed above, was based on the conservation of heat; heat ‘fell’ from the heat source to the cooler surroundings, just like water falls through a water wheel. This falling action was what produced work, and the heat (or the water) was neither consumed nor destroyed. On the other hand, Joule suggested that heat could be created or destroyed during the consumption or production of mechanical work.

4. Using examples from the story, how might culture influence science and/or scientists?

There was another, more pressing problem for Thomson. If the action of heat falling from hot to cold produced work, what happened to this ‘potential work’ when the heat fell from hot to cold without a machine in place to produce work? In terms of the water wheel: if water fell a particular distance without generating work, what happened to this productive potential? In Thomson’s thinking, since force could neither be created nor destroyed, this mechanical effect had to have gone somewhere.

Thomson’s concern with waste of potential useful work and the efficiency of engines likely came from his social and cultural background. Although Thomson was primarily an academic working in mathematical physics, he also had connections to industry and engineering. Glasgow, Scotland was an important port that showcased innovations to steam powered ships. Thomson’s concerns with waste and efficiency likely stemmed in part from the same concerns as other engineers, concerns that had driven the work of engineers like Carnot.

Additionally, like many of his colleagues, Thomson was a devout Presbyterian. This religion taught any kind of waste of nature’s gifts was inherently sinful. Humans were supposed to use nature’s powers to improve society, and anything less was a ‘sin of dissipation.’ Thomson believed that the waste of useful work was a component of the inherent imperfections of humanity. Humans (and their machines) could strive for the ideal, but never quite attain it. These religious sentiments also explain in part why Thomson and others were so concerned with waste and efficiency.

Notice that scientific progress in this story seems to be affected by technological demands, economic concerns and even religious beliefs. All of these factors could be summarized as cultural influences.
transmission of heat occurred in steam engines. Some heat was converted into work, while the rest transferred from the heat source to the cold source. Both processes were required!

Figure 7. Rudolf Clausius

Clausius pointed out that mixing Carnot’s and Joule’s ideas required a ‘natural direction’ for phenomena. This natural direction was found in the ‘natural’ movement of heat from a hot to a cold body. Heat naturally tends to flow from hot to cold bodies, but not from cold to hot bodies without some external driving force or work causing this unnatural transfer. Clausius noted that “Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time.” This was Clausius’s formulation of the second law of thermodynamics.

In later works, Clausius formulated the second law mathematically, producing the relation \( S = Q \left( \frac{1}{T_2} - \frac{1}{T_1} \right) \). Q represented the heat transferred from heat source at temperature \( T_1 \) to cold source at temperature \( T_2 \). S represented a term Clausius called “entropy”. This entropy was a measure of the heat “lost” irrecoverably, or a measure of a systems inability to do work. Clausius’s 1865 formulation of the second law claimed “the entropy of the universe tends to a maximum.” This tendency implied a beginning minimum of entropy, an implication that Thomson seized upon, as we shall see.

Thomson eventually supported Clausius’s line of thinking. However, the notion that both conversion and transfer occur in engines hit at Thomson’s second problem: what happened to this ‘lost’ potential work, dissipated as heat or friction? If some heat fell into the cold reservoir without being converted into work, what happened to the ‘potential’ for work that the heat represented? In 1852 Thomson explored his concerns, and he again noted that in real engines a certain amount of heat would flow to the cold reservoir without creating work. This ‘waste’, was unavoidable in the imperfect machines made by imperfect humans. However, the heat wasn’t lost forever to nature – the energy present in the heat not converted to work was simply transferred to the cold source. Energy was conserved, as the First Law would predict. The problem of waste lay therefore in human imperfection.

This insight had implications for engineering practice and for Thomson’s views about the ‘progressive’ aspect of nature. By progressive, Thomson meant that everything moved towards a particular endpoint, whether that endpoint was the natural movement of heat from hot source to cold source, or the dissipation of the energies of the universe. In Thomson’s views, only God could create or destroy, and only God could reverse the inevitable progression of the universe – a progression marked by the dissipation of heat and the decreasing potential for human access to work. Thus the laws of thermodynamics, and especially entropy, were made to fit with the Christian universe of Thomson and his contemporaries.

While many scientists may believe in supernatural beings, as Thomson clearly did, they do not use these supernatural beings to answer questions about nature. While Thomson linked theological implications to his understanding of heat, he did not simply resort to “God did it”. This is not very different from our own lives. When our car breaks down, our first impulse is not to say, “a demon possessed my car”.

5. Why do you think even scientists who believe in the supernatural do not use the supernatural in their scientific explanations?

Micro level considerations, dealing with the interaction of tiny particles, provided other insights about the nature of the second law and entropy. Thomson and other physicists, including James Clerk Maxwell (1831-1879), wanted to know how the motion of microscopic particles could explain the second law. A key problem for these physicists was the reversibility of mechanical laws. Imagine water being poured out of a glass onto a table. After the water was spilled, if all the velocities of the water particles were reversed exactly, the water would gather back on the table and spring back into the glass. Such an action did not break any physical laws; however, no one ever observed such a peculiar action in nature. Water falling out of a glass
seemed to have a ‘natural direction’ just as heat had a ‘natural direction’ of moving from hot to cold. What then seemingly ‘guaranteed’ this directionality of micro-processes?

Maxwell addressed this question with a thought experiment, later called “Maxwell’s demon.” Imagine two separate containers, systems A and B, filled with particles moving at various velocities, bouncing off each other and the walls of their container chaotically. According to the dynamical theory of heat (and the kinetic theory of gases), the average velocity of the particles in a system is the temperature of that particular system. Next imagine that A and B are connected by a small door. This door remains open, allowing some particles to move back and forth between containers as they bounce around. Next imagine a small creature of high intelligence observed the containers and was able to control the opening and closing of the door (without any energy input into the system). This small demon would watch the particles bouncing around A and B. When he saw a particularly fast particle in A whiz towards the door, he would open the door to let it move from A to B. When he saw a particularly slow particle in B move towards the door, he would open it, allowing the particle to move from B to A. Over time, the average velocity of the particles would increase in B and decrease in A. Thus, the temperature of B would increase with no input of work or energy from the outside. This was in direct contradiction to the second law of thermodynamics, which, according to Clausius and Thomson, did not allow the unaided or spontaneous transfer of heat from cold bodies to hot bodies.

The explanation for this seeming contradiction again relied on the limits of human intelligence and perception. If humans could act like the ‘demon,’ then work could be recovered from cold bodies through this manipulation of individual particles. The second law thus wasn’t absolute; it was only a statistical likelihood, a function of human inability to control microscopic motions. Thus, water jumping off of a table, or heat moving from a cold body to hot body, was not absolutely impossible. It was just incredibly unlikely. The ‘natural’ direction of processes was only natural relative to human ability. In Clausius’s terms, entropy (inability to do work) could spontaneously decrease in a system, though such decrease was just as unlikely as heat flowing unaided from an ice cube to a furnace.

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Many people believe all scientists use “the scientific method”. Yet, in no version of the scientific method will you see “imagine a demon with a frictionless door”. Maxwell’s thought experiment is not unique. Scientists such as Einstein and Galileo have used thought experiments. Scientists are not limited to one scientific method, they will use any means necessary to gain greater understanding of the natural world, including imaginative thought experiments.

As the 19th century continued, the concept of entropy found applications in areas other than engineering. For example, entropy became a foundational concept for understanding chemical reactivity and thermochemistry. Entropy fully entered chemistry with the work of Josiah Willard Gibbs. Gibbs’s chemical thermodynamics treated entropy as an important property of a system, on the level of measurable properties like energy, pressure, temperature, etc. Gibbs, as well as Hermann von Helmholtz (independently), based chemical reactivity and thermodynamics on a quantity called “Gibbs energy,” or “free energy.” Gibbs energy (G), immortalized in the equation learned by many chemistry students, $G = H - T S$, depended not only on the heat of the reaction ($H$) but on the entropy change ($S$) as well. Spontaneous chemical reactions occurred when Gibbs energy was released. Thus scientists in various places and disciplines developed entropy from its beginnings as an engineering concern with engine efficiency to a general conception of a system’s capacity for work, from a statistical likelihood to a chemical concept useful on the laboratory bench.

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Many people wrongly believe that science is completely objective and leaves no room for creativity. How does this story illustrate that science is a creative endeavor?
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 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 of 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 what with 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.

To resolve this problem, Black measured the amount of time required to raise a certain amount of water from a known starting temperature to its boiling point. He also measured how long it took the water to boil away. Using these measurements, Black calculated the rate at which the temperature increased every minute. Assuming that heat entered the water at a constant rate, he could then determine the temperature the water would have reached during the time it was boiling if it somehow could avoid being turned into steam. Black's calculations indicated that the amount of heat entering the water to transform it into steam would be sufficient to raise the temperature of liquid water by 960°F. Black extended the concept of latent heat to freezing and melting as well. He noted that before completely melting, a piece of ice absorbed enough heat to raise a comparable volume of liquid water’s temperature by almost 140°F.

### 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 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 - that 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.
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 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 kitchens.

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 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.

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?
The Study of Matter:
What is the basic stuff of the universe?

Pre-reading Questions:
1. Why might scientific ideas change over time?

The question, "What is the basic stuff of the universe?" appears obvious. The answer most people have given through history is "look around—trees, soil, rocks, air, water—these are some of the basic substances in the universe. Philosophers in the sixth century B.C. were also looking around, but took a critical perspective, questioning whether we can always trust what we see. For instance, consider optical illusions; many examples exist showing how our senses often deceive us. Might what we see be deceptions that hide ultimate reality? The deep implication of the question "What is the basic stuff of the universe?" is that there may be more than what is obvious on first glance. It is a question that is still asked today.

The earliest explanations for what makes up matter came from primitive people's experiences with the world around them; rain and snow, hot and cold, sweet and sour, birth and death. While plants and animals were always being born, growing and dying, it seemed that the world remained much the same. The unknown causes for natural phenomena were assigned to the actions of gods and demons that were thought to control nature. Such myths helped primitive man explain events that could be seen but not rationally understood such as the creation of the world and why the seasons change.

Over time humans developed some control over their local environments, learning how to stay warm and dry, grow food and make tools. By 600 B.C., Greek philosophers began to create explanations for natural events that did not depend on the actions or the whims of gods, demons, or other mythical creatures. The earliest Greek philosophers believed that all the different things in the world were made out of a single substance. Some believed this fundamental substance to be water, some thought it to be air, while others favored fire. Yet none of these substances seemed to have enough properties to produce the enormous variety of substances in the world.

To better explain how simple substances could create all other matter, Empedocles proposed in 450 B.C. that four basic substances! earth, air, fire and water! are the fundamental units of all other matter. He argued that these four basic substances could combine, separate and recombine in various proportions to produce the many different types of matter we see around us. However, he maintained that the four basic materials, or elements, would persist through all of these changes. This is the first known model of matter in which all material objects are composed of a few basic elements.

Around 550 BC, Pythagoras (whom you likely associate with the Pythagorean Theorem) proposed a very different explanation for what is the basic stuff of the universe. He and his followers (called Pythagoreans) proposed that what we see is actually created out of something that is not material. They argued that numbers are the essence of all things and make up the ultimate reality that we see around us. As Aristotle later noted, "Those who are called Pythagoreans were the first to have an interest in mathematics... Because they were steeped in this science, they believed that its principles were the principles of all things..."

You are likely puzzled how numbers can be associated with physical reality. But consider the following: 1 is a point, 2 points make a line, 3 points result in an area (a plane), and 4 points creates three dimensions (a solid). Since everything has a shape, and shapes can be resolved into points, lines or surfaces which were created from numbers, numbers are the basis of our concrete reality. However, Pythagoreans still believed the four elements to be important as they were created from numbers.

2. Aristotle noted that the Pythagoreans saw numbers as the basis of reality because of their beliefs in the importance of numbers. How does a scientist's beliefs affect what possible explanations they may consider?

Around the same time that Empedocles was putting forth his explanation, the philosopher Leucippus and his student Democritus (Figure 1) proposed an atomic theory to explain the nature of matter. They noted that all objects can be broken down into something smaller, and that those smaller pieces can be broken down even further. Taken to its logical conclusion, the
ultimate components of reality are invisibly small things that are indivisible. Apart from those invisibly small things, the only thing left is the spaces between those indivisible small things. Hence, only two things make up ultimate reality — atoms (in Greek "Atom" means indivisible) and spaces between atoms (the void). Everything is reducible to that level. Note that unlike Pythagoras’ idea, Democritus and Leucippus maintain that the source of everything is material. Their model made further speculations about atoms.

Democritus’s Speculations about Atoms

- Atoms are invisibly small and indivisible portions of matter.
- Atoms move around in the void.
- Atoms, while made of a single primeval element, differ in their sizes and shapes.
- Atoms can combine in ways that may also separate back into the original individual atoms (this, they proposed, accounts for the observable changes we see in the world).
- Atoms combine and separate according to natural laws, which, while not understood in their time, do not require the actions of supernatural powers.

Aristotle would later argue against the existence of a void. He reasoned that if such a condition did exist, an atom in motion would have no opposing force and would thus have an infinite speed. Because infinite speed is unreasonable, he rejected the idea of a void and atoms with their continual motion. (Nearly 2000 years would pass before Torricelli in the 17th century would demonstrate that a vacuum could indeed exist). Aristotle argued that in addition to the four basic elements! Earth, Air, Fire and Water! all matter was also composed of four qualities! Cold, Hot, Moist and Dry. Unlike atoms and the void, his explanation had the advantage that it was based on things people could see or feel. Aristotle’s ideas, reflecting his significant influence in many areas of philosophy, would stand for the next two thousand years.

3. How might great respect for authority figures hinder the progress of science ideas?

During the 17th Century several important ideas emerged that undermined the authority of Aristotle. The Copernican and Newtonian revolutions showed much of Aristotelian thinking to be mistaken, and Torricelli demonstrated that a vacuum could indeed exist. In trying to understand the fundamental nature of matter, scientists once again were drawn to the idea that matter is composed of particles.

Reflecting this reconsideration that the ultimate stuff of reality is made up of material particles, Robert Boyle attempted to account for the relationship between pressure and volume in terms of "gas particles." In this same vein, Isaac Newton wrote that, "... it seems probable to me, that God in the Beginning form’d Matter in solid, massy, hard, impenetrable, moveable Particles ... and that these primitive Particles being Solids, are incomparably harder than any porous Bodies compounded of them; even so very hard, as never to wear or break in pieces...”

As you continue to read the story, note that scientific laws and scientific 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.

As the eighteenth century dawned, a coherent theory explaining the nature of matter emerged. However, the process was not straightforward and many claims were controversial. During the late 1700s several scientific laws regarding
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.

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.
Forty years after Proust’s proposal, in 1855 Heinrich Geissler invented a vacuum pump that could remove enough air from a glass tube to create conditions equivalent to 0.01 percent of normal atmospheric pressure. A friend of his placed metal electrodes at each end of such a glass tube, connected them to a battery, evacuated the air in the tube, and found that electricity would flow through the tube and the tube itself would glow a pale green color. In the 1870s, Sir William Crookes concluded that whatever caused the green glow seemed to come from the cathode (negative) end of the tube and travel in a straight line to the negative electrode and that these rays always had the same properties regardless of the type of metal used. This was interpreted to mean that the rays were due to something that was common between all metals. These phenomena were later named “cathode rays.”

Some scientists thought the cathode rays to be light because they exhibited some of the same properties that light displays (e.g. travels in straight lines, and produces chemical changes and fluorescent glows). However, earlier work had established that a magnetic field bends the path of positively charged particles in one direction and negatively charged particles in the opposite direction. Similarly, when the cathode rays were subjected to a magnetic field, they were bent in the same direction as negatively charged particles. Thus, many scientists thought cathode rays are streams of negatively charged particles. In 1891 the name ‘electron’ was given to these negatively charged particles.

However, despite these insights and significant contributions to understanding matter, many scientists (some among the most well respected in the history of science) still preferred to think that atoms were indivisible. In 1897, J.J. Thomson provided evidence that was interpreted by most all scientists that cathode rays were indeed negatively charged particles! what we call electrons. Thus the idea that atoms are indivisible, which originated with Greek philosophers some 2500 years ago and had been reaffirmed by John Dalton in his atomic theory of 1810, was replaced by an understanding that the atom is composed of even smaller structures.

Attention was now turned to developing a model of the internal structure of the atom that would account for the known properties of the atom. Given what was known at this time, proposed models needed to account for the following:

- negatively charged particles (electrons),
- positively charged particles (these were not yet identified, but assumed to exist because atoms were electrically neutral),
- the periodicity that Mendeleev had shown in developing the periodic table,
- the atomic volume and weight data,
- the characteristic spectra of light which are given off by each element (series spectra),
- why atoms are stable, and
- how molecules are formed.

Inventing a model to account for all this information is clearly a difficult task. In 1904 Nagoka proposed a nuclear model, similar in some ways to the one accepted today, where the electrons traveled in circular paths around a positively charged center. While his model accounted for the series of spectral emissions that characterized each element, it received little support because small forces, such as occur when two atoms collide, would cause an electron’s orbit to become unstable and thus destroy the atom.

In that same year, J.J. Thomson, realizing that the nuclear model was unstable, proposed what has been called the "plum-pudding" model. His model proposed that the atom was a sphere of positive charge with electrons embedded in rings within this charge. While Thomson’s model did account for much that was known about atoms at the time, it did not explain the series spectra produced by each element. However, Thomson’s immense reputation (He would later receive the Nobel in 1906 for his work on electrons), ensured that his model of the atom received widespread attention. Eventually, even Thompson’s model of the atom was replaced with alternative models that better explained new evidence. Although scientists no longer question the existence of atoms, modern scientists continue to ask the question, "What is the universe made of?"

6. Scientific knowledge has a durable character. That is, once ideas have been well established, they often work well for long periods of time. However, how does the story regarding the study of matter also indicate that all scientific knowledge also has a tentative character?

7. Science textbooks often give credit to one individual for a revolutionary idea and imply the idea came all at once. In what ways does this distort how science really advances?
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.

Data do not tell scientists what to think. Instead, scientists must try and make sense of their data. As you read this story, pay attention to how humans must creatively interpret data and develop patterns to account for data.

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.

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.

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

3. 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?
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

Public Domain Image

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?

Mendelev 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 – for instance, 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:

\[
\begin{align*}
F &= 19 \\
Cl &= 35 \\
Br &= 80 \\
I &= 127
\end{align*}
\]

The oxygen group of elements:

\[
\begin{align*}
O &= 16 \\
S &= 32 \\
Se &= 79 \\
Te &= 128
\end{align*}
\]

And the nitrogen group of elements:

\[
\begin{align*}
N &= 14 \\
P &= 41 \\
As &= 75 \\
Sb &= 122
\end{align*}
\]

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:

\[
\begin{align*}
F &= 19 \\
Cl &= 35 \\
Br &= 80 \\
I &= 127
\end{align*}
\]

\[
\begin{align*}
O &= 16 \\
S &= 32 \\
Se &= 79 \\
Te &= 128
\end{align*}
\]

\[
\begin{align*}
N &= 14 \\
P &= 41 \\
As &= 75 \\
Sb &= 122
\end{align*}
\]

2
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.

Many people enjoy solving puzzles, yet think they would not enjoy a science career. Mendeleev is trying all sorts of ideas to make sense of the data.

4. How is what Mendeleev is doing like solving a puzzle? How does his work illustrate that doing science requires creativity and imagination?

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.

Many people wrongly believe that a scientific theory will become a law once it is supported by enough evidence.

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.

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. Nilson isolated a rare earth metal that did not correspond to any known element. Nilson 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.

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 1918 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!
Again, note how scientific laws and theories are different, yet related kinds of claims about the natural world. Also note 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.

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?
A Matter of Degrees: The Struggle for a Standard Measure of Temperature

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?

In 1776, as the British empire struggled with its rebellious subjects for control over the American colonies, seven members of the Royal Society of London met to resolve a conflict. For more than a century, the Society’s membership had committed itself to the exploration of the natural world. The Society emphasized the value of quantitative measurements which could be used for mathematical analysis. Such an approach required standardized instruments whose measurements could be trusted. Although there was relative agreement about the accuracy of existing clocks, measuring sticks, and systems of weights, the British scientific community could not say the same about its thermometers. There was no established scale to measure temperature. Although the Royal Society had attempted to resolve this problem, by 1776, the matter remained unresolved until the commission established the boiling point of water as a standard reference point for future instruments.

This investigation hints at some of the problems which emerged when scientists began to think seriously about the study of heat. Unlike measurements such as length or mass, temperature is not based upon a visible phenomenon. Although we are born able to recognize the difference between hot and cold, we are unable to make any quantitative statements about temperature without a thermometer.

Many people think that science should be based on ordinary observation of phenomena. In fact, science teachers and textbooks often convey this notion. However, note that scientists working with heat and temperature are attempting to measure an unseen phenomenon.

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 gradated 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 Santorre, a professor of medicine at the University of Padua, took an interest in Galenic medicine. The physicist Galileo Galilei was a colleague of Santorio’s at Padua. Both Santorre and Galilei created instruments to indicate changes in temperature (Figure 1). Santorio 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
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.

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](image)

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.

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°.

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).
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.

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 C: VOSSI QUESTIONNAIRE

## Views on Science and Scientific Inquiry

For the 12 items below: 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. **Scientific Observations:**

<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>Scientists' observations of the same event may be different because the scientists' prior knowledge may affect their observations.</td>
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<tr>
<td>B.</td>
<td>Scientists' observations of the same event will be the same because scientists are unbiased.</td>
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<tr>
<td>C.</td>
<td>Scientists' observations of the same event will be the same because observations are facts.</td>
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<tr>
<td>D.</td>
<td>Scientists may make different interpretations based on the same observations.</td>
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</tbody>
</table>

Explain why you think scientists' observations and interpretations are the same OR different, and provide examples to support your answer.
2. Social and Cultural Influences on Science:

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

Explain how society and culture affect OR do not affect scientific research, and provide examples to support your answer.

3. Established science ideas:

<table>
<thead>
<tr>
<th></th>
<th>A. Previously well supported and established science ideas are not easily abandoned by scientists, even in the face of contradictory data.</th>
<th>D  U  A  S  A</th>
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<tbody>
<tr>
<td></td>
<td>B. Scientists should not be so resistant to abandon previously well supported and established ideas.</td>
<td>D  U  A  S  A</td>
</tr>
<tr>
<td></td>
<td>C. When data arises that contradicts a previously well supported and established science idea; that science idea is likely in need of modification or replacement.</td>
<td>D  U  A  S  A</td>
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<tr>
<td></td>
<td>D. When data arises that contradicts a previously well supported and established science idea; the problem likely lies with either the data, research that produced the data, or interpretation of that data.</td>
<td>D  U  A  S  A</td>
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Explain why you think a previously well supported and established science idea is usually or is usually not easily abandoned when contradictory data arises, and provide examples to support your answer.
### 4. Imagination and Creativity in Scientific Investigations:

<table>
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<th></th>
<th>Description</th>
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<th>D</th>
<th>U</th>
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<tbody>
<tr>
<td>A</td>
<td>Scientists use their imagination and creativity when they collect data.</td>
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<tr>
<td>B</td>
<td>Scientists use their imagination and creativity when they analyze and interpret data.</td>
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<tr>
<td>C</td>
<td>Scientists do <strong>not</strong> use their imagination and creativity because these conflict with their logical reasoning.</td>
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</tr>
<tr>
<td>D</td>
<td>Scientists do <strong>not</strong> use their imagination and creativity because these can interfere with the need to be unbiased.</td>
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Explain why scientists use OR do not use imagination and creativity, and provide examples to support your answer.

### 5. Methodology of Scientific Investigations:

<table>
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<tr>
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<th>Description</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>Considering what scientists actually do, there really is no such thing as the scientific method.</td>
<td></td>
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<tr>
<td>B</td>
<td>Scientists follow the same step-by-step scientific method.</td>
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<tr>
<td>C</td>
<td>When scientists use the scientific method correctly, their results are true and accurate.</td>
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<tr>
<td>D</td>
<td>Experiments are the only way scientists develop valid scientific knowledge when they investigate the natural world.</td>
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Explain whether scientists follow a single, universal scientific method OR use different types of methods, and provide examples to support your answer.
6. Social Interaction among Scientific Researchers:

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

7. Development and Acceptance of Science Ideas:

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<tbody>
<tr>
<td>A. Credible scientific ideas are usually generated 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. 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>C. Credible scientific ideas are usually generated over a period of years to decades.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
<tr>
<td>D. Scientific ideas usually come to be accepted by the scientific community over a period of years to decades.</td>
<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 then accepted by the scientific community, and provide examples to support your answer.
8. Scientific Knowledge:

| A. | Well supported and established scientific knowledge is subject to on-going testing and revision. | SD | D | U | A | SA |
| B. | Well supported and established scientific knowledge may be completely replaced by new ideas in light of new evidence. | SD | D | U | A | SA |
| C. | Well supported and established scientific knowledge may be changed because scientists reinterpret existing evidence. | SD | D | U | A | SA |
| D. | Well supported and established scientific knowledge based on accurate research will not change. | SD | D | U | A | SA |

Explain why you think well supported and established scientific knowledge changes OR does not change over time, and provide examples to support your answer.

9. Science Explanations:

| A. | The scientific community should be more open to the use of supernatural events or beings in scientific explanations. | SD | D | U | A | SA |
| B. | Supernatural explanations are not useful for helping scientists understand the natural world. | SD | D | U | A | SA |
| C. | Explaining natural phenomena without reference to the supernatural is necessary for advancing scientific knowledge. | SD | D | U | A | SA |
| D. | Scientists who will not use supernatural explanations when doing science can still believe in a supernatural being. | SD | D | U | A | SA |

Explain why supernatural explanations should OR should not be used in credible scientific ideas, and provide examples to support your answer.
10. Scientific Laws Compared to Theories:

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<tbody>
<tr>
<td>A.</td>
<td>Scientific theories exist in the natural world and are uncovered through scientific investigations.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
<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>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
</tbody>
</table>

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

11. Discovery and Invention:

In responding to the four items below, assume that a gold miner “discovers” gold while an author “invents” a story.

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</thead>
<tbody>
<tr>
<td>A.</td>
<td>Scientific theories (for example, atomic theory, plate-tectonic theory, gene theory) are discovered.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td>B.</td>
<td>Scientific laws (for example, laws of planetary motion, gas laws, gravitational law, law of pendulum motion) are discovered.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td>C.</td>
<td>Scientific theories (for example, atomic theory, plate-tectonic theory, gene theory) are invented.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td>D.</td>
<td>Scientific laws (for example, laws of planetary motion, gas laws, gravitational law, law of pendulum motion) are invented.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
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</tbody>
</table>

Explain whether scientific laws and theories are invented OR discovered, and provide examples to support your answer.
12. Science and Religion:

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<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>Science and religion are usually in conflict with one another.</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>B.</td>
<td>The truths of religion are not amendable to scientific investigation.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.</td>
<td>Science ideas that have religious implications usually set scientists who do believe in supernatural beings against those who do not believe in supernatural beings.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.</td>
<td>The truths of religion may comfortably coexist with the discoveries of modern science.</td>
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</tr>
</tbody>
</table>

Explain why science and religion are OR are not in conflict with one another, 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 in the future if needed. Your honest feedback is much appreciated.
APPENDIX D: SEMI-STRUCTURED INTERVIEW QUESTIONS

1. The National Science Education Standards includes learning about how science works and how science ideas are developed as a goal for secondary science education. How important do you think this goal is for secondary science classrooms?
   - For what reasons do you consider this (to be / not to be) an important goal for your classroom?
   - To what extent, if any, do you feel this goal is promoted in your classroom?
     - In what ways do you promote this goal in your classroom?
     - What obstacles, if any, have you faced trying to promote this goal?
     - How available have you found curricular materials for teaching about the nature of science?
       - How useful have you found these materials? (Why?)

2. How did you implement the student surveys in your classroom?
   - How much time was provided for students to complete the surveys?
   - Were both surveys given to students during the same class period?
   - What, if anything, did you do to ensure students took the surveys seriously?
   - In what ways, if any, were students held accountable for completing the surveys and taking them seriously?
   - To what extent do you think students took the surveys seriously and honestly answered the survey questions?

3. Which stories did you implement?
   - Why did you choose these particular stories and not others from the 7 you were provided?

4. When did you implement each of the readings you chose to utilize and how did you make this decision?
   - How did each story you used fit into your other classroom instruction and the units you were teaching?
   - I noticed during my observations, you used a story at (specify place within the unit or instruction). Why did you decide to use the story at that point?
   - What difficulties, if any, did you face deciding when to best implement a story?
5. **How did you implement the readings as part of your classroom instruction?**

- What procedures did you follow when implementing each story?
- In what ways was your implementation of the stories similar or different to other class activities you used during the year?
- During my observations, I noticed during your ____ class that you chose to (read the stories aloud / have students read individually / have students read in small groups). What influenced this decision?
- During my observations, I noticed during your _____ class that you chose to (have a whole class discussion about--- / have small group discussions about --- / not to discuss the embedded questions). What influenced this decision?
- What steps, if any, did you do to help students understand and make sense of the stories?
- In what ways, if any, did you hold students accountable for putting effort towards reading?
- In what ways, if any, did you hold students accountable for putting effort toward answering the embedded questions?
- What obstacles, if any, did you encounter when implementing the readings and/or having students answer the embedded questions?

6. **[for control/treatment teachers] What did you do during your control periods during the times you implemented stories in the treatment periods?**

- How did you decide what to do during the control periods?
- What difficulties, if any, did you face having to plan differently during the control and treatment class periods?
- In what way, if any, did having to plan for the control class periods impact how you decided to implement the stories in the treatment class periods?
- What might you have done differently if you were using the short stories in all your (biology / chemistry) class periods?

7. **What were your general impressions after utilizing the short stories?**

- What about the readings and their structure did you find helpful or useful?
- What difficulties did you face when implementing these stories?
- What changes to the readings or their structure would make the stories more useful to you?
8. In what ways, if any, do you think the readings impacted your students?
   - In what ways, if any, did the stories impact your students’ learning, interest, and understanding of the science content?
   - In what ways, if any, do you think the readings impacted your students’ learning, interest, and understanding of the nature of science?
   - In what ways, if any, the stories impact your students’ interest or participation in your class?

9. In what ways, if any, do you feel the readings impacted your own understanding of the nature of science?
   - What about the stories did you find useful in helping you clarify your ideas about the nature of science?
   - What other features or resources would you find beneficial for helping you come to better understand the nature of science?

10. To what extent are you interested in and willing to continue utilizing similar stories in your teaching?
    - For what reasons (are you / are you not) interesting in using these types of stories in the future?
      - What changes would make you more likely to utilize these types of stories in the future?
      - If multiple teachers in your department were using these stories, how would that impact your interest in using the readings as part of your classroom instruction?
    - What resources could we provide with the stories that you would you find helpful in future implementation of the stories?
    - If new stories were developed, what topics would you find beneficial?
APPENDIX E: STORY IMPLEMENTATION PROTOCOL AND RESEARCH DERIVED EXEMPLARS

**Story Implementation Evaluation Protocol**
Evaluation based on classroom observations and post-implementation interviews

1. **Concept Development**

<table>
<thead>
<tr>
<th></th>
<th>Not At All</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>To a Great Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Support for Understanding Reading</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>B. Support for Reflecting on NOS Ideas</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

**Synthesis Rating for Concept Development**

<table>
<thead>
<tr>
<th></th>
<th>Very Limited Concept Development</th>
<th>Concepts Developed to a Great Extent</th>
</tr>
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<tbody>
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<td>1</td>
<td>2</td>
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</table>

Justification:

2. **Student Accountability**

<table>
<thead>
<tr>
<th></th>
<th>Very Limited Student Accountability</th>
<th>Students Accountable to a Great Extent</th>
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</thead>
<tbody>
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<td>1</td>
<td>2</td>
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Justification:
### 3. Classroom Culture (Section of the LSC-COP)

<table>
<thead>
<tr>
<th></th>
<th>Not At All</th>
<th>To a Great Extent</th>
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<tbody>
<tr>
<td>A.</td>
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<td>2</td>
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<td>B.</td>
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<td>C.</td>
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<td>D.</td>
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<td>E.</td>
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<td>F.</td>
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<td>G.</td>
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<tr>
<td>H.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>I.</td>
<td>1</td>
<td>2</td>
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</tbody>
</table>

#### Synthesis Rating for Classroom Culture

<table>
<thead>
<tr>
<th>Classroom Culture Interfered with Student Learning</th>
<th>Classroom Culture Facilitating the Learning of All Students</th>
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</thead>
<tbody>
<tr>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
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</table>

**Justification:**
### Scoring Guidelines: Support for Understanding the Readings

<table>
<thead>
<tr>
<th>1. Concept Development</th>
<th>Not At All</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>To a Great Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Support for Understanding the Reading</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>• Teacher availability to support understanding</td>
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<tr>
<td>• Availability of peers to support understanding</td>
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<td>• Implementation within the unit</td>
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<td>• Time spent reading uninterrupted</td>
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<tr>
<td>• Additional reading strategies</td>
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#### Exemplars for score of 1
- The entire story was read out of class with no teacher guidance.
- Students read at home or the teacher was not present when students read in class.
- The story was read prior to teaching the relevant science content.
- Students read as homework or the entire story was read uninterrupted in class.
- Typically, no reading strategies were used with students to help them make sense of the reading.

#### Exemplars for score of 3
- Students typically read individually in class without support from group members or the teacher.
- Portions of the story were read at home without teacher guidance/support.
- The teacher was present when students read, but interaction with students was minimal.
- Content was taught simultaneously with utilization of the story.
- Time spent reading was broken up, but students still read for extended lengths of time (20+ minutes) without discussion or other activities.
- Additional reading strategies may have occasionally been used, but their use or effectiveness was limited.

#### Exemplars for score of 5
- The story was typically read in small groups or aloud by the teacher.
- The teacher was present and interacted with students to a large extent to help them make sense of the story and questions.
- Students had already been taught relevant science content prior to utilizing the story. This may involve splitting the story into sections to be interspersed with relevant content instruction prior to reading portions of the story.
- Extended periods of reading were avoided by interspersing discussion or other related activities.
- The teacher appropriately used reading strategies and created a learning environment conducive to helping students make sense of the reading.
### Scoring Guidelines: Support for Reflecting on NOS Ideas

<table>
<thead>
<tr>
<th>1. Concept Development</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Support for Reflecting on NOS Ideas</td>
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<td></td>
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<tr>
<td>• Students’ reflection on NOS questions</td>
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<tr>
<td>• Discussion of embedded questions</td>
<td></td>
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<tr>
<td>• Students’ communication of their NOS ideas</td>
<td></td>
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</tr>
<tr>
<td>• Teachers’ accurate portrayal of NOS</td>
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<tr>
<td>• Teacher questioning to increase student reflection.</td>
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</table>

#### Exemplars for score of 1
- Students may not have been expected to answer the embedded NOS questions.
- No group or whole class discussion of NOS or the embedded questions was utilized.
- Students only reflected on the stories/questions individually and did not have to communicate with others in the class regarding the NOS.
- The teacher may have inaccurately portrayed views of NOS ideas from the stories.
- The teacher did not question students regarding their responses to the NOS questions or questioning did little to encourage deeper thought about their responses.

#### Exemplars for score of 3
- Students must answer all the embedded NOS questions, but are typically not pushed to expand upon their initial answers.
- Implementation typically included either whole class or small group discussion of the NOS ideas from the stories.
- Students had to communicate their ideas regarding the reading/questions in pairs or small groups of students.
- The teacher did not expound upon the NOS views expressed in the stories during class discussion.
- The teacher occasionally used questioning to increase students’ reflection about their responses to the NOS questions.

#### Exemplars for score of 5
- Students’ initial answers are often challenged or expanded on through small group and/or whole class discussion.
- Implementation typically included both small group and class discussion of NOS ideas from the story.
- Students had to present and defend their ideas during whole class discussion and/or had to work towards consensus of ideas in small groups.
- The teacher portrayed accurate NOS views during discussion/class activities.
- The teacher extensively used questioning to increase students’ reflection about their responses to the NOS questions.
### Scoring Guidelines: Student Accountability

#### 2. Student Accountability

**Student Accountability:**
- NOS included on assessments
- Grading of embedded questions
- Expectation that students would participate in class/group discussion of the embedded questions.
- Teacher monitored students’ work on the reading/questions and discussion.

<table>
<thead>
<tr>
<th>Exemplars for score of 1</th>
<th>Exemplars for score of 3</th>
<th>Exemplars for score of 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOS was never included on summative assessments.</td>
<td>NOS concepts appear sporadically on summative assessments.</td>
<td>NOS concepts are frequently included on summative assessments.</td>
</tr>
<tr>
<td>Embedded questions were not collected.</td>
<td>Embedded questions were collected for a completion grade.</td>
<td>Embedded questions were graded for content of answers.</td>
</tr>
<tr>
<td>Lessons were structures such that all or most students could avoid participation in discussion of the NOS concepts in the story.</td>
<td>All students had to participate in small group discussion of NOS concepts from the story.</td>
<td>All students were expected to contribute ideas to whole class discussion of the NOS concepts in the story.</td>
</tr>
<tr>
<td>The teacher was not present or did not monitor students while they worked.</td>
<td>The teacher occasionally moved among students and monitored their on-task behavior/progress during individual and small group work.</td>
<td>The teacher extensively monitored students’ on-task behavior/progress and moved around the room among students during individual and small group work.</td>
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</tbody>
</table>
Views on Science and Scientific Inquiry – For Biology Classes

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. Scientific Observations:

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<tbody>
<tr>
<td>A. Scientists’ observations of the same event may be different because the scientists’ prior knowledge may affect their observations.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td>B. Scientists’ observations of the same event will be the same because scientists are unbiased.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td>C. Scientists’ observations of the same event will be the same because observations are facts.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td>D. Scientists may make different interpretations based on the same observations.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
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</tbody>
</table>

Explain why you think scientists’ observations and interpretations are the same OR different, and provide examples to support your answer.
### 2. 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>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Cultural values and expectations influence what science is conducted and accepted.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
<tr>
<td>C</td>
<td>Cultural values and expectations influence how science is conducted and accepted.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
<tr>
<td>D</td>
<td>All cultures conduct scientific research the same way because science is universal and independent of society and culture.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
</tbody>
</table>

Explain how society and culture affect OR do not affect scientific research, and **provide examples to support your answer.**

### 3. Imagination and Creativity in Scientific investigations:

<table>
<thead>
<tr>
<th></th>
<th>Scientists use their imagination and creativity when they collect data.</th>
<th>SD</th>
<th>D</th>
<th>U</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<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>
<td>A</td>
<td>SA</td>
</tr>
<tr>
<td>C</td>
<td>Scientists do <strong>not</strong> use their imagination and creativity because these conflict with their logical reasoning.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
<tr>
<td>D</td>
<td>Scientists do <strong>not</strong> 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>
<td>A</td>
<td>SA</td>
</tr>
</tbody>
</table>

Explain why scientists use OR do not use imagination and creativity, and **provide examples to support your answer.**
4. Methodology of Scientific Investigations:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Considering what scientists actually do, there really is no such thing as the scientific method.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>B.</td>
<td>Scientists follow the same step-by-step scientific method.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>C.</td>
<td>When scientists use the scientific method correctly, their results are true and accurate.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>D.</td>
<td>Experiments are the only way scientists develop valid scientific knowledge when they investigate the natural world.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
</tbody>
</table>

Explain whether scientists follow a single, universal scientific method OR use different types of methods, and provide examples to support your answer.

5. Development and Acceptance of Science Ideas:

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

<table>
<thead>
<tr>
<th>Option</th>
<th>SD</th>
<th>D</th>
<th>U</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. The scientific community should be more open to the use of supernatural events or beings in scientific explanations.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Supernatural explanations are not useful for helping scientists understand the natural world.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Explaining natural phenomena without reference to the supernatural is necessary for advancing scientific knowledge.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D. Scientists who will not use supernatural explanations when doing science can still believe in a supernatural being.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Explain why supernatural explanations should OR should not be used in credible scientific ideas, 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 G: VOSSI QUESTIONNAIRE FOR CHEMISTRY STUDENTS
Views on Science and Scientific Inquiry – For Chemistry Classes

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.

<table>
<thead>
<tr>
<th>SD</th>
<th>D</th>
<th>U</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly Disagree</td>
<td>Disagree More Than Agree</td>
<td>Uncertain or Not Sure</td>
<td>Agree More Than Disagree</td>
<td>Strongly Agree</td>
</tr>
</tbody>
</table>

1. Social and Cultural Influences on Science:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></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>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>B.</td>
<td>Cultural values and expectations influence what science is conducted and accepted.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>C.</td>
<td>Cultural values and expectations influence how science is conducted and accepted.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>D.</td>
<td>All cultures conduct scientific research the same way because science is universal and independent of society and culture.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
</tbody>
</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>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</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>
</tr>
<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>
</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>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Scientists <strong>usually</strong> 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 <strong>usually</strong> 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 <strong>usually</strong> work alone when conducting research.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>D.</td>
<td>Scientific knowledge <strong>usually</strong> emerges from discussions and social interactions among scientists.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
</tbody>
</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>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Credible scientific ideas are usually generated in a matter of days, weeks or months.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>B.</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>
</tr>
<tr>
<td>C.</td>
<td>Credible scientific ideas are usually generated over a period of years to decades.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>D.</td>
<td>Scientific ideas usually come to be accepted by the scientific community over a period of years to decades.</td>
<td>SD</td>
<td>D</td>
<td>U</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>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Well supported and established scientific knowledge is subject to on-going testing and revision.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>B.</td>
<td>Well supported and established scientific knowledge may be completely replaced by new ideas in light of new evidence.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>C.</td>
<td>Well supported and established scientific knowledge may be changed because scientists reinterpret existing evidence.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
</tr>
<tr>
<td>D.</td>
<td>Well supported and established scientific knowledge based on accurate research will not change.</td>
<td>SD</td>
<td>D</td>
<td>U</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.**
6. 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>SD</th>
<th>D</th>
<th>U</th>
<th>A</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Unlike theories, scientific laws are not subject to change.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
<tr>
<td>B.</td>
<td>Scientific laws are theories that have been proven.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
<tr>
<td>C.</td>
<td>Scientific theories explain scientific laws.</td>
<td>SD</td>
<td>D</td>
<td>U</td>
<td>A</td>
<td>SA</td>
</tr>
</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 H: STUDENT INTEREST AND ATTITUDE SURVEY 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.

<table>
<thead>
<tr>
<th>Biology</th>
<th>Chemistry</th>
</tr>
</thead>
</table>

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
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>J.</td>
<td>The really smart students don’t have to work hard to do well in school.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>K.</td>
<td>Reading is beneficial to me.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>L.</td>
<td>When learning science, I want to understand how to use the information we learn about.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>M.</td>
<td>If I do poorly on a test, it is likely the ideas were just too hard for me.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>N.</td>
<td>I enjoy reading outside of class-work and assignments.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>O.</td>
<td>When learning new information, relating it to experiences outside of class helps me.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>P.</td>
<td>Students who are “average” in school will remain “average” for the rest of their lives.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>Q.</td>
<td>Coming up with my own ways to solve problems in science class is a waste of time.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>R.</td>
<td>I find understanding what I read difficult.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>S.</td>
<td>I want to learn about the people who developed the ideas we learn in science class.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>T.</td>
<td>If I do well on a test, most likely I was just lucky.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>U.</td>
<td>Students should be tested on their understanding of not only science ideas, but also how scientists came to understand those ideas.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>V.</td>
<td>Reading does not help me learn.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
</tbody>
</table>
**W. The harder I work at preparing for a test, the more likely I am going to do well.**

<table>
<thead>
<tr>
<th>完全不同意</th>
<th>不同意</th>
<th>中立</th>
<th>同意</th>
<th>完全同意</th>
</tr>
</thead>
</table>

**X. I learn science best by memorizing information.**

<table>
<thead>
<tr>
<th>完全不同意</th>
<th>不同意</th>
<th>中立</th>
<th>同意</th>
<th>完全同意</th>
</tr>
</thead>
</table>

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

<table>
<thead>
<tr>
<th>完全不同意</th>
<th>不同意</th>
<th>中立</th>
<th>同意</th>
<th>完全同意</th>
</tr>
</thead>
</table>

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.

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>我完全没有兴趣</td>
<td>我不太感兴趣</td>
<td>我完全决定</td>
<td>我正在考虑</td>
<td>我非常确定</td>
</tr>
</tbody>
</table>

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 I: MULTI-ITEM INDICIES CONSTRUCTS FROM INTEREST AND ATTITUDE SURVEYS 1 AND 2

### Construct: Positive attitude towards reading

<table>
<thead>
<tr>
<th>Question</th>
<th>Item</th>
<th>Coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>I find reading enjoyable.</td>
<td>+</td>
</tr>
<tr>
<td>D</td>
<td>I find reading difficult. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>H</td>
<td>Reading is boring. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>K</td>
<td>Reading is beneficial to me.</td>
<td>+</td>
</tr>
<tr>
<td>N</td>
<td>I enjoy reading outside of class-work and assignments.</td>
<td>+</td>
</tr>
<tr>
<td>R</td>
<td>I find understanding what I read difficult. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>V</td>
<td>Reading does not help me learn. (reverse)</td>
<td>-</td>
</tr>
</tbody>
</table>

### Construct: Conception of effective science learning environment consistent with reformist views of science education.

<table>
<thead>
<tr>
<th>Question</th>
<th>Item</th>
<th>Coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Developing my own experiments in science class is a waste of my time. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>E</td>
<td>I learn better when we do a hands-on activity before a teacher explains a science idea.</td>
<td>+</td>
</tr>
<tr>
<td>G</td>
<td>When learning science, I want to understand how scientists developed science ideas.</td>
<td>+</td>
</tr>
<tr>
<td>I</td>
<td>When learning science, I only want to be told what facts I need to know for tests. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>L</td>
<td>When learning science, I want to understand how to use the information we learn about.</td>
<td>+</td>
</tr>
<tr>
<td>O</td>
<td>When learning new information, relating it to experiences outside of class helps me.</td>
<td>+</td>
</tr>
<tr>
<td>Q</td>
<td>Coming up with my own ways to solve problems in science class is a waste of time. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td>I want to learn about the people who developed ideas we learn in science class.</td>
<td>+</td>
</tr>
<tr>
<td>U</td>
<td>Students should be tested on their understanding of not only science ideas, but also how scientists came to understand those ideas.</td>
<td>+</td>
</tr>
<tr>
<td>X</td>
<td>I learn science best by memorizing information. (reverse)</td>
<td>-</td>
</tr>
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</table>

### Construct: Attributes Successes/Failures to Factors Within Their Control

<table>
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<tr>
<th>Question</th>
<th>Item</th>
<th>Coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>If I do poorly on a test, it is likely because I didn’t work hard enough to prepare.</td>
<td>+</td>
</tr>
<tr>
<td>F</td>
<td>Successful students understand things in class quickly. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>J</td>
<td>The really smart students don’t have to work hard to do well in school. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>M</td>
<td>If I do poorly on a test, it is likely the ideas were just too hard for me. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>P</td>
<td>Students who are “average” in school will remain “average” for the rest of their lives. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>T</td>
<td>If I do well on a test, most likely I was just lucky. (reverse)</td>
<td>-</td>
</tr>
<tr>
<td>W</td>
<td>The harder I work at preparing for a test, the more likely I am</td>
<td>+</td>
</tr>
<tr>
<td>going to do well.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>If I do poorly on a test, it is likely the teacher did not teach well.</td>
<td></td>
<td></td>
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<tr>
<td>- (reverse)</td>
<td></td>
<td></td>
</tr>
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APPENDIX J: BIOLOGY INTEREST AND ATTITUDE SURVEY 2
Interest/Attitude Survey Part 2 (Biology 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.

1. The readings your teacher utilized this semester may have included:
   - One or two readings about the structure of DNA
   - One or two readings about the age of the earth
   - A reading about the work of Mendel
   - A reading about the work of Darwin
   - A reading about global warming

   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

2. Please explain what you liked about these readings:

3. Please explain what you did not like about these readings:
4. 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

5. 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

6. 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

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? 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.)

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? 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.

9. 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
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.

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Completely Agree</th>
</tr>
</thead>
</table>

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

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Completely Agree</th>
</tr>
</thead>
</table>

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

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Completely Agree</th>
</tr>
</thead>
</table>

D. I find reading difficult.

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
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</tr>
</thead>
</table>

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

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Completely Agree</th>
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</thead>
</table>

F. Successful students understand things in class quickly.

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
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</tr>
</thead>
</table>

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

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
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</thead>
</table>

H. Reading is boring.

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
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</table>

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

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
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J. The really smart students don’t have to work hard to do well in school.

<table>
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<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
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<th>Somewhat Agree</th>
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</table>

K. Reading is beneficial to me.

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Completely Agree</th>
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L. When learning science, I want to understand how to use the information we learn about.

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Completely Agree</th>
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M. If I do poorly on a test, it is likely the ideas were just too hard for me.

<table>
<thead>
<tr>
<th>Completely Disagree</th>
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<td>N. I enjoy reading outside of class-work and assignments.</td>
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<td>Students who are &quot;average&quot; in school will remain &quot;average&quot; for the rest of their lives.</td>
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<td>R.</td>
<td>I find understanding what I read difficult.</td>
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<td>I want to learn about the people who developed the ideas we learn in science class.</td>
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<td>T.</td>
<td>If I do well on a test, most likely I was just lucky.</td>
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<td>V.</td>
<td>Reading does not help me learn.</td>
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<td>The harder I work at preparing for a test, the more likely I am going to do well.</td>
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<tr>
<td>X.</td>
<td>I learn science best by memorizing information.</td>
<td></td>
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<tr>
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<td>Completely Disagree</td>
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<td>Y.</td>
<td>If I do poorly on a test, it is likely the teacher did not teach well.</td>
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<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
</tbody>
</table>
11. 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.

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

13. 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 K: CHEMISTRY INTEREST AND ATTITUDE SURVEY 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.

1. 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

2. Please explain what you liked about these readings:

3. Please explain what you did not like about these readings:
4. 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

5. 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

6. 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

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? 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.)

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? 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.

9. 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
10. Please read statements A - Y below.
Mark an X in ONLY ONE BOX to indicate your level of agreement with each statement.

<p>| | | | | |</p>
<table>
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<tr>
<th></th>
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<tbody>
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<td>I find reading enjoyable.</td>
<td>Completely Disagree</td>
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<td>Developing my own experiments in science class is a waste of time.</td>
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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>
<td>Completely Disagree</td>
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<td>D.</td>
<td>I find reading difficult.</td>
<td>Completely Disagree</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>Successful students understand things in class quickly.</td>
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<td>Completely Disagree</td>
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<td>L.</td>
<td>When learning science, I want to understand how to use the information we learn about.</td>
<td>Completely Disagree</td>
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<td>N.</td>
<td>I enjoy reading outside of class-work and assignments.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>V.</td>
<td>Reading does not help me learn.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>W.</td>
<td>The harder I work at preparing for a test, the more likely I am going to do well.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>X.</td>
<td>I learn science best by memorizing information.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
<tr>
<td>Y.</td>
<td>If I do poorly on a test, it is likely the teacher did not teach well.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
</tr>
</tbody>
</table>
11. 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.

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

13. 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 L: CONTROL INTEREST AND ATTITUDE SURVEY 2
**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>
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A. I find reading enjoyable.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Completely Disagree</td>
<td>Somewhat Disagree</td>
<td>Neutral</td>
<td>Somewhat Agree</td>
<td>Completely Agree</td>
</tr>
</tbody>
</table>

   | 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 |

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

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Completely Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>! of goal should not be a goal of HS science classes.</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>! of goal should be of little importance in HS science classes.</td>
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<td></td>
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<tr>
<td>! of goal should be somewhat important in HS science classes.</td>
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<td></td>
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<tr>
<td>! of goal should be important in HS science classes.</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>! of goal should be extremely important in HS science classes.</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Completely Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Completely Agree</th>
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<tbody>
<tr>
<td>I have absolutely no interest at all in a science-related career.</td>
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<tr>
<td>I have very little interest in a science-related career.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I am completely undecided about my interest in a science-related career.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I am considering a science or science-related career.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I am absolutely sure I want to pursue a science-related career.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
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.