Historical short stories in the post-secondary biology classroom: Investigation of instructor and student use and views

by

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THANKS AND DEDICATION

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I want to dedicate this work to my son, Lincoln. I have so much hope for you and cannot wait to see what you do with your life. I hope you find your passion as I have found mine. I also want to dedicate this work to my former middle school and high school students. You inspired me each and every day I worked with you. I know the memories we shared will continue to be a source of motivation for me as I work with future teachers. Thank you.

ABSTRACT

This study investigated the use of five historically accurate short stories in a post-secondary introductory biology course. The stories were designed to include both high levels of science content as well as explicitly attend students to nature of science ideas through bulleted points and reflective questions embedded within the stories. The stories targeted fundamental science ideas including: age of the earth, biological evolution, and genetics.

Through mostly qualitative methods, student and instructor use and views of the short stories were investigated. That is, this study investigated 1) how the stories were implemented in a post-secondary biology course, 2) instructor views of the stories, 3) student views of the stories, and 4) how students interpreted the stories. Data sources included course observations and artifacts, student homework, student questionnaires, and instructor interviews. Data was analyzed to produce substantive categories or rich descriptions.

Findings from the study are used to support several conclusions. First, most students are able to accurately interpret historical short stories that are designed to explicitly draw students' attention to nature of science (NOS) ideas. Second, use of the historical short stories increases students' reported interest in science careers. Third, the nuanced and contextual nature of NOS poses significant problems for student understanding of NOS in light of students' inaccurate conceptual frameworks. Finally, instructor use of the historical short stories is highly linked to the instructor's perceived value of the short stories and NOS more generally.

These findings have implications for science educators and curriculum designers. Design of historical materials must take an explicit/reflective approach to NOS inclusion. Furthermore, curricular materials need to somehow address students' prior thinking before

introducing contextual episodes. Additionally, historical curricular materials ought be included in science content course to stimulate and retain student interest in science. However, effort must be turned toward helping science content teachers understand the benefit of including history and nature of science in their courses.

CHAPTER 1: GENERAL INTRODUCTION

Scientific Literacy

> The phrase "scientific literacy for all learners" expresses the major goal of science education—to attain society's aspirations and advance individual development within the context of science and technology. Certainly, most science educators rally around this statement because it embodies the highest and most admirable goals of science teaching. But what does it actually mean? (Bybee, 1997, p. 70).

While scientific literacy has become the central goal of science education, defining scientific literacy has been inherently difficult. Scientific literacy first emerged out of the social climate of the 1960s and 70s. With concerns of equity and access, educators pushed for science education that applied not only to individuals planning to enter a scientific field. Situated under the larger umbrellas of progressivism of the 1950s and new progressivism of the 1970s, "scientific literacy" was used to focus the science curriculum on socially relevant issues with instructional methods catering to individual students needs and interests (DeBoer, 1991). Yet the term lacked utility due to lack of precision.

While scientific literacy moved to the forefront during the 1960s and 70s, the term's origins can be traced to Paul Dehart Hurd of Stanford University in 1958 (DeBoer, 1991). Hurd focused on understanding science and its societal applications. He claimed that, "More than a casual acquaintance with scientific forces and phenomena is essential for effective citizenship today. Science instruction can no longer be regarded as an intellectual luxury for the select few" (Hurd, 1958, p. 13).

Despite this original focus on connections to societal issues, scientists and science educators have often viewed improved scientific literacy as higher levels of content or greater familiarity with a specific area of scientific inquiry. Yet, science educators have added dimension beyond content knowledge including: knowledge necessary to read and understand science that appeared in popular culture and familiarity with scientific processes. In 1967 Milton Pella searched 100 science education articles for how the term "scientific literacy" was used. Milton found six variations on the term. The categories are listed below from most to least common (DeBoer, 1991):

1. Interrelations between science and society
2. Ethics of science
3. Nature of science
4. Conceptual knowledge
5. Science and technology
6. Science in the humanities

As time went on, despite the multiple dimensions above, science teachers continued to implement science instruction aimed at acquisition of science facts that were organized around the concepts of the science disciplines. Yet, efforts to create more connected and applicable science learning continued. The Science-Technology-Society movement of the 1980s sought to make explicit connections to science learning and the ability to consider societal concerns as well as every day decision-making (DeBoer, 1991).

As the goals for science education were debated and refined over many years, "scientific literacy" has come to be a possible point of confusion. Importantly, scientific literacy is multifaceted — reflecting the manner in which science is carried out and the pervasive influence of science in our lives. The *National Science Education Standards' (NSES)* accentuate these diverse dimensions to scientific literacy. The *Standards* state:

> An essential aspect of scientific literacy is greater knowledge and understanding of science subject matter, that is, the knowledge specifically associated with the physical, life, and earth science. Scientific literacy also includes understanding the nature of

> science, the scientific enterprise, and the role of science in society and personal life (NRC, 1996, p. 21).

While the *Standards* provide a useful, multifaceted definition of scientific literacy, Bybee (1997) notes that educators often omit aspects of the document. Bybee (1997) goes on to state that the use of “scientific literacy” implies more general education rather than specific education used for science programs. Despite the efforts of professional organizations and individual science educators to articulate a robust definition of scientific literacy, the term in practice is often relegated to memorizing extensive lists of science “facts”, solving problems using algorithms, discipline specific instruction, and following predetermined laboratory procedures. All of these issues conspire to misrepresent what authentic science is like.

The role of Nature of Science in Scientific Literacy

Nature of science (NOS) refers to the “values and assumptions inherent to the development of scientific knowledge” (Lederman and Zeidler, 1989), the epistemic and ontological stance with which scientists approach investigations of the natural world (Matthews, 1994), and how society impacts and is impacted by science (Clough, 2006). While science education reform efforts emphasize the need for students to understand science concepts central to each discipline, they also place significant importance on understanding the history and nature of science.

> Scientific literacy also includes understanding the nature of science, the scientific enterprise, and the role of science in society and personal life. The *Standards* recognize that many individuals have contributed to the traditions of science and that, in historical perspective, science has been practiced in many different cultures. Science is a way of knowing that is characterized by empirical criteria, logical argument, and skeptical review. Students should develop an understanding of what

> science is, what science is not, what science can and cannot do, and how science contributes to culture (National Research Council, 1996, p. 21)

Additionally, the *Standards* note "students need to understand that science reflects its history and is an ongoing, changing enterprise" (NRC, 1996, p. 107).

In *Benchmarks for Science Literacy* (1993), the American Association for the Advancement of Science articulates the interaction between understanding both science content and nature of science for more complete scientific literacy.

> Acquiring scientific knowledge about how the world works does not necessarily lead to an understanding of how science itself works, and neither does knowledge of the philosophy and sociology of science alone lead to a scientific understanding of the world. The challenge for educators is to weave these different aspects of science together so that they reinforce one another (The Nature of Science, Paragraph 2, accessed 10/25/10).

The *Benchmarks* also more forcefully provide rationale for students to understand how science works.

> When people know how scientists go about their work and reach scientific conclusions, and what the limitations of such conclusions are, they are more likely to react thoughtfully to scientific claims and less likely to reject them out of hand or accept them uncritically (The Nature of Science, Paragraph 1, accessed 10/25/10).

Effectively Teaching the Nature of Science

Like all content to be taught, clearly conceptualizing what ought to be taught is a first step to effective instruction. Some specific nature of science ideas that ought to be explicitly taught in the science classroom include (NSTA, 2000; McComas, Clough, Almazroa, 1998; Moore, 1983; McComas, 2004; McComas & Olson, 1998; Abd-El-Khalick et al, 1998; Clough, 2007; Kruse, 2008):

- Science requires creativity and imagination
- Science relies on methodological naturalism

- Science affects and is affected by society, culture and politics
- Science is a highly social endeavor
- While science and technology impact each other, basic science is not concerned with practical outcomes
- Scientific theories and laws are distinct ways of knowing
- Scientific knowledge is both durable and tentative

Regardless of intent, science teachers always convey messages concerning NOS (Clough & Olson, 2004). The language and activities teachers use during instruction carries powerful implicit messages (Dibbs, 1982; Benson, 1984; Lederman, 1986b; Zeidler & Lederman, 1989). When focusing solely on end products of science, using cookbook activities, and misusing words with specific scientific meaning, teachers send inaccurate messages about how science works. For example, when students have, by and large, only completed step-by-step laboratory activities, they are likely to use these experiences to create or hold onto the misconception that a universal scientific method exists. Thus, science teachers do not have the luxury of choosing whether to convey messages about the NOS, only whether to portray NOS accurately.

Students walk into classrooms with many other misconceptions regarding NOS. Both students and teachers develop these misconceptions from years of inaccurate implicit and explicit instruction as well as inaccurate messages that dominate popular media regarding NOS. Common misconceptions include: with enough evidence theories become laws, scientific laws are unchanging, an ahistorical universal scientific method exists, science is not creative, science can answer all questions, scientists are objective, all science is experimental, science is a solitary endeavor, science and technology are the same, and many more

(Chiappetta & Koballa, 2004; Abd-El-Khalick & Lederman, 2000a; McComas, 1998; Clough, 1995: Lederman, 1992; Ryan and Aikenhead, 1992). These misconceptions are not surprising given the way science is often taught in both secondary and post-secondary education. DeBoer, (1991) compares cookbook labs, common instructor and textbook language to the positivist philosophy that dominated the early 20th century, but is no longer accepted by philosophers of science. This overstatement of physical evidence leading to answers wrongly removes the creativity and social aspects of the scientific endeavor.

Even though students enter the classroom with so many misconceptions, simple memorization of NOS ideas is counterproductive. Rather than providing students with a list of tenets to be memorized, teachers must confront students' deeply held beliefs about how science works. Teachers who emphasize tenets of NOS may inadvertently encourage students to superficially recall those ideas rather than understand the rich complexity that NOS entails (Clough, 2007). When designing NOS instruction to develop deep understanding, teachers must consider how students assimilate new ideas into mental structures. Simply telling students how science works or having them read about science is not enough (Rowe & Holland, 1990; Saunders, 1992). Teachers must find out what their students are thinking and design activities that lead students to more accurate understanding (Clough, Clark & Berg, 2000). Students cannot be indoctrinated into understanding the nature of science. Even in model classrooms, long-term conceptual change can prove difficult (Clough, 1995).

Activities to help teachers accurately address the nature of science have typically included "black-box" type activities (Lederman & Abd-El-Khalick, 1998). Such activities are not designed to teach students about science content, yet work well to engage students in

NOS discussion. Additionally, inquiry-based science content instruction more accurately models an accurate nature of science. However, inquiry alone is not enough! Abd-El-Khalick & Lederman (2000a) have noted the need to explicitly draw students' attention to the nature of science and have students reflect on NOS concepts. Simply having students read about or even perform activities that accurately portray the nature of science are not enough to counter the years of inaccurate portrayals that students have experienced.

Clough (2006) has added to the explicit/reflective suggestions for effective nature of science instruction by noting the importance of scaffolding students' thinking about NOS ideas. Clough maintains that reflecting on their own classroom experiences is not enough for students to deeply understand subtle nuances of NOS. Beyond modifying classroom activities, inclusion of the history of science encourages students to further develop and internalize accurate NOS understandings (Clough, 2006; NRC, 1996).

Using the History of Science to Teach Nature of Science

The inclusion of historical and contemporary science examples in science education has long been promoted (Conant, 1957; Klopfer & Cooley, 1963; Matthews, 1994; Clough, 1997, 2004; Abd-El-Khalick, 1999; Lonesbury & Ellis, 2002). The AAAS (1990) claims, "Generalizations about how the scientific enterprise operates would be empty without concrete examples" (p. 145). Lonesbury & Ellis (2002) note the utility of the history of science for providing these concrete examples. Matthews (1994) asserts that history is necessary to understand not only nature of science, but also science content. Clough (2006) notes that students are less likely to disbelieve accurate NOS ideas when they are tied to the workings of authentic scientists, and teachers are more likely to incorporate history and nature of science instruction when it is tied to the content they already teach.

While empirical studies concerning the use of historical materials to teach NOS have had some success (Klopfer & Cooley, 1963; Lonesbury & Ellis, 2002), problems with historical materials have been noted (Tao, 2003). Moreover, science teachers at all levels resist using many laudable history and nature of science materials because of the time they take from science content instruction. Thus, more extensive work is needed in developing historical materials that address NOS concepts that will be implemented by teachers. Research should be undertaken to understand how teachers use such materials, how students' NOS conceptions are affected by these kinds of materials and how use of these materials might be improved.

Purpose of study

This study investigates the use of historical short stories (ranging from 4-7 pages) designed for use in introductory college-level science courses. This study and the development of the science historical short stories have been supported, in part, by a grant from the National Science Foundation (Clough, Olson, Stanley, Colbert & Cervato, 2006). The purpose of this study is to describe how five historical stories were implemented in a post-secondary introductory biology class, the instructor's perspectives on the stories and their implementation, and student struggles to accurately interpret the stories.

Instructional Materials

Historically accurate short stories that focus on the development of fundamental science concepts were designed as part of the aforementioned NSF grant. The short stories are designed to provide accurate accounts of how ideas are generated and eventually accepted by the scientific community, and explicitly draw students' attention to key NOS ideas and have them reflect on the NOS. Five short stories were incorporated into the biology course in this study. Two short stories focus on the scientific community's early struggles to determine the age of the Earth, two others focus on the early development of ideas regarding biological evolution, and the fifth addresses early efforts to understand how genetic traits are passed from one generation to the next.

The stories were designed taking into account what previous research has indicated is important for effective NOS instruction. The stories accurately portray actual scientists doing science. The stories contain bullet points and embedded questions that draw students' attention to NOS ideas and ask them to reflect on how the story illustrates specific aspects of the NOS. Furthermore, the stories are designed to be rich in science content appropriate for introductory biology students.

Research Questions

This study intends to answer the following research questions.

1. How were five historical short stories implemented in a post-secondary introductory biology course for biology majors?
    a. What were the general teaching practices exhibited by the biology instructor?
    b. How were the short stories implemented by the biology instructor?

c. In what ways was NOS addressed beyond the short stories?

2. What are the biology instructor's impressions of the short stories after having implemented them in his course?

3. What are the students' impressions of the short stories and what impact do students report the HSS have on their NOS understanding and interest in pursuing a science career?

4. To what extent and in what ways do students' misinterpret the historical short stories?

Methodological Overview

Five historical short stories were implemented within an introductory post secondary biology course at a large Midwestern university. The lecture included 156 students who are typically pursuing a science related degree. All course sessions were observed or videotaped and field notes taken regarding instructional practices. Students were assigned the five short stories throughout the semester as each story's science concepts were discussed. Students were asked to return typed, hardcopy answers to the embedded short story questions. Near the end of the semester-long course, the students completed two anonymous questionnaires seeking their views regarding the short stories. After completion of the course, the professor was interviewed on two separate occasions regarding their views of the short stories. Using the data collected (class session field notes, student responses to short story questions, student questionnaire responses and instructor interview transcripts) this study sought to generate descriptive themes to answer the research questions.

To understand how the short stories were implemented and to inform other areas of data analysis, field notes and classroom artifacts were read and descriptive themes were generated concerning general classroom conduct as well as themes related to short story implementation. These descriptions were considered when trying to understand the origins of students' problematic language as well as when working to make recommendations for improving both the short stories and the short story implementation.

Transcripts from instructor interviews were read and grouped into large chunks of text pertaining to related topics. Each of these chunks was read and initial codes were generated. Initial codes were grouped into common themes. Then, chunks of text were reread and coded related to the identified themes. Then thematic texts were grouped and read together to develop greater insight and thematic detail.

Qualitative analysis was used to develop descriptions of students' problematic interpretations of the historical short stories. Each student response was read and, using open-coding (Strauss and Corbin, 1998), student misconceptions or inaccurate interpretations were given a descriptive label. Once all student responses hade been read for a given question, the open-codes were reduced into common axial codes. Inaccurate student responses were then reread and placed into axial coded groups. Students were also asked to complete a Likert scale questionnaire concerning their experience with the short stories and how the short stories affected their disposition toward science careers. This data was analyzed using descriptive statistics and one-sample t-tests when appropriate.

Data analysis will depend largely on researcher understanding of NOS and views of HOS materials. Therefore, chapter two explores how the researcher, with reference to the extensive science education literature regarding NOS, conceptualizes NOS. Additionally, both philosophical and empirical work regarding HOS will be explored. The discussion of HOS, NOS, and their intersection ought provide important perspective and transparency concerning the researcher's conceptual framework that will impact researcher interpretation of data. Additional limitations of this study are explored further in chapter three.

CHAPTER 2: REVIEW OF LITERATURE

Scientific Literacy

Scientific literacy has become the central goal of science education, yet remains an illusive construct in both concept and practice. Reacting to the social climate of the 1960s and 70s, educators pushed for science education that applied to more than individuals planning to enter a scientific field. Rather than strict preparation of future scientists, the notion of "scientific literacy" focused the science curriculum on socially relevant issues with instructional methods catering to individual students needs and interests (DeBoer, 1991).

Tracing "scientific literacy" back to 1958, Paul Dehard Hurd of Stanford University focused on understanding science and its societal applications (DeBoer, 1991). He claimed that, "More than a casual acquaintance with scientific forces and phenomena is essential for effective citizenship today. Science instruction can no longer be regarded as an intellectual luxury for the select few" (Hurd, 1958, p. 13). Scientific literacy was becoming a necessity for all, not just future scientists.

The original focus on societal issues is often lost in translation. Many scientists and science educators view increased scientific literacy as higher levels of content or greater familiarity with a specific area of scientific inquiry. The imprecision of "scientific literacy" is not a new problem. In 1967 Milton Pella searched 100 science education articles for how the term "scientific literacy" was used. Milton found six variations on the term listed below from most to least common (DeBoer, 1991):

1. Interrelations between science and society
2. Ethics of science
3. Nature of science

4. Conceptual knowledge
5. Science and technology
6. Science in the humanities

Although several variations of scientific literacy existed in the literature, science literacy in practice has continued to implement science instruction aimed at acquisition of science and organize curriculum around the concepts of the science disciplines. Yet, efforts to link science learning to societal issues continued. The Science-Technology-Society movement of the 1980s and 90s (Yager, 1996) sought to make explicit connections to science learning and the ability to consider societal concerns as well as every day decision-making (DeBoer, 1991).

Consensus concerning scientific literacy has been elusive and uses of the term may cause confusion. Yet, adopting robust notions of scientific literacy are important for guiding science education reform. Importantly, scientific literacy is multifaceted -- reflecting the manner in which science is carried out and the pervasive influence of science in our lives. The *National Science Education Standards' (NSES)* succinctly discuss these diverse dimensions to scientific literacy. The *Standards* state:

> An essential aspect of scientific literacy is greater knowledge and understanding of science subject matter, that is, the knowledge specifically associated with the physical, life, and earth science. Scientific literacy also includes understanding the nature of science, the scientific enterprise, and the role of science in society and personal life (NRC, 1996, p. 21).

No longer should science coursework be concerned only with science content. Instead, Bybee (1997) notes how the use of "scientific literacy" implies more general education rather than specific education used for science programs.

Despite these efforts of professional organizations and individual science educators to articulate a robust definition of scientific literacy, the term in practice is often relegated to memorizing extensive lists of science “facts”, solving problems using algorithms, discipline specific instruction, and following predetermined laboratory procedures. While the *Standards* (1996) provide a useful, multifaceted definition of scientific literacy, Bybee (1997) notes that educators often omit aspects of the document. These omissions often misrepresent what authentic science is like. As the AAAS (2009) notes, “Acquiring scientific knowledge about how the world works does not necessarily lead to an understanding of how science itself works…”. Science content instruction is not enough. Explicit attention must be given during science instruction toward encouraging students to understand how science works.

Understanding how science works includes understanding the processes, assumptions, logic, and norms of science. That is, scientifically literate students must come to understand the nature(s) of science (NOS). Understanding NOS helps students understand “how science tends to differ from other modes of knowing” (AAAS, 2009). Despite being called for in science education literature, NOS has not been a main emphasis of science classrooms (Dodick & Orion, 2003).

Nature of Science in Science Education

The science education community’s conceptualization of ‘nature of science’ (NOS) has changed over the last several decades (Abd-El-Khalick and Lederman, 2000; Duschl, 1985) moving from process skills to including characteristics of scientific knowledge and most recently to include social and psychological factors (Tao, 2003). Yet, “although the ‘nature of science’ has been defined in numerous ways, it most commonly refers to the values and assumptions inherent to the development of scientific knowledge” (Lederman, 1992, p. 331). More completely, McComas (2008) summarizes NOS:

> …as a hybrid domain which blends aspects of various social studies of science including the history, sociology and philosophy of science combined with research from the cognitive sciences such as psychology into a rich description of science; how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors (p. 249-250).

This study was carried out from a postpositivist perspective in which scientific ideas are the result of creativity and invention on the part of scientists; observations are theory-laden; the work of science is influenced by social factors; scientists base their ideas on their observations, but prior knowledge and logic are just as important; scientists use a variety of methods to investigate nature; scientists’ methods and ideas fit within paradigms that govern normal scientific research; and science ideas or even paradigm structures can be modified (Bauer, 1992; Palmquist & Finely, 1997; Kuhn, 1962; Schwab, 1962). This view is carefully situated between positivism’s over-reliance on observation to the point of naïve empiricism and postmodernism’s view that the universe is “unreliable in its behavior and incapable of being understood” (Longbottom and Butler, 1999, p. 482). While these succinct definitions and positions are useful, some explanation and exploration of nuances are worth discussing as examples to illustrate the complexities inherent in NOS aspects.

The “values and assumptions” noted by Lederman (1992) include ontological and epistemological stances characteristic to the modern scientific enterprise (Matthews, 1994). The ontological shift of the scientific revolution has slowly marched scientific reasoning away from mysticism and egocentrism. Strictly speaking, science does not deny the claims of the mystic, but finds them of little use in reaching scientific conclusions (Gould, 1999).

This adherence to methodological naturalism has been undeniably useful in science, but does not necessitate scientists or students adopt ontological materialism. By highlighting the limits of science, or presenting science as bounded (Southerland et. al., 2006) science educators give students a “place to stand” to better compare ways of knowing (Scharmann, 1990).

In addition to limits of what the scientific enterprise counts as valid knowledge, NOS understanding requires consideration of how such knowledge comes to be generated and validated, or the epistemology of science. Rather than the adherence to dogma or submission to authority that characterizes many traditional epistemologies, the epistemology of science relies on empirical evidence, theoretically testable ideas, and an “awareness of alternatives to the established body of theoretical tenets” (Horton, 1971, p. 153). That is, science ideas are always open to modification based on new evidence or new interpretations of evidence. However, modifications to existing paradigms do not proceed in a straightforward manner (Kuhn, 1962). While science ideas are always open to change, there is a sense of authority structure and adherence to dogma within a particular paradigm until a new paradigm replaces the old. While the potentiality that all science ideas can change is a well-accepted aspect of NOS in the science education community, how science ideas change is a complex and contextualized process.

One further example may help to illustrate how complex aspects of NOS can be. The socially and culturally embedded nature of science is a common goal of NOS instruction. This aspect of NOS explores how scientists’ work is affected by the greater society both in how they research and in what they decide to research. Yet, if one were to take a postmodern perspective, one could say that scientific knowledge is simply socially constructed ideas with little connection to the real world, if a real world exists beyond the mind. While postmodernism has philosophical merit for important social critique, humanity's ability to design products and accurately make prediction based on scientific knowledge would indicate that there is greater validity in scientific knowledge than obvious socially constructed ideas like race or gender. Importantly, this discussion is not to say that natural science is superior to social science, only that natural science seems to be both affected by culture and to transcend culture. Therefore, both naïve realism and pure social constructionism pose problems when trying to understand NOS. Deeply understanding NOS requires wrestling within these "murky waters".

Clough (2006) notes that while many aspects of NOS are uncontroversial, others are "more contextual with important and complex exceptions" (Clough, 2006, p. 463). While contextual variances of NOS are often embedded in the history and progression of scientific thinking or the differences among scientific disciplines, some differing views of NOS are rooted in ideological and political agendas rather than deep reflection on the work of actual scientists. Importantly, even the supposedly uncontroversial ideas regarding how science works are fraught with nuance. In reflection of these contextualized differences and the nuanced nature of NOS, this paper has adopted, as have other researchers (Abd-El-Khalick and Lederman, 2000), the phrase "NOS" rather then the more aesthetic "the NOS".

Despite some disagreement and subtle nuances, well-accepted ideas worth teaching about NOS exist. A range of ideas worth teaching about the nature of science have been proposed (Abd-El-Khalick, *et al.*, 1998; Clough, 2007; NSTA, 2000; McComas 1998; McComas et. al., 1998; McComas & Olson, 1998; Driver et. al, 1996; Osborne et. al, 2003). These ideas were synthesized into the list below (Kruse, 2008, p. 16):

- Scientific knowledge is tentative, yet durable.
- Science includes both a sense of discovery and requires invention.
- Scientists are human beings who are influenced by the wider culture, their prior thinking, and other factors beyond the drive to understand the natural world.
- Basic science, applied science, and technology are distinct, yet related, endeavors that influence each other greatly.
- Science adopts methodological naturalism resulting in rejection of supernatural explanations as scientific. Yet, by limiting itself to theoretically empirically testable ideas, science makes no claim about the existence of supernatural beings.
- While science relies on empirical evidence, scientists must make meaning of data using theory and creativity to interpret evidence.
- No universal scientific method exists. While "the scientific method" seems like a useful problem solving method, when looking at what scientists actually do/did, there is little reason to think that all scientists use(d) the same "method".
- Absolute proof is elusive – scientists cannot know if their ideas are correct, but in some cases can gain overwhelming evidence supporting their ideas leaving little room for doubt.
- Scientific theories and laws are different, yet related, kinds of knowledge. Theories do not become laws because they serve a different and more encompassing purpose for understanding the natural world.
- Scientific models are useful for working through problems and testing ideas. Models may be representations of what scientists think to be reality or may be a heuristic device for furthering understanding and research.

Importantly, deep understanding of NOS requires knowledge of the complexity and context of the ideas listed above rather than simply being able to repeat 'tenets' concerning how science works (Clough, 2007). Moreover, taking an essentialist view of science in which a single set of tenets can accurately describe all of science activity is unreasonable (Eflin et. al., 1999). While some disagreement exists regarding the philosophy of science, these issues are characteristic of any field in which inquiry is on going. For the sake of science education, using a well-established set of ideas regarding how science works is necessary for pragmatic reasons. Though Alters' (1997) efforts to better understand the NOS landscape by seeking the views of philosophers of science may have been well-intentioned, his quantitative methods are simply inappropriate for gaining insight into the complex nature of the philosophy of science. Furthermore, expecting secondary or introductory science students to wrestle with the same nuances as actual philosophers of science is unreasonable. As Matthews (1998, p. 168) notes, "It is unrealistic to expect students or prospective teachers to become competent historians, sociologists, or philosophers of science". Instead, like the fundamental science content ideas, students of science ought to be engaged with understanding the nuances of fundamental, well-accepted ideas concerning how science works. That is, NOS ideas ought be explored rather than simply "learned".

While the disagreement among philosophers of science Alters (1997) points out is very real and expected, other groups have put forth NOS ideas to serve ideological or political agendas. While these ideas ought not inform science educators, their influence is undeniable. One widely known instance of inaccurate NOS ideas being put forth were the Kansas State Standards by the Kansas Stated Board of Education (Staver, 1999). In this document, the state board proposed that "Historic science, which includes the study of past events such as the origin of life and the universe is not good science because these ideas are not testable, as the past is not verifiable, falsifiable, or repeatable" (Staver, 1999). This item is a direct attack on the fundamental science idea, evolution, and exemplifies the need for a nuanced understanding of the NOS. While the historic sciences are not repeatable in the sense that scientists can rewind history, the claims of historic science are falsifiable through prediction and additional evidence. In addition to other inaccurate claims about how science works, the Kansas State Standards claim "scientific law is considered to be more important than scientific theory" (Staver, 1999). Unfortunately, this misconception is wide spread and often stems from the belief that scientific theories become laws with additional evidence or acceptance. Importantly, scientific theories and laws are intricately tied to one another - *each* serving important purposes in scientists' understanding of the natural world.

Despite the ideological disagreements and the ambiguity present at the frontiers of the philosophy of science research field, the consensus views regarding NOS in the science education community must be harnessed to meet students developmental needs (Eflin et. al., 1999). While the agreed upon ideas ought not become NOS dogma (Clough, 2007), the accepted ideas regarding NOS will provide both direction and an anchor to inform NOS instruction.

Rationales for Including NOS in Science Curricula

Combating widespread ignorance is perhaps the most fundamental reason for including NOS in science curricula. When compared to consensus views of NOS, studies continue to demonstrate that students and teachers have inaccurate views of NOS (Aikenhead and Ryan, 1991; Duschl, 1990; Mackay, 1971; Rubba et. al., 1981; Zeidler and Lederman, 1987; Lederman, 1992). Perhaps some would say, "Ignorance is bliss" and see little problem with students misunderstanding NOS. Fortunately, many other arguments have been made in the nearly 100 years NOS has been advocated for in science education (Abd-El-Khalick, Bell, & Lederman, 1998). Hodson (2009) argues that inclusion of aspects of NOS may

> enable all students to leave school with a robust knowledge about the nature of scientific inquiry and theory building, an understanding of the role and status of scientific knowledge, and ability to understand the use the language of science appropriately and effectively, the capacity to analyze, synthesize and evaluate knowledge claims, some insight into the sociocultural, economic and political factors that impact the priorities and conduct of science, a developing capacity to deal with the moral-ethical issues that attend some scientific and technological developments, and some experience of conducting authentic scientific investigations for themselves and by themselves." (Hodson, 2009, p. 18).

While Hodson's rationale is succinct, exploring facets of his and others' rationale in more detail may provide greater insight. NOS is a crucial aspect of scientific literacy (AAAS, 2009; NRC, 1996) - providing insight into the process, not just the products, of the scientific endeavor. Furthermore, increased understanding of NOS ideas is not only linked to increased understanding of science content, but better understanding of how science interacts with wider culture. NOS understanding not only contributes to scientific literacy, but to cultural literacy.

In our technologically and scientifically advanced society, basic understanding of fundamental science ideas is necessary to make informed decisions. However, deep understanding of these fundamental science ideas cannot be fully attained with insufficient NOS understanding (Matthews, 1994). For example, understanding the laws of pendulum motion make little sense unless the notion of idealization in science is well understood. Without the philosophical logic of idealization, the pendulum laws are nonsensical as anyone can release two pendulums of equal length, but different mass and see the periods do not match. However, in an idealized case in which point masses are used, the laws would hold true. In order to make the laws of pendulum motion applicable throughout the universe, idealization is necessary. Without deeply understanding the nature of science and the role of idealization, deeply understanding how the laws of pendulum motion relate to the natural world would be extremely difficult.

Beyond improving content learning, understanding NOS is part of being an informed citizen. Informed contribution to democratic dialogue regarding science requires understanding the NOS (AAAS, 1989; Driver et al., 1996; Millar and Osborne, 1998; NRC, 1996; OECD, 2001; Winchester, 1989). More specifically, consideration of socioscientific issues requires NOS understanding (Abd-El-Khalick, 2003; Kolsto, 2001; Millar and Wynne, 1988; Ryder, 2001). Millar and Wynne (1988), when examining non-scientist statements about the Chernobyl accident highlight the need for just as much emphasis on the "process by which scientific knowledge is generated and validated" as the traditional content of science (p. 395). Another detrimental misconception related to democratic dialogue is the appropriation of public funds. Many people assume all science must directly relate to new technological development. This assumption could stifle the scientific enterprise and negates the role of basic science in expanding our understanding of the natural world.

Understanding the role of basic research requires understanding how scientists go about doing science, or the process of science. The "process of science" contrasts with the "products of science" or understanding scientific concepts. While the "products of science" are often the focus of science education, they are but one aspect of science (Carey & Strauss, 1970). Scientifically literate individuals must understand how scientific knowledge is generated. That is, students ought to learn the tactics and strategies used by scientists

(Conant, 1957). Better understanding how scientists work may illuminate the curiosity, creativity and human sides of science.

In addition to better understanding the process of science, increased understanding of NOS ideas is also purported to decrease resistance to controversial science ideas such as evolution (Scharmann and Harris, 1992; Sinatra & Southerland, 2003). Rudolph and Stewart (1998) state that understanding biological evolution requires:

> students to become familiar with the metaphysical assumptions and methodological process that Darwin laid out. Theoretical context and scientific practice, in this view, are not just interdependent, but really two views of a single entity. (p. 1085)

Johnson and Peeples (1987) found that college biology students' acceptance of evolution was dependent on their understanding of what science is and how science works. Many of these "controversies" are rooted in perceived conflict between accepted scientific ideas and religious beliefs. Inclusion of NOS instruction alongside content instruction may alleviate this internal conflict. "By involving students in explicit nature of science activities which illustrate the boundaries of science, they can begin to see that an acceptance of a scientific theory does not eliminate the existence of a supernatural entity" (Martin-Hansen, 2008, p. 318). Scientifically literate students understand the limits of science, that science cannot answer questions of the supernatural or the ethical. That is, scientific literate individuals ought understand science provides insight useful in manipulating the natural world; however, science makes no claims concerning if we *should* manipulate the natural world.

Unfortunately, the clash of worldviews, rooted in misconceptions of NOS, affects more than students' acceptance of scientific ideas. Worldview conflict may result in misunderstanding fundamental science ideas (Coburn, 1991; Pintrich et al., 1993; Schnieder & Pressley, 1989). That is, students may inaccurately conceptualize scientific concepts when they assimilate scientific teaching into non-scientific worldviews. For example, students might believe aquatic fossils found on land to be evidence of a catastrophic flood. Beyond concept assimilation, perceived worldview conflict may affect students' motivation to learn science (Garner, 1990). Through explicit NOS instruction, students can be encouraged to understand how diverse worldviews can coexist (Gould, 1999). If we avoid these philosophical issues, the dominance of one worldview in a person's mind complicates instruction (Martin-Hansen, 2008). Rather than negating traditional worldviews of various cultures, NOS instruction illuminates the importance of culture in science. Understanding NOS draws out the intricacies of the scientific culture and its relationship to wider cultures. Helping students navigate the differences in various epistemologies may prevent lumping together of different ways of knowing – preventing the perceived conflict that arises in science classrooms (Martin-Hansen, 2008).

Beyond avoiding unnecessary conflict and highlighting the human side of science, NOS instruction may increase student interest in science. Tobias (1991) followed well-qualified and successful science students who opted out of science education as they took college science courses. She reports that these students found science classes to be lacking historical, philosophical and sociological perspectives that created an unpalatable atmosphere. By including historical and philosophical perspectives, students are likely to gain a more accurate picture of what science is like. Seeing that science is a human endeavor in which creativity and collaboration are essential may help the "second tier" find more authentic interest in science.

Perhaps most compelling for including accurate portrayals of NOS in science education is the fact that messages about how science works are present in *all* science instruction (Clough and Olson, 2004). That is, a view of NOS is portrayed in the hidden science curriculum of teacher actions, assumptions and language (Hodson, 1986; Irwin, 2000; Kolsto, 2008; Munby, 1976). The question science educators must really address is whether the dominant messages about science are accurate. When science teachers use cookbook, step-by-step laboratory procedures they are not leaving out NOS, they are inaccurately portraying NOS. In addition to the kinds of activities teachers use, the language teachers use sends messages about NOS (Munby, 1976; Ziedler and Lederman, 1989). Because messages about NOS are always present in science instruction, teachers ought pay careful attention to both the explicit and implicit messages they are sending students.

While the many reasons above ought be compelling enough to include NOS in science education, some fringe arguments exist against NOS inclusion. While Alters (1997) raised concerns about what ought be taught concerning NOS, Davson-Galle (2008) questions whether NOS ought be included at all. Considering the previously mentioned notion that some portrayal of NOS is always present (Clough & Olson, 2004), Davson-Galle's notion that leaving out NOS as an option is problematic, yet the argument is carefully aimed at philosophy of science rather than nature of science. Although Davson-Galle is not specifically questioning NOS inclusion and calls NOS "intellectually passive", the arguments against philosophy of science are worth considering.

Davson-Galle's (2008) most prominent argument is to question whether there is enough benefit to either the individual or society to outweigh losing freedom of choice to forced learning. Perhaps this argument is better aimed at more traditional science content. What benefit is there for the individual or society in all students knowing the names of continental plate boundaries? Considering the technological and scientific society in which we live, understanding the process, assumptions and worldview of scientists through engaging in basic philosophy of science will better prepare students to make informed decisions in both their personal life and as part of a democratic society (Driver et. el 1996).

While Davson-Galle is aiming his argument at more esoteric philosophy of science rather than nature of science, deep understanding of NOS ideas requires students to engage in some philosophical wrestling with ideas. As Clough (2007) notes, memorizing NOS tenets does not equate to robust, useful understanding. While Davson-Galle calls NOS "intellectually passive", teachers can encourage students to deeply mentally engage with the ideas by addressing NOS issues as questions to be explored rather than tenets to be learned (Clough, 2007). While students might easily accept being told that science relies on evidence, they might struggle when being asked, "How do scientists gain confidence in their ideas?" Such a question also illuminates how NOS ideas are interconnected as evidence, social systems, and coherence of ideas all play a part in validating knowledge claims. Understanding these interconnections requires more than passive consideration of how science works. Although, Davson-Galle (2008) views NOS as intellectually passive, teachers can create learning situations in which students mentally wrestle with NOS ideas (Clough, 1997; Clough and Olson, 2001; Kruse, 2008).

In summary, Davson-Galle's (2008) arguments are well intentioned but misplaced. Not including NOS instruction because it is "intellectually passive" seems to be a question of pedagogy, not of content. Sacrificing freedom of choice seems to be more a question of compulsory schooling than science curriculum.

While Davson-Galle's arguments may be misdirected, the above discussion sheds light on a pervasive problem in all of science education: pedagogy. Unfortunately, when approaching instruction on NOS, many instructors use traditional, expository methods. Perhaps narrative is a more compelling manner in which NOS ideas can be illuminated. Martin and Brouwer (1991) note:

> A problem with the formal, expository delivery of philosophy of science topics is that it presupposes that the student already holds considerable knowledge of science and philosophy. Yet the kernel of many of the ideas about the epistemology of science can be communicated – at least tacitly – through story and anecdote (p. 713).

Rationales for History of Science in Science Education

Including the history of science (HOS) in science education may be used to illuminate the human side of science. Knowing how scientists have worked to generate what is known about the natural world can demonstrate the idiosyncratic way in which human understanding has changed over time. Seeing the contextual, philosophical and human sides of science may provide affective motivation for many students who do not find science inherently interesting (Metz, 2003: Tobias, 1990).

While increasing student interest is a compelling rationale for HOS inclusion, perhaps most pertinent to this study are arguments that history of science inclusion aids in the teaching and learning of NOS (Clough, 2006; Kolsto, 2008; Irwin, 2000; Matthews, 1994; Monk and Osborne, 1997; Bauer, 1992). The history of science provides highly contextualized episodes in which NOS ideas can be drawn out (Clough, 2006). Specifically, HOS can provide insight into procedural, contextual, and conceptual aspects of science (Klopfer, 1969); the “how” of science, not just the “what” (Kyle, 1997). That is, students can better understand how scientists investigate their questions, how the cultural climate influences such investigations, and how science ideas have been conceptualized and changed over time. By exploring the history of science, students come to see science as more than a collection of facts isolated from society (Chamany et.al., 2008). Through history, students may come to see that our current "collection of facts" is but a stepping-stone. As Brauer (1992) notes:

> Through learning textbook science, one is misled about the nature of scientific activity by learning only about relatively successful science, the things that have remained within science up to the present. In scientific texts, one hardly ever encounters the phenomenon of unsuccessful science, and yet history teaches that the science being done at any given time will largely be discarded, even in the short space of a few years, as unsuccessful. (p. 11).

Because the history of science can offer context useful to draw out NOS ideas (Kolsto, 2008), rationales for HOS inclusion often mirror rationales for NOS inclusion. Kolsto (2008) notes how science-society historical interactions may better enable participation in democratic societies. Furthermore, including the history of science may increase student interest in science by illuminating the social side of science (Irwin, 2000; Thomsen, 1998). When students are able to identify with the stories of real scientists emotional and affective connections are made (Klassen, 2006). Students "may be comforted by the fact that each discovery was not achieved alone" (Chamany et. al., 2008). By highlighting the human side of science and providing instructional variation, HOS provides motivation for students (Holton, 1995; Millar and Osborne, 1998; Shamos, 1995). Heilbron (2002) even notes that inclusion of inspirational HOS may inspire the next generation of students and that "those who rise the furthest tend to have broader culture than those who remain at the bench" (p. 328).

More generally, incorporating HOS in science instruction better prepares students for the interdisciplinary nature of 21st century problems (NRC, 2005). By gaining an interest in the humanities and developing a well-rounded education, students will likely be better problem solvers (Heilbron, 2002). These statements mirror Conant's (1957) goal to help students in the humanities or the social sciences "relate developments in the natural sciences to those in other fields of human activity" (Irwin, 2000, p. 8).

Traditionally, science instructors have been most interested in improving student understanding of science content. Importantly, "learning about the history of science might help students to improve their general understanding of science" (NRC, 1996, p. 200). Some evidence suggests HOS may improve student understanding of science concepts (Galili and Hazan, 2000; Lin, 1998) or, at the very least, not interfere with content learning (Irwin, 2000). Millar and Osborne (1998) propose that the use of narrative in science teaching (as HOS materials are normally found) aids in making ideas coherent, memorable and meaningful – results most conducive to long-term learning of science.

Interest and motivation are important mediators in learning (Pintrich et al, 1993) and HOS inclusion may improve students' motivation regarding science learning (Meyling, 1997; Metz, 2003) and attitudes toward science (Allchin et al., 1999). Many students might believe they are inherently bad at science and knowing that real scientists struggled to make meaning of observations may encourage them to continue striving to learn material. Seeing scientists as fallible, imperfect human beings encourages students to air their own misconceptions, take risks, and ask questions (Chamany et.al., 2008).

Beyond encouraging students, including history of science in science instruction may help students integrate science learning more deeply. All students enter instruction with existing schema rooted in personal and cultural experiences (Vygotsky, 1978; Ausubel et. al., 1978). Learning is dependent on prior conceptual frameworks (Hodson, 1988). Any new learning must be integrated into or added to these schemas or frameworks. When students study the historical context in which science ideas are developed they can make greater connections to experiences and studies outside of science coursework (Chamany, et. al., 2008; Lattuca et. al., 2004). Rather than making connections only to previous science learning, historical context encourages student to make interdisciplinary connections. Klassen (2006) notes the importance of context in creating mental connections:

> New information is always connected to similar information where conceptual overlap or context is the dominant factor. By this path of reasoning one arrives at the importance of context to the learning process, since information cannot exist in isolation in long-term memory and, even in the reasoning process, there are constant attempts to make connections among concepts (p. 34).

In addition to providing context, exposure to past science ideas may help students understand new science ideas. For example, “exposure to old astronomy can materially assist students of modern astronomy’ (Heilbron, 2002, p. 322). That is, making sense of past ideas my aid in making sense of current ideas. Not only do historical perspectives aid in learning about new ideas, increasingly new ideas are generated from analysis of historical data. Geology, paleontology and evolutionary biology are heavily rooted in historical data. Ignoring history ignores methods scientists use to study the natural world.

While many scholars in science education focus on the rich content HOS episodes necessarily contain, this focus may, in part, be due to pressures from content focused science departments to leave out HOS & NOS because it is seen as extraneous. While noting how HOS & NOS inclusion aids in content understanding is valuable, if we take NOS understanding as inherently valuable, Irwin (2000) notes that an advantage of using HOS to teach about NOS is that historical episodes involve concepts “more likely to be within the compass of the student” (p. 8). Yet, in the same study, Irwin (2000) provides evidence that student understanding of traditional content is not diminished by inclusion of lessons from

HOS and NOS. Irwin is not alone in noting how using HOS may make NOS more accessible. Kolsto (2008) describes how academic science, as opposed to post-academic science will "have a better chance of becoming transparent to the learner, and thus provide insights" (p. 988).

One last rationale for including HOS in the classroom deserves mentioning. Some have indicated that the conceptual hurdles of scientists may at times resemble the learning hurdles encountered by students (Wandersee, 1992, 1985; Monk and Osborne, 1997, Campanario, 2002). While this view makes some intuitive sense, caution must be used before assuming students will piece together their own scientific understandings in the same way scientists have historically. Getting students to think like scientists from a different time presents problems (Abd-El-Khalick and Lederman, 2000), and the likelihood of student naïve mental models resembling historical models is slim. Instead of using the history of science to scaffold student learning of science, the author suggests using the history of science as a source of *possible* naïve ideas and an opportunity to demonstrate to students how science changes - as do students' ideas - and that learning takes time and hard work – whether a scientist or a student.

Suggestions for Effective Inclusion of HOS in Science Education

Importantly, including HOS in the science classroom must be done with care. As with science content instruction, inappropriate HOS instruction may reinforce students' misconceptions regarding how science works. While historical resources are available, oftentimes these resources do not tell a story about science that "historians and philosophers of science would prefer that children hear" (Stinner et al., 2003, p. 626). These undesirable

HOS resources often take the shape of short excerpts appearing as text boxes in textbooks. These text boxes usually highlight single scientists, are only biographical in nature, and do not discuss the contextual nature of the scientist's work. Unfortunately, these text boxes or other superficial inclusion of historical perspectives usually reinforce students' misconceptions about how science works. Simply including HOS does not necessarily result in the benefits of HOS inclusion outlined above. Therefore, careful consideration as to how to integrate HOS with science instruction is crucial.

First of all, historical examples or episodes should not be superficial. Simply mentioning historical figures does not convey the deep contextual nature of knowledge development. In other words, for HOS inclusion to be useful, inclusion must be more than surface deep. As Heilbron (2002) notes,

> the history of science has an important, even a fundamental role to play in science education. Unfortunately, its most conspicuous current use is as a sugar coating to the hard nuts of the real curriculum (p. 321).

Historical examples ought "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). Historical narratives with sufficient depth provide opportunities to draw out complex and nuanced NOS ideas. Using superficial historical episodes likely results in superficial or inaccurate NOS understanding. As Matthews (1994) notes, "where quasi-history is substituted for history, the power of history to inform the present is nullified" (p. 75).

Perhaps more important than avoiding superficial accounts, is the need for educators to avoid "fictionalized idealizations" of historical accounts (Monk and Osborne, 1997, p.406). Oftentimes textbooks paint idealistic pictures of scientific progress. Yet, science is not simply “triumphant discovery” or “pathological error” (Allchin, 2000). Avoiding these idealizations or cookbook histories is difficult. Unfortunately, few science educators have formal training in the history of science (Chamany et. al., 2008).

Adding to the difficulty of maintaining accuracy is the need for students to understand the historical episodes (Kolsto, 2008). While inclusion of high-level content is desired, student confusion about the HOS, NOS, or science content may be exacerbated by overly complex historical examples. To help scaffold student NOS/HOS understanding alongside their science content studies, HOS ought be integrated throughout students’ science education experiences (Duschl, 1988, 1990; Hodson, 1988). By integrating HOS study, more sophisticated examples may be used as student science content and NOS understanding increases.

To aid in integrating HOS instruction through out science education, some have suggested including HOS via case studies (Bybee, 2002; Stinner et al., 2003; Heilbron, 2002). These case studies should be modular so that they can be employed alongside pertinent science content (Heilbron, 2002). Comparison of such case studies can be used to draw out subtleties concerning how science works or even how NOS changes in context (Kolsto, 2008). Because case studies slip easily into courses, science teachers, whose most prevalent concern is science content, are more likely to make use of such materials. To further aid in encouraging use by content oriented instructors, the primary purpose of these case studies ought not be history (Heilbron, 2002). Epistemological and methodological lessons should be strive for, but not at the expense of watered down science content.

History is Not Enough – NOS Pedagogy

Simply including HOS case studies or examples within science courses is not enough for students to develop accurate NOS views. As Klopfer (1969) noted, "adequate time should be allowed for discussion so that the subtle understandings in the historical narrative may be fully developed" (p. 93). Abd-El-Khalick and Lederman (2000) provided empirical support for Klopfer's statement when they studied the views of students enrolled in college-level HOS courses. Importantly, these students did not improve their NOS views and some seemed to reinforce their misconceptions by misinterpreting the HOS examples to which they had been exposed. Clearly, and quite expectedly, HOS is not enough to combat the many years of inaccurate messages students are sent by traditional schooling and media outlets. After studying the NOS literature concerning attempts to improve NOS understanding, Abd-El-Khalick and Lederman (2000) concluded that a key component of successful NOS instruction was to explicitly draw students attention to NOS ideas and encourage students to reflect on their NOS understanding. This important insight had been alluded to by prior science education research (Klopfer, 1969; Carey & Strauss, 1970; Kimball, 1967; Robinson, 1965, 1969; Wood, 1972; Russell, 1981; Carey et. al., 1989) and has become a staple suggestion for NOS instruction.

Coming to understand the deep complexities of NOS, as with all learning, requires mental effort. "Learning is…a sense-making activity by the learner, whereby she or he tries to accommodate new information into existing mental structures" (Klassen, 2006, p.33). Simply including HOS episodes or examples in science courses will not necessarily lead to desired accommodation. Explicit NOS instruction is needed to encourage students to challenge their own thinking about NOS (Akerson & Abd-El-Khalick, 2003; Clough, 1998; Lederman & Abd-El-Khalick, 1998).

In addition to paying close attention to student thinking, NOS instruction must account for students' level of mental development. While HOS stories are useful for drawing out subtleties in NOS, the stories are highly abstract and ask students to think about the experience of other people. For greatest effect, scaffolding to historical episodes must be carefully planned (Clough, 2006). Without appropriate experiences on which students can reflect and to which students can make connections, more detailed and nuanced NOS instruction my not be fully understood.

Clough (2006) confronts the challenge to NOS learning by drawing on conceptual change theory (Posner, et. al., 1982). As with other science content, students must first become dissatisfied with their inaccurate ideas and new ideas must be intelligible, plausible and fruitful. This original conception of conceptual change was limited to student cognition and did not account for motivational factors. Abd-El-Khalick and Akerson (2004) outline controversies with the conceptual change model. The author agrees with their conclusion that some critiques were not useful (e.g. Cobern, 1996) and others helped to illuminate addition factors affecting learning in addition to cognitive factors (e.g. Pintrich et al., 1993). Through critique of the original model, a "hot" conceptual change model came to be accepted in which students' motivation, dissatisfaction with prior ideas, and ability to understand new ideas all play a role in learning. Importantly, despite all the critiques, the original conception of learning remained unchanged and additional motivational factors moderated by "activating" or "blocking" fundamental cognitive processes.

Clough (2006) makes use of the cognitive aspects of the conceptual change model to propose the utility in scaffolding between decontextualized, moderately contextualized and highly contextualized NOS activities and curricular materials to create dissatisfaction with naïve conceptions and introduce more plausible conceptions of NOS. He uses the term "contextualized" to denote the level of association an activity has with real science. A decontextualized activity might serve to accurately model the thought processes of scientists, but is clearly not science. For example, a magic trick can help students understand methodological naturalism, but scientists do not study magic tricks. Other examples of decontextualized activites are well documented (Lederman and Abd-El-Khalick, 1998; NRC, 1996). These activities provide students with concrete experience divorced of science content on which they can reflect during NOS discussion, but are easily dismissed by students as not reflecting real science and by teachers as not containing enough science content.

Clough's (2006) next level of instruction, moderately contextualized, includes activities such as laboratory investigations. By using inquiry-based laboratories students investigate natural phenomena. Like the decontextualized activities, students are required to think like scientists. However, while students investigate natural phenomena, their investigations are not identical to those scientists conduct. Students do not have the deep background knowledge a practicing scientist does, nor do they have access to the same resources. Furthermore, scientists do not have a teacher asking carefully crafted questions to help spark ideas and make connections. Because of these differences, students may still dismiss inquiry-based laboratory experiences as contrived experiences in which answers are already known.

Last in Clough's (2006) continuum are highly contextualized activities in which students learn about the work of real scientists. Students might read the writings of real scientists or read/hear stories about the work of real scientists while teachers ask questions that have students reflecting on the NOS issues inherent in the stories. Because these activities or curricular materials use real science episodes, students are less likely to dismiss the information as not reflecting real science. Because historical stories about how science ideas came to be developed and accepted necessarily include high-levels of science content, teachers are less likely to dismiss the activities as superfluous. Furthermore, highly contextualized and detailed historical accounts "provide the concretizations and convincing details necessary to develop [NOS] understanding (Kolsto, 2008, p. 981).

Importantly, Clough (2006) does not suggest using the three levels of NOS instruction in linear sequence. Instead, he suggests consistently making connections among the levels. Decontextualized activities are not reserved solely for introducing NOS, but also throughout instruction to bring out new aspects or revisit those NOS ideas previously discussed. When moderately and highly contextualized activities are used to draw out NOS ideas, students should be encouraged to connect these experiences to decontextual activities. For example, when reading about a scientist who does not use their religious beliefs when doing science, students should be asked how the scientists' thinking is like their own thinking during a magic trick. By making connections to concrete experience, students are better able to engage with difficult concepts.

Despite teachers' best efforts to carefully scaffold student thinking to develop robust understanding, students may oversimplify NOS ideas. Oftentimes when students encounter new information contrary to their original beliefs about NOS, they jump from one extreme position to another. For example, many students think that doing science does not require creativity. Once they are introduced to the role of creativity in science, students might wrongly jump to the incorrect view that science has no ties to empirical evidence. This example illustrates the need to have students reflect throughout their learning of NOS ideas. Students should come to understand complexities of NOS issues rather than jump from one extreme to the next (Kolsto, 2008; Clough, 2007). To achieve this complexity of understanding, students' attention must be drawn to these tensions between extremes through questions based on student current understanding (Clough, 2006). Importantly, the history of science may aid in preventing students from jumping to extremes. Kolsto (2008) notes how actual cases from HOS provide context and details that illuminate the complexity and interplay of NOS ideas that may prevent students from jumping to extremes positions such as giving more importance to theory over observation or vice versa.

Teacher's Role

While teacher knowledge of NOS is important, "teachers' understanding of NOS can be regarded only as necessary but not sufficient conditions for fostering students' understandings of NOS" (Tao, 2003, p. 150; Lederman, 1992). In addition to focusing on the impact teacher knowledge has on student learning, attention must be paid to the impact of teacher actions on student learning of NOS. That is, careful use of NOS/HOS activities and curricular materials must be accompanied by appropriate teacher behaviors. The message implicitly communicated by the teacher's actions and words should not conflict with the NOS picture desired (Kolsto, 2008). Unfortunately, many teachers hold inaccurate views of NOS that impact their teaching practices (Brickhouse, 1990; Gallagher, 1991; Lederman and

Zeidler, 1987). These beliefs translate into teacher actions and language that send powerful messages concerning NOS (Dibbs, 1982; Zeidler and Lederman, 1989). Considering teachers are always portraying a picture of science, that picture ought be developed accurately through implicit and explicit classroom experiences (Clough and Olson, 2004). Carey and Strauss (1970) explicitly note how teachers impact the dominant message about science:

> Regardless of the nature of the curriculum materials…the teacher continues to play the key role in instruction. If the teacher's understanding and philosophy of science is not congruous with the current interpretations of the nature of science; if the objectives that he establishes are not congruous with the dynamic spirit of science, then the instructional outcomes will not be representative of science in spite of all the efforts that may be expended by those charged with the development of relevant curricular materials (p. 368).

Roadblocks to NOS Instruction

> Unfortunately, a long-standing line of research into pre-college students' views of NOS indicates that the greater majority of students still harbour the sort of naïve views of science […] that would hinder engagement in critical discourse regarding socioscientific issues. (Abd-El-Khalick, 2003, p. 46)

To most effectively implement the suggestions for HOS and NOS inclusion above, educators ought be aware of the obstacles for student learning. Simply adhering to recommendations for NOS instruction is not enough if student misconceptions are not carefully sought, acknowledged and attacked. While the suggestions for NOS and HOS given above may at times seem straightforward, science teachers at all levels have an uphill battle against popular images of science and persistent student misconceptions.

Public images of science rarely reflect reality. Television shows and movies focus on experimental science rather than observational science. These same outlets portray scientists to be eccentric "nerds" with few interests outside of science. In addition to portraying scientists as one-dimensional, these shows misuse NOS vocabulary. Most prominently is the use of the word “theory” to denote an educated guess with little evidentiary support.

These popular images of science are not surprising given the literature documenting NOS misconceptions of students, teachers, and the general public (Abd-El-Khalick et al. 1998; Bianchini & Colburn, 2000; Eick, 2000; Schwartz et al., 2000). Of course these misconceptions may be caused by, or at least exacerbated by the misconceptions found in science textbooks (McComas, 2003; Abd-El-Khalick, 2008; Irwin, 1996; Ziman, 1980; Duschl, 1990; Hodson, 1988). Textbooks often include several paragraphs on “the scientific method” with perhaps a one-sentence caveat noting that alternative strategies can be used. These same books include cookbook laboratory exercises in which students follow step-by-step instructions. When most textbooks comment on the development of science ideas they present an individualistic picture rather than collective and institutional dimensions of science (Ziman, 1980). This heroic view of scientists (Milne, 1998) portrays the progress of science as the result of individuals single-handedly making discoveries (Tao, 2003).

From textbooks, teachers, popular media and other outlets, people develop complex, interrelated, and self-supporting conceptual frameworks concerning NOS (Southerland et. al., 2006). More often than not, these frameworks are littered with misconceptions. Students’ NOS frameworks make intuitive sense and are incredibly resistant to change (Wandersee, Mintzes, & Novak, 1994). Oftentimes, students’ naïve ideas align with logical positivism/scientism (Ryan and Aikenhead, 1992). Ryan and Aikenhead (1992) explain scientism using Nadeau and Desautels (1984) dissection of scientism into categories:

1. Naïve Realism: scientific understanding reflects things as they actually are.
2. Blissful Emprицism: all science understanding results from direct observation.

3. Credulous Experimentalism: verification comes from controlled experiments.
4. Blind Idealism: scientists are able to be objective and disinterested.
5. Excessive Rationalism: science gradually approaches Truth through objective logic.

A scientistic view of science removes the importance of creativity, the need to interpret evidence, the use of models, and the role of theory in scientific investigation. Yet, these views should not be surprising when science is taught as a series of conclusions rather than a dynamic, investigative process.

These deep-rooted misconceptions not only hinder students' interest and understanding of science, but also prevent students from accepting more accurate notions of how science works. When students encounter accurate messages concerning how science works, they use their inaccurate framework as a lens to view the accurate messages. Using their misconception-laden lens, students actually make meaning of accurate NOS curricular materials in ways that reinforce their inaccurate frameworks (Tao, 2003). These idiosyncratic interpretations of accurate history and NOS instruction present significant challenges to teachers and curriculum designers. The students' minds are clearly not "tabula rasa" as Locke (1690/1959) might have us think.

Beyond their naïve ideas, students' overall conceptual ecologies (Toulmin, 1972), or "learning ecologies" (Abd-El-Khalick and Akerson, 2004) may prevent complete conceptual change regarding NOS ideas. That is, conceptual change with respect to NOS is a "hot" process influenced by affect, goals, motivation and beliefs, not just prior schema (Strike and Posner, 1992; Pintrich et al., 1993). Dissatisfaction with current ideas and a more plausible alternative is necessary but insufficient for learning. Southerland et al. (2006) describe how teachers' learning dispositions, motivation, need for authority, and comfort with ambiguity all serve to moderate the conceptual change process during NOS learning. The work by Southerland et al. (2006) refined previous work on NOS conceptual ecologies (e.g. Abd-El-Khalick and Akerson, 2004; Tsai, 2002). These findings are not surprising, but provide additional insight as to how complex and difficult learning about NOS can be.

Past Efforts to Incorporate the History of Science in Science Education

Considering the multiple perceived benefits for including the history of science in science education including improved NOS understanding and interest in science, science educators have consistently worked to inject HOS into the science curriculum. Past work in science education to insert historical perspectives have largely focused on creating new curricular materials (Clough & Olson, 2004; Conant, 1957; Klopfer & Cooley, 1963; Rutherford, Holton, & Watson, 1970) or philosophical arguments for the inclusion of HOS in science education (Matthews, 1994; Kolsto, 2008; Hodson, 2009; Clough, 2006; Brusch, 1974; Duschl, 1985; Bauer, 1992; Haywood, 1927; Rutherford, 1964; Klopfer, 1969; Conant, 1947). While some have sought to empirically investigate the benefits of HOS for student learning of content & NOS (Solomon et al, 1992; Dawkins & Vitale, 1999; Abd-El-Khalick & Lederman, 2000a; Lin & Chen, 2002; Dass, 2005; Irwin, 2000; Tao, 2003 Martin-Hansen, 2008), little has been done to empirically investigate how instructors and students come to make sense of historical materials in the science classroom with respect to both affective and cognitive factors. Up to this point, much attention has been directed at literature-based rationale and suggestions for inclusion of both HOS and NOS, now attention must be given to previous work targeting the use of historical materials in the science classroom

Curricular Developments

The most famous and extensive curricular developments regarding HOS include: Harvard Project Physics (Rutherford, Holton, & Watson, 1970), Harvard Case Histories in Experimental Science (Conant, 1957), and History of Science Cases (Klopfer and Cooley, 1963). Each of these sets of curricular materials sought to use the history of science pervasively in the science curriculum and each noted the expected improvement in students understanding of NOS as part of their rationale. Unfortunately, each was either not adopted, or not adopted in any large scale way and are but historical signposts for teachers and researchers interested in HOS in science education.

Conant's (1957) case histories focused on historic scientific discoveries from the 17^{th} through the 19^{th} centuries. He thought that by exploring historical examples students could learn lessons about the practice of science. Conant's Harvard Case Studies were designed for non-science students so that they might have a "feel" for how science is done and how science relates to other areas of human activity. Despite having lofty goals for readers learning of NOS, the case studies included very little explicit attention to NOS ideas and at no point asked readers to reflect concerning how science works. Each case was highly detailed, including pictures of apparatus and work of many scientists across many years. However, this detail comes at the cost of length with some cases containing over 50 pages of text. This length likely prevented adoption of the case studies by classroom teachers.

Klopfer and Cooley (1963) expanded on Conant's work when they created a series of case studies in the form of booklets based on primary sources. As part of each booklet, students read historical accounts and repeated aspects of scientific developments. Booklets were broken into sections with questions to answer after each section. Some of the questions were NOS related while others addressed science content. These cases also contained pictures of apparatus as Conant's case histories had. Klopfer's case studies were still over twenty pages long – posing problems for widescale adoption by teachers who might see HOS as superfluous to science content instruction.

Harvard Project Physics (Rutherford, Holton, and Watson, 1970) featured historical elements and students were expected to form their own conclusions about the work of scientists (Stinner et al., 20003). The Harvard Project Physics curriculum valiantly sought to teach physics entirely through an historical approach. This curriculum took on the traditional structure of a textbook complete with student workbooks and teacher support materials. While the project became increasingly popular in the 1960's and 70s, by the 1980s interest had died down due to perceived lack of science content that might be expected from high-stakes tests.

Each of the above projects took an "all or none" approach. That is, teachers were expected to adopt these materials as their curriculum rather than as supplements to their curriculum. Each of these projects demonstrated tremendous integration of history and philosophy of science with science content. However, the length and implicit expectation of exclusivity likely prevented flexible and continued use of these materials in the science classroom.

McComas (2008), when searching for historical examples, noted the imbalance of historical resources toward physics. While the history of physics is rich with examples and could be viewed as extending further back in time, McComas argues for including HOS examples in various disciplines to help students understand those characteristics of science that transcend disciplines. McComas further notes how most examples come from older science, but many of the NOS ideas apply today as well. Kolsto (2008) adds to this sentiment when he argues that students ought compare contemporary and historical episodes to draw further insight about how science works.

Because the availability of historical resources has been limited, Heilbron (2002) called for science educators to team with historians and philosophers of science to create materials that could be made easily available and inserted easily into courses. Clough et al. (2006) took on this challenge and have created historical short stories informed by the NOS and HOS literature. These stories span all major disciplines in the sciences including: Astronomy, Physics, Chemistry, Biology and Geology. These stories, written in collaboration with historians, philosophers and educators of science, portray the contextual development of fundamental science ideas. Each story includes bullet points and reflective questions that explicitly target NOS ideas.

To combat previously mentioned concerns of flexibility, the stories developed by Clough et al. (2006) are modular. That is, each story stands on its own so teachers can make use of the stories when appropriate. Furthermore the stories are only 4 -7 pages long, making them easy additions to science courses. The stories include high levels of science content as well as NOS ideas. NOS ideas are explicitly noted by bulleted points and reflective questions embedded in the stories.

Empirical Studies Investigating HOS in Science Education

Some attempts to include HOS in science education have been quite superficial, while others have sought to incorporate HOS into all aspects of the curriculum. Some have simply included HOS examples with little explicit NOS instruction, and some have focused almost exclusively on NOS learning. Taken together, these studies provide important insight for the rationale and use of HOS in science education.

Huybrechts' (2000) study used five lessons in which short biographies were included with descriptions of how to repeat "important" scientists' experiments. This study showed no difference between control and treatment groups in their attitudes toward science. The finding is not surprising considering the HOS was limited to biographies and the laboratory experiences seemed to be largely cookbook in nature. These implicit messages that are "always part of the story" (Clough and Olson, 2004) are powerful indicators to students that science is simply a step-by-step verification process.

Mamlok-Naaman et al. (2005) had tenth grade students read original writings and repeat experiments of scientists related to the Phlogiston and Oxygen debates. The authors claimed that student attitudes toward science improved and seemed to link this improvement to historical aspects, but student quotes used to demonstrate change in attitudes more likely indicated that student attitudes changed because of the de-emphasis on equations and rote-memorization. The researchers also noted that student understanding of scientists improved, however, few links were made to whether the historical components were causing the increased understanding.

When investigating the effect of HOS courses on college students' NOS understanding, Abd-El-Khalick and Lederman (2000) found the HOS courses to have little effect. As noted previously, Abd-El-Khalick and Lederman (2000) used this finding to substantiate their admonition for the importance of taking an explicit and reflective approach to NOS instruction. While Abd-El-Khalick and Lederman's work seemingly provided a turning point in NOS research paradigm, their position had been previously noted (Klopfer, 1969; Carey & Strauss, 1970; Kimball, 1967; Robinson, 1965, 1969; Wood, 1972; Russell, 1981; Carey et. al., 1989) and should not have been of great surprise (Clough, 2006).

Klopfer and Cooley (1963) more pervasively approached HOS integration than the other studies previously mentioned by creating booklets for chemistry, biology and physics. These booklets contained historical narrative, quotations from scientists, and pertinent student experiments and exercises. The researchers found that students gained greater understanding of science and scientists. Also, content understanding of the treatment group matched that of control groups in chemistry and physics. However, the treatment group for biology demonstrated slightly lower scores in content understanding than the control group.

A number of studies have taken similar approaches as Klopfer and Cooley by investigating both students' NOS understanding and their content understanding. Roach (1993) when studying undergraduate non-science majors made use of historical vignettes. The treatment group showed significantly higher gains in understanding of NOS and both control and treatment groups performed the same on a content exam. Lonsbury and Ellis (2002) found similar results when investigating the effect of a high school biology genetics unit infused with history. No differences were found between control and treatment content understanding and the group who used the history infused unit performed significantly better on NOS assessment. These researchers noted that the greatest improvement in students' NOS understanding was that science knowledge is testable, or based on evidence.

Other researchers have noted how HOS inclusion has resulted in great improvement of student understanding in particular NOS aspects. Dass (2005), when studying students in a college-level history of science elective course, found that students improved in their understanding that scientists do not use the scientific method, use creativity, and are not objective, etc. However, he noted only marginal gains in students' understanding of science's effect on society and no gains on the socially contextualized aspects of nature (how society affects science). Such modest gain made in some areas raises a question regarding what characteristics of scientists that students struggled to understand. However, because qualitative data was only taken summatively rather than during the learning process, Dass' (2005) study could not, or at least did not reflect on students' struggles to make sense of the NOS ideas.

Solomon et al. (1992) took on a whole-year action research study in which they collected data through pre/post tests, interviews and questionnaires. The research took place in five classrooms of 11-14 year old students and sought to investigate the effects of HOS on students NOS understanding. The researchers noted a particular aspect of improvement related to NOS. They claimed that at the end of the study more of the students expressed the view that scientists seek out explanations rather than make discoveries. More generally, the researchers argued that the exposure to the history of science materials provided alternative images of scientific epistemology that generated greater reflection.

When studying the NOS views of 14 year olds in the U.K., Irwin's (2000) conclusions were less conclusive, but generally encouraging. His treatment was much shorter than Solomon et al.'s (1992), only comprising one unit infused with HOS. Through qualitative analysis, Irwin (2000) notes a general improvement in the treatment group's NOS understanding when compared to the control and no differences in content knowledge. He noted that students moved from naïve realism toward more instrumental views of science and were more willing to engage in philosophical discussion after the HOS infused unit.

Lin and Chen (2002) used a control and treatment design to investigate how teaching pre-service teachers to teach chemistry through an historical approach might affect the teachers' NOS views. While the treatment group teachers improved their understanding of NOS, the control group teachers actually moved toward logical empiricism on many items – indicating a shift away from more accepted NOS views. Lin & Chen analyzed qualitative data in an effort to understand how and why students improved their NOS understanding, but did not investigate student struggles. Perhaps knowing what struggles students' encounter in understanding the NOS through HOS instruction may be as useful as understanding their successes.

Martin-Hansen (2008) studied a freshman survey course and made use of both the explicit/reflective NOS literature (e.g. Abd-El-Khalick and Lederman, 2000) and the decontextualized to contextualized continuum (Clough, 2006). That is, she had explicit discussion concerning NOS, introduced ideas using black-box activities and even had students reading and discussing historical episodes of science. Her analysis indicates that students made many positive gains in their NOS understanding. Student improvement in NOS understanding occurred most notably regarding scientists level of honesty, scientists lack of objectivity, and the differences between theory and law. However, two of seventeen students' views of NOS were not changed. Martin-Hansen (2008) claimed that the two students' young-Earth creationist stance likely impeded any shift that may have occurred. Also, student gains in some areas of NOS were not as robust as others and some items even showed slight negative movement. Unfortunately, little discussion is given concerning why students might struggle to make sense of these ideas other than speculation.

Tao (2003) studied 7th graders in Hong Kong using four historical short stories to investigate students' NOS views. The students showed very little improvement in NOS understanding. However, Tao's goal was not to study the effect of the stories, but to elicit "students understandings of NOS and investigate how students reacted to the science stories in the peer collaboration setting" (p. 148) because "very few studies have investigated the process by which students develop understandings of NOS" (p. 148). Tao's study examined how groups of two made sense of four historical stories. His most prevalent conclusion is that "the stories have served only to confirm and reinforce their inadequate views (Tao, 2003, p. 169). For example, students claimed that scientists "discover" ideas and interpreted the stories to confirm their inaccurate notions.

Importantly, Tao's (2003) stories seem to be just stories with no reflective questions or other ways to draw students' attention to NOS ideas. Furthermore, the stories were given to students and then the teacher did nothing else to help students understand the NOS ideas. While Tao's effort to understand how students come to understand NOS is well intentioned, his treatment is lacking when considering the NOS and HOS literature. Furthermore, Tao gave very little detailed analysis of what things might be hindering students' conceptual change and only generally notes that the stories were interpreted in a manner that reinforced naïve views.

From the research outlined above, two general conclusions can be made. First, students' understanding of NOS is positively impacted by HOS inclusion when students are explicitly attended to the NOS and encouraged to reflect on it (Dass, 2005; Irwin, 2000; Klopfer and Cooley, 1963; Lonsbury and Ellis, 2002; Lin and Chen, 2002; Roach, 1993; Martin-Hansen, 2008; Solomon et al., 1992; Yager and Wick, 1966). Second, student content learning seems to be unaffected by inclusion of historical materials (Irwin, 2000; Lonsbury and Ellis, 2002; Roach, 1993; Yager and Wick, 1966). Yet, questions remain.

Most of the studies discussed have taken place with middle school students or non-science majors at the college level. While investigating these non-science populations is important for increased scientific literacy in society, Tobias (1990) raises concern about those students who are science capable, but opt out because they fail to see science as a creative, social, and human endeavor. Furthermore, the studies outlined above show only modest improvements in NOS understanding and only superficially investigate the struggles students have when learning about NOS ideas. While some emergent research has been done on NOS conceptual ecologies (Abd-El-Khalick and Akerson, 2004; Southerland et al., 2006), these studies look at student NOS understanding generally rather than in the specific context of learning NOS ideas from historical materials.

While there has been some work done to investigate student views of HOS materials (Tao, 2003; Welch and Walberg, 1972) more is needed and virtually no research has investigated instructor views of the HOS materials or how they are used. This last omission is likely an artifact of many of the researchers also serving as instructors in the classes studied. Therefore, the instructor's views toward HOS in the science classroom would be obviously postive. However, scalable reform efforts must take into account the role of the teacher. This study will explore the views of both the instructor and the students toward the historical short stories.

Conclusions and Research Motivations

While students' misconceptions and conceptual ecologies have been investigated, many of these studies have been conducted under seemingly "ideal" conditions where the instructor placed great emphasis on NOS. Unfortunately, this does not describe most science classrooms. This study investigates the use of historical short stories within a content-focused post secondary lecture-based science course.

While many researchers have noted the tenacity of student misconceptions, they have written them off as due to lack of explicit attention to NOS (Abd-El-Khalick and Lederman, 2000). One aspect of this study will be to explore student struggles to understand NOS ideas from short stories that have been designed taking into account the explicit/reflective recommendations for NOS instruction. This research hopes to shed light on the ways in which students continue to struggle with NOS ideas *in the process of learning* even when NOS ideas are explicitly noted by curricular materials.

Despite the efforts of curricular designers and researchers, long-term change of science education curriculum seems largely unaffected. While past plans have required extensive shifts in the curriculum, the materials developed for this study are modular so could be used simply as homework assignments that are not dependent on modifications to the greater curriculum. That is, the materials do not require substantial reorganization of courses or course content. Instead the short stories slip easily within existing content (Heilbron, 2002; McComas, 2008). However, because the stories contain extensive science content, more inclusive uses of the stories is possible for instructors wanting to integrate

HOS more fully into their course. This study seeks to investigate in ways the short stories might be implemented in a post secondary science classroom.

In summary, this study seeks to 1) investigate the way in which historical short stories are implemented in a post secondary introductory biology course, 2) understand instructor views of the historical short stories, 3) investigate student views of the short stories, and 4) investigate student misconceptions to elaborate on specific factors affecting conceptual change as well as provide recommendations to improve future curricular materials.

CHAPTER 3: METHODS AND PROCEDURES

Introduction

Some students choose not to pursue science careers because of how science is taught rather than genuine disinterest in science. Tobias (1990) investigated the views of students who demonstrated high proficiency in science, but dropped out of science coursework. She found that these "second-tier" students crave more emphasis on the history, philosophy, sociology and psychology of science. Unfortunately, post-secondary science courses are known for placing high importance on science content and little, if any, attention is paid to helping students develop an accurate understanding of how science works or the nature of science (NOS). By illuminating the human side of science, instructors can help students see science as a dynamic and creative field.

When considering the inherent difficulties of developing NOS understanding, Clough (2006) notes the need for instructors to scaffold between decontextualized NOS learning and highly contextualized instruction. By beginning NOS instruction with activities divorced from science content, students can more easily engage with difficult NOS ideas. Yet, using only decontextualized activities does not promote deep contextual understanding of NOS and many instructors claim to not have time for activities not related to science content. Importantly, highly contextual NOS instruction uses real science episodes to create seamless integration of content and NOS instruction. By integrating NOS and content instruction, the two complement one another. Because of heavy content focus, highly contextualized NOS curricular materials might be useful in the post-secondary science classroom. This study seeks to illuminate aspects of a highly contextualized approach to NOS instruction within a post-secondary introductory biology class.

This work is one portion of a larger National Science Foundation-funded project intended to develop and study the effect of explicit NOS instruction through the use of historical short stories (Clough et al., 2006). Faculty members from science education, history of science, geology and biology, as well as graduate students from science education and history of science developed curricular materials related to the study. Creating the short stories comprised of 1) researching and writing short stories (4-6 pages in length) that exemplify elements of NOS through historically accurate descriptions of scientific work in the fields of geology and biology that relate to content of the course studied including: age of the Earth, Darwin, Wallace, and Mendel; 2) writing statements and questions designed to draw students' attention to both content and NOS concepts – particularly evidence use, the variety of processes involved in the construction of scientific knowledge, the need for creative interpretation of data, science is but one way of knowing relying heavily on methodological naturalism, the effect of experience, culture and society on science, subjectivity, and the tentative, yet durable, nature of scientific knowledge.

Purpose of Study

This study seeks to formatively assess and investigate the use of historical short stories designed for use in introductory college-level science courses. The development of these materials and this study have been supported, in part, by a grant from the National Science Foundation (Clough, Olson, Stanley, Colbert & Cervato, 2006). This study serves to explore both instructor and student views of the stories as well as ways the stories might be improved. Toward these ends, one purpose of this study was to identify and describe idiosyncratic interpretations and struggles of introductory biology students when reflecting on NOS through the use of five historical short stories. Students' reported interest in the short stories and the reported impact of the short stories on their NOS understanding and their interest in science careers was also investigated. Lastly, the instructor's views on the use of short stories in their course were sought.

Research Questions

This study intends to answer the following research questions.

1. How were five historical short stories implemented in a post-secondary introductory biology course for biology majors?
   a. What were the general teaching practices exhibited by the biology instructor?
   b. How were the short stories implemented by the biology instructor?
   c. In what ways was NOS addressed beyond the short stories?
2. What are the biology instructor's impressions of the short stories after having implemented them in his course?
3. What are the students' impressions of the short stories and what impact do students report the HSS have on their NOS understanding and interest in pursuing a science career?
4. To what extent and in what ways do students' misinterpret the historical short stories?

Methodological and Theoretical Framework

This study sought to explore student and instructor views of historical short stories used in the post secondary classroom. The study also explored how students made sense of the short stories. Collecting and analyzing qualitative data that might provide deep insight into participant views and struggles best served the exploratory nature of this study. Although some quantitative data was collected, the self-report nature of the quantitative data poses significant problems for any sort of hypothesis testing. Instead, the quantitative data was used as a means to describe student views in general to augment specific student views identified through qualitative analysis.

The methods used in analyzing qualitative data stem from the grounded theory tradition (Glaser and Strauss, 1967). Data was analyzed using open and axial coding (Strauss and Corbin, 1998) using a constant comparative method in which codes and themes were developed from data analysis and reflexively refined as necessary (Maxwell, 2005). While grounded theory methods best describe the procedures and goals of data analysis in this study, data collection and analysis cannot be separated from previous theoretical commitments of the researcher (Emerson et al., 1995). Although data was constantly compared against itself, the researcher does not claim that themes "emerged" from data. Instead, a naturalistic inquiry (Lincoln and Guba, 1985) stance was taken for data analysis. For example, students' problematic views of NOS were identified based on the researcher's understanding of NOS. Because prior theoretical commitments act as a lens through which data is interpreted, great pains were taken in chapter two to detail how NOS is conceptualized by the researcher with connections made to the science education literature.

While a grounded theory methodology under a naturalistic inquiry theoretical framework might be perceived as problematic, the interaction reflects the tension apparent in the researcher's views. A naturalistic inquiry framework notes the dependence of knowledge on the knower while a grounded theory approach focuses on generating knowledge from observation. Taking either of these views to extreme is unproductive. That is, to ignore the role of theoretical commitments or to ignore the relation of data to reality are both problematic. Therefore, using methods that strive to be "grounded" in data while adopting a stance that accepts the theory-laden nature of data analysis most accurately reflects the researcher's stance *between* positivism and postpositivism.

Research Participants and Study Context

The research participants in this project were students enrolled in a one-semester, undergraduate, introductory biology course at a large, public, Midwestern U.S. university (N = 156). The study was classified as exempt from the university's Internal Review Board because the instructor of the course was using the short stories as part of his regular instruction. Therefore, informed consent documentation was not required. The student participants were informed that the research team would use their short story question responses and their voluntary questionnaire responses.

First year students who intend to major in biology or other related science disciplines typically take the introductory biology course section studied. The course addresses a variety of biological concepts including, but not limited to: diversity of life, classification, genetics, biological evolution, and ecology. The primary method of instruction included lecture based on instructor-designed PowerPoint presentations that were available to students online.

However, the instructor also had students discuss in small groups, share ideas with small groups, and ask questions in class as well as using an online platform on which students could submit questions. Greater detail regarding the nature of instruction is provided in chapter four when discussing data collected from research question one: How were five historical short stories implemented in a post-secondary introductory biology course for biology majors?

Development of Materials Used in the Study

Short Stories and Embedded Questions

Development of the historical short stories was informed by science education literature concerning NOS instruction and incorporation of historical materials for teaching science. To draw students' explicit attention and provide opportunities for reflection on NOS ideas (Abd-El-Khalick and Lederman, 2000a) questions and bulleted points were inserted within each of the stories. Furthermore, the stories represent authentic science episodes and are rich in science content to provide rich context for the NOS ideas being promoted (Clough, 2006). Heilbron (2002) notes the need for more than history when he notes: "Whenever possible the case studies should carry epistemological or methodological lessons and dangle ties to humanistic subject matter. But never should the primary purpose of the cases be the teaching of history" (p. 330). Heilbron's thinking further informed the development of the short stories through his suggestions of 1) creating case studies that can be easily inserted into science courses; 2) creating case studies that convey useful scientific information; and 3) case studies ought to be written by teams of historians, philosophers, scientists and teachers.

With these suggestions in mind, a team of science educators, historians of science, geologists, and biologists created historically accurate short stories containing carefully worded questions and bulleted points to highlight and guide student thinking about the nature of science and the science content. For the biology course studied, five short stories were used – two stories on the age of the Earth, and a story each on Mendel, Darwin, and Wallace. Full text of the short stories can be found in Appendix B.

The geology stories were selected to help students understand the tremendous age of Earth. Students' understanding of deep time is a prerequisite for understanding the great amount of time needed for biological evolution to result in the great diversity of species now inhabiting the Earth. Despite the need to understand deep time to understand evolution, Trend (2001) notes that people's cognitive frameworks of deep time "differ greatly from the scientific consensus" (p. 192). Half of one sample population (10-11 & 14-15 year olds) believed that the Earth and life originated at about the same time (Marques and Thompson, 1997b). If students do not have an accurate notion of how long the Earth has existed or how long life has been around, there is little wonder why they dismiss evolution *a priori*. Two short stories were used near the beginning of the course to address some of these misconceptions about how scientists have come to understand the age of the Earth as well as introduce students to some fundamental NOS ideas, including: data must be interpreted, science is socially and culturally embedded, science is but one way of knowing, subjectivity and the theory-laden nature of research, and the role of creativity in science.

Another short story used concerned the work of Gregor Mendel. As part of the introductory biology curriculum, students were expected to be introduced to basic genetic principles. Because students were learning about Mendel's Laws, the short story that had been developed about his work was appropriate for the content. Additionally, the Mendel story helped to further illustrate NOS ideas promoted by the geology short stories and added key ideas such as: the lack of a "scientific method", the role of consensus building, as well as the revolutionary character of scientific knowledge development.

Confronting students' naïve NOS ideas is especially important when teaching biological evolution. Southerland and Sinatra (2003), when studying how students' learning disposition correlate to their acceptance of biological evolution, note the possible link between student NOS understanding and acceptance of biological evolution. Johnson and Peeples (1987) claimed college biology students' understanding of evolution through natural selection was dependent on their understanding of NOS. To highlight nature of science within the context of evolution short stories were assigned to students on both Darwin and Wallace. These short stories draw attention to the two most prominent individuals associated with the development of evolution and encourage students to see evolutionary theory as more than the work of a single man. The Wallace and Darwin stories reaffirm many of the NOS ideas promoted by the other three stories and also explicitly address additional NOS concepts, including: rationales for methodological naturalism, the immense time for ideas to be developed and accepted, the tentative nature of ideas, the difference between scientific laws and theories, and the difference between observational and experimental science.

Student Views Questionnaire

A questionnaire was developed to investigate student attitudes toward science and student interest in the short stories (Appendix A). The questionnaire made use of Likert scale responses and asked students to indicate how interesting the stories were, rank order the stories based on interest, indicate to what extent the stories taught them something new about how science works, indicate to what extent the stories changed their views regarding how science works, and how many short stories they would prefer in a one semester course. Additionally, the students were asked to make comments concerning the short stories. On a separate sheet students were asked to indicate to what extent the stories impacted their interest in a science career. Again, this Likert scale item ranged from 1 = decreased my interest to 5 = greatly increased my interest. Students were also asked to provide additional comments on this sheet. Both of these questionnaires were anonymous so that student answers would be honest reflections of their thinking.

Data Collection and Analysis

In this section the specific methods used to investigate each research question will be discussed.

1. How were five historical short stories implemented in a post-secondary introductory biology course for biology majors?

a. What were the general teaching practices exhibited by the biology instructor?

b. How were the short stories implemented by the biology instructor?

c. In what ways was NOS addressed beyond the short stories?

Course Observations

To establish story implementation conditions and to help answer the first research question, two researchers observed each class session. Careful note was taken of instances in which the instructor explicitly or implicitly commented on the NOS either within a

PowerPoint slide or during discussion. Observations were made to more clearly understand how the instructor used the short stories in his class and if/how reference was made to the stories or NOS beyond deliberate discussions about the short story assignments.

To create descriptive patterns regarding the instructor's short story and NOS implementation, field notes and PowerPoint artifacts were read and instances of NOS instruction were identified. Initially, instances were grouped into two categories – associated with short stories and not related to short stories. These two groups were then subdivided into teacher-oriented or student-oriented. Teacher-oriented instances included lecture, teacher talk, or explicit NOS inclusion on a PowerPoint slide. Student-oriented instances included having students write about NOS related topics, having students discuss NOS ideas in groups, or having students ask/respond to NOS questions in class. Specific descriptions and patterns are developed in chapter 4. Rich instructional and course profiles were developed to better understand how the short stories were used and to aid in analysis of instructor interviews as well as student responses to the short stories and questionnaire.

When documenting data, codes were developed to aid in identifying the source of data used. The instructor organized PowerPoint slides by exam. Therefore codes for data taken from slides are referenced as, (Exam 1, ppts). This code means the data was found in the slides used prior to the first course examination. Fieldnote data is referenced as such including the data. For example, (Fieldnotes, 11/2/07) means the data is from fieldnotes taken on November 2nd, 2007.

2. What are the biology instructor's impressions of the short stories after having implemented them in his course?

Instructor Interview

An initial open-ended interview was conducted with the instructor just after the end of the course. During the initial interview the instructor was asked to share ideas, insights, likes and dislikes of the short stories. While researchers asked for clarity and explanation as well as added to the discussion, the interview was conversational rather than directed. The interview was recorded, transcribed and analyzed to generate initial ideas regarding instructor views to inform the second, semi-structured interview.

To more carefully investigate the instructor's views of short story use, a second interview was conducted to discuss the use of the short stories, the nature of science and how the instructor has been impacted by the story implementation. This second interview resembled Piaget's (1926) clinical interview in which specific information was sought, but the instructor was encouraged to also explore tangential ideas (in Posner & Gertzog, 1982). The two-hour, semi-structured interview explored divergent ideas while maintaining focus on discussing the integration of the short stories and NOS within the course. Throughout the interview, ideas were returned to and clarification was asked for often to provide greater confidence in research interpretation of the instructor's views.

Each interview was transcribed in full and analyzed for themes. Transcripts were broken into manageable chunks by identifying portions of transcript that maintained focus on a specific topic. Once chunks were identified, they were read and open-coded. Open codes were axial coded and grouped into substantive categories (Maxwell, 2005; Strauss & Corbin, 1990). Chunks of transcript were then reread and grouped into the substantive categories including: *stories as outsourcing*, *stories to teach NOS*, *content focus*, and others. Each thematic group of transcript was then read again and analyzed for continuity and possible additional themes.

3. What are the students' impressions of the short stories and what impact do students report the HSS have on their NOS understanding and interest in pursuing a science career?

To answer this research question, all students (N = 156) were asked to fill out two anonymous questionnaires asking about their interest in the short stories and the effect of the short stories on their understanding of how science works as well as the short stories' impact on their interest in a science career. Researchers administered these questionnaires during the last two weeks of the course. Both questionnaires can be found in Appendix A.

Reported Interest in Short Stories

In the first questionnaire (see Appendix A), students were asked to respond to a Likert (1 – 5) item ranking their interest in the short stories as a whole. Student responses were analyzed using one sample t-tests to test for statistical significant differences from $\mu = 3$ (neutral).

As part of the same questionnaire, students were asked to rank order the short stories based on interest and how many short stories they would prefer to complete. These numbers were averaged and descriptive statistics run. Each question provides insight for future short story implementation.

The questionnaire also solicited additional comments about the short stories from students. These comments were read and grouped into common categories first based on whether the comments were positive or negative, and then the comments were further divided into more specific categories based on what aspect of the short stories the comment addressed.

Reported Influence on Nature of Science Understanding

On the first questionnaire, students were also asked two Likert scale (1 – 5) items addressing to what extent the short stories influenced their understanding of NOS. One question asked about whether the short stories taught the student anything new about how science works and the other question asked if the short stories changed their views regarding how science works. Student responses were analyzed using descriptive statistics.

Reported Influence on Interest in Science Career

To understand how the short stories affected student interest in science careers, all students were given a second anonymous and voluntary questionnaire (see Appendix A) asking about how the stories affected their interest in pursuing a science career. Students responded using a Likert (1 – 5) scale, with five indicating increase in interest and one indicating decrease in interest. Additionally, the students were asked to provide additional comments concerning the short stories.

The career interest student questionnaires were analyzed using one sample t-tests to test for statistically significant differences from an expected $\mu = 3$ (no change in interest). The student comments were first grouped into three categories: decrease in interest, increase in interest, and no change in interest in science related careers. Within these groups the student comments were read and placed into more specific categories. The categories were generated through constant interaction with the data. That is, categories were developed during data analysis rather than prior to data analysis. When a student comment could not be placed into an already existing category, a new category was created. The categories were then compared and combined under more broad themes when appropriate. This process resulted in several descriptive themes for each level of student reported short story effect on their interest in science careers (decrease, no change, increase).

4. To what extent and in what ways do students' misinterpret the historical short stories?

Student Homework

Data was collected from students who were enrolled in an introductory biology course during the Fall of 2007. These students were asked to read a total of five short stories and complete the embedded questions as homework. To answer this final research question, the short story homework that was turned in was collected in hardcopy, usually typed, format.

Because the short stories used in this study account for Abd-El-Khalick and Lederman's (2000) need for explicit/reflective NOS instruction as well as Clough's (2006) call for highly contextualized instruction, the student responses to the short stories ought to be fertile ground for identification (and categorization) of elements that hinder students' NOS understanding and exploring the interconnections of these struggles. This study sought to create descriptive themes of student struggles to interpret the short stories as desired. Substantive themes were developed using constant comparative methods (Glaser and Strauss, 1967) during numerous interactions with the data. By illuminating the nuances and extent of student struggles to understand NOS from historical short stories, future research and development of curricular materials may be powerfully informed.

To begin analyzing short story question responses, each student response for a single embedded question was read and searched for misconceptions or language indicating unclear understanding of NOS ideas. In addition to misconceptions regarding NOS, alternative interpretations to those intended of the short-story questions or text were noted. During the initial reading and open coding (Strauss and Corbin, 1998), descriptive words and phrases were used to identify chunks of student writing. After initial open coding, codes were grouped and reduced into common categories or themes. The initial codes usually resulted in more than fifty words or phrases to describe student misconceptions or idiosyncratic interpretations such as: prove/true, Wallace-journal Darwin-book, Darwin-new Wallace-old, theory/law, Wallace didn't take credit, etc (taken from analysis of Wallace short story, Question 1). Then, these phrases were reduced to between five and ten themes for each short story question, including: Students ignore evidentiary argument for Darwin's prominence and create/focus on other reasons for Darwin's idea being more accepted, Wallace had no evidence, General NOS misconceptions, Focus on scientists' feelings, and others (taken from analysis of Wallace short story, Question 1). When appropriate, sub-themes were developed to distinguish nuances within major themes. Each theme or sub-theme was assigned a temporary number or letter code. All final coding schemes can be found in chapter four under research question four.

Once initial themes were developed, student responses to the embedded questions were reread and chunks of student responses were highlighted and numbered to designate the theme in which that chunk could be grouped. Some student writing was placed into more than one theme. Once student writing for each question was grouped by themes, each theme data set was read again to refine thematic descriptions and gain additional insight.

After each question was analyzed and subsequent themes developed, questions identifying related NOS concepts were compared for similarities or contradictions in themes. Finally, all themes developed for each question were compared to understand the pervasiveness of student misconceptions and struggles as well as identify additional or interrelated themes to help explain student struggles with conceptual change.

When attempting to ascertain the source of student undesirable interpretations of the stories or the questions, any reference to the story by students was carefully looked at in an attempt to understand in what way the students made sense of the story that may have lead to the undesired interpretation. Furthermore, when student responses seemed to deviate from the intended question, the language of the response and the question were carefully compared so that any problems with question language might be identified. Possible sources of student problematic interpretations were identified and refined during the initial open coding and subsequent reduction of codes to descriptive themes.

Limitations of Study

The interpretive nature of this study is limited by the researcher's ability to make sense of participant writing or speech. Because meaning is made through the lens of the researcher, rich descriptions with example participant words will be provided in the findings section to help make clear the origin of conclusions and themes. Additionally, descriptive themes that were developed as part of this study were refined through several immersions in available data. Only descriptive themes that could be supported using data from multiple student participants are reported. In the case of the instructor, two separate interviews were conducted as a form of member checking and to serve as triangulation for researcher interpretation. Additionally, only themes that were observed at different times within interviews are reported.

As with all research, bias presents a great challenge to qualitative research. Data analysis will be dependent on researcher understanding of NOS, expectations of college student work, and interpretation of the stories. To address bias and make researcher beliefs more transparent, conceptualization of NOS was explored in detail in chapter two. Furthermore, substantive themes are supported in chapter four with extensive quotations from participants. Extensive quotations are provided to make researcher interpretations more transparent. Beyond providing extensive, data-based support for substantive categories, the researcher discussed developing categories throughout data analysis by way of informal discussions with other NOS scholars and through formal presentation at professional research conferences.

The descriptive themes developed in this study apply to the instructor and the group of students studied. Any generalizations are limited to post-secondary biology majors at a large Midwestern research university. Furthermore, while this study focuses on the use of historical short stories, any conclusions must be considered in light of the greater context of the study. The instructor made many in-class comments concerning the nature of science unrelated to the short stories and students are consistently bombarded with various messages concerning NOS from other courses, the textbook, and media outlets. While conclusions and explanations of this study are tied to the short stories, the complex nature of knowledge construction would imply that more than the short stories impact student ideas and thinking. Since students make sense of new information using their own unique experience as a lens, different students may have different interpretations of the stories. Yet, because of the large number of students studied, the researcher hopes to have shed light on many common problems regarding the implementation of historical short stories in the post-secondary science classroom that might be useful for further development and use of such materials.

In some instances, researcher interpretation is limited by student responses. Some student responses to the short stories were vague or lacked enough detail to draw conclusions about the accuracy of student thinking. In these cases, it is unknown if the student has made an undesired interpretation of the story, or interpreted the story as intended without record.

Conclusion

The goal of this study was to explore ways that students and instructors interpreted the historical short stories. Because of the complex nature of interpretation, qualitative data was collected in hopes of gaining greater depth of insight into student and instructor thinking. From this data, substantive categories were developed to aid in making useful sense out of deeply contextualized data. Using these descriptive categories, recommendations and new insight might be gained for designing and implementing historical short stories in the science classroom.

CHAPTER 4. RESULTS

Overview

The goal of this study was to provide insight into how instructors and students view, use, and interpret five historical short stories in a post-secondary biology course. Data was collected in the form of course observations, written responses to short story questions, student questionnaires, and interviews with the instructor. Means are reported for quantitative data collected from questionnaires and one-sample t-tests were used when appropriate. Descriptive themes were developed from qualitative data and are discussed. From the analysis of various data sources, how the stories are used, the views of both the professor and students regarding the stories, and the struggles students encounter when reading and responding to the short stories were determined.

Research Questions

1. How were five historical short stories implemented in a post-secondary introductory biology course for biology majors?
    a. What were the general teaching practices exhibited by the biology instructor?
    b. How were the short stories implemented by the biology instructor?
    c. In what ways was NOS addressed beyond the short stories?
2. What are the biology instructor's impressions of the short stories after having implemented them in his course?
3. What are the students' impressions of the short stories and what impact do students report the HSS have on their NOS understanding and interest in pursuing a science career?
4. To what extent and in what ways do students' misinterpret the historical short stories?

Research Question 1

How were five historical short stories implemented in a post-secondary introductory biology course for biology majors?

To better understand how the short stories are used, each course session was either observed or videotaped. Descriptive field notes were taken during observations with particular attention directed at how the instructor included aspects of NOS in the course. From these observations and artifacts such as in-class handouts or Power Point slides, rich descriptions of general teaching practices, implementation of the short stories, and NOS instruction were developed.

General Teaching Practices

The professor of this course, Glenn (pseudonym), clearly saw the student-professor relationship as a two-way street. While developing relationships with students is often noted of utmost importance in k-12 settings, in a lecture class of between 150-200 students Glenn worked to get to know his tertiary students and encouraged them to know him even. On the first day of class the students filled out index cards noting how the course supports their career goals, why they think learning about microscopic organisms might be boring, and a question they have about the professor. Glenn then answered several of the questions during class.

Although this course took place at a large university, Glenn worked to engage students in learning rather than simply presenting information. Glenn's focus on student learning is prevalent even in his syllabus:

> In general, people do not learn things thoroughly simply by being "told" something one time. People often need to review new ideas several times before they learn them.

> In addition, people often need to engage with the new information in a variety of ways (seeing diagrams or pictures, discussing with peers, working problems, writing about, etc.) before they come to a full understanding of the new information and can integrate the new information into their previous understanding. Even greater effort is often required to REPLACE previous misconceptions with new more accurate (or more complete) conceptions.

Glenn even explicitly and verbally addressed learning with the students on the first day of class. He discussed how learning is something they do rather than something that is done to them. He noted that different strategies will work for different people and provided suggestions for how to be better prepared for the class including finding other people with whom to study, participating in class activities, and asking questions.

Despite having lofty goals for his teaching and his students' learning, much of Glenn's teaching reflected common attributes of a "traditional" lecture course. Many slides of the course presentations were bullet-point text. For example, a slide introducing Class Gastropoda had the following bullet points with no pictures (Exam 2 ppts):

- About 40,000 extant species
- Feed using a rasp-like organ called a "radula"
- Open circulatory systems
- Most are herbivores, grazing on algae or plants
- Some are predators

These kinds of slides seemed to be most concerned with providing information. Additionally, the course was dominated by "teacher talk". Although Glenn was interested in student learning, his course meetings were largely aimed at presenting information. While Glenn may want to engage students in more discussion, a class of over 150 students presents many challenges.

Although the course had many characteristics of a "traditional" lecture course, Glenn was clearly concerned with helping his students learn. As noted earlier, he answered questions in class, asked questions in class (clearly expecting responses), and provided opportunities for students to express concerns and to get to know him better. Although Glenn was constrained by the size of his class he worked to make learning engaging and meaningful for his students.

Glenn continually attempted to relate content to the "real world". In one class he brought in examples of products that make use of algae (Field notes, 9/6/07). He also made reference to how many organisms being discussed are used in food production, sewage treatment, and other areas impacting human beings (Field notes, 9/13/07). When introducing flowering plants, Glenn noted the economic importance of flowering plants including food, medicine, fuel, and raw materials. More forcefully Glenn noted that "Human civilization would be vastly different without cereal grain crops" and that "1 billion tons of cereal grain crops directly feeding over 1/2 the world's human population are harvested each year" (Exam 2 ppts). He also included local species in his presentations whenever possible. Clearly, Glenn sought to help students see how science affects all aspects of life rather than the all too common approach of simply presenting science content divorced from its application.

Beyond connecting science to their everyday lives, Glenn consistently encouraged students to understand the "big picture" of the ideas being presented. This "big picture" was multifaceted. In some ways Glenn wanted students to understand how various organisms affect the entire ecosystems. For example, he noted how fungi had "ecological significance" in their role as decomposers (Exam 2 ppts). Later, the presentation noted how Lichens serve as a "pioneer species" by establishing themselves in newly cleared rock or soil (Exam 2 ppts).

Glenn seemed to want students to understand how various organisms each played an important role in the story of nature.

Glenn also wanted students to see the “big picture” in regards to science ideas. While he spent much time presenting details of biology, Glenn organized the course around intelligible “big ideas”. For example, when introducing the section on Diversity of Life, Glenn’s Power Point slide noted the big idea was that “There’s a whole lot of creatures out there (and, for that matter, in there......) (Exam 1 ppts).

Not only were new topics introduced with the “big picture” in mind, Glenn’s entire course was organized around the all encompassing biological idea, evolution. Whenever introducing a new category of organisms, Glenn’s presentation discussed the history of the organisms including discussion of their fossil history and how the organisms relate to other categories of organisms. These details regarding each category set up his later discussion on how evolution is the most important idea in biology.

In addition to organizing the course in meaningful ways, Glenn sometimes made his pedagogical decisions transparent to students. For example, one slide asked, “Why aren’t we spending more of our time on the “real” animals - the vertebrates?**”** To which the presentation responded, “Vertebrates (fish, amphibians, reptiles, birds, and mammals) make up less than 5% of the known animal species on Earth” (Exam 2 ppts). Glenn even provided advice on how to mentally organize the concepts in the course. He gave the following recommendations when explaining how to study animal diversity (Exam 2 ppts). For each category of organisms, students should be able to:

•Describe history on Earth, which groups are most similar
•Describe body plan
•Describe how they

- •Eat/Digest
- •Exchange gases
- •Exchange wastes
- •Circulate fluids
- •Support themselves/move
- •Reproduce

•Know general habitat and ecological role
•Compare and Contrast - note trends and relationships

Making these patterns clear supports student learning and likely decreases their view that hundreds of isolated facts must be memorized. Letting students in on this organization also encourages students to see how ideas are connected, which ought to result in deeper learning.

While carefully organizing his course and making the organization explicit to students indicates how Glenn focused on the "big picture" and student learning, he did many things within *each* class that indicate his interest in helping student learn. Glenn included a lot of pictures and some videos during his lectures. He also provided references to the course text for further reading. Including these aspects supports student learning of complex ideas by providing more concrete representations and pointing students to additional information.

Perhaps most surprising in such a large lecture hall was that Glenn had students discuss ideas in class. Some of Glenn's presentation slides were titled "TTYP" (Talk To Your Partner). For example one slide titled TTYP asked students to discuss "Are Cnidarians protostomes or deuterostomes? What is your rationale?" (Exam 2 ppts). After a TTYP slide Glenn would give students a few minutes to discuss the question with those around them. While the students discussed he would walk around and listen in or even take part in the small group discussions. Then he would ask for some ideas from the class. On occasion he threw out pieces of candy to students who provided answers. He sometimes threw out pieces of candy randomly and whoever caught the candy was expected to either answer the question or pass the candy to a partner (Field notes, 9/13/07). Clearly Glenn valued student participation.

The participation Glenn encouraged was often review in nature, but Glenn did not ignore students' prior conceptions. As part of his presentations, Glenn would explicitly note common misconceptions. When addressing misconceptions related to evolution Glenn included: evolution is "just a theory", evolution explains the origin of life on Earth, evolution happens in individuals, evolution violates the 2^{nd} Law of Thermodynamics, no transitional fossils have been found, and several other common misconceptions (Exam 3 ppts).

Beyond encouraging student participation and addressing common misconceptions, Glenn demonstrated reflexive teaching practices by taking students' questions in class and embedding students' questions submitted via WebCT into his presentation slides. Class sessions typically included two or three WebCT questions and Glenn encouraged students to ask questions during class. In one class session he addressed eight student questions in a row before returning to the planned presentation (Field notes, 11/15/07).

Glenn exhibited characteristics of a reflective practitioner and encouraged students to be reflective learners. In one class session he asked students to answer the following questions on an anonymous piece of paper (Field notes, 9/20/07):

1. What about this course is helping you learn biology?
2. What am I doing to help myself learn biology?
3. What about this course is hindering my learning of biology?
4. What am I doing that is hindering my learning of biology?

While Glenn is faced with the same restraints as typical large lecture hall classes, he is clearly making efforts to improve student learning. Glenn's acknowledgement of misconceptions, encouraging students to discuss ideas, and encouraging questions demonstrates his understanding that learners on not "blank slates" on which to write.

Implementation of Historical Short Stories

When each short story was assigned, students were given about a week to read and complete the embedded questions. Students were to bring typed responses to class on the days the short story assignments were due. Both stories concerning the age of the Earth were assigned together near the beginning of the semester. The Mendel story was assigned later in the semester when genetics and chromosomes were being discussed in class. The Darwin and Wallace stories were assigned together near the end of the semester when evolution was more explicitly addressed.

Glenn placed significant emphasis on the short stories. Student responses to embedded questions were collected and students received two points for completing the short story questions. Students were told that quiz and test questions would come from the short stories and that test questions would not focus on names and dates, but big ideas about how science works (Field notes, 9/13/07). In addition to collecting short story homework and basing assessment items on the stories, Glenn also took some class time to discuss the stories. During class, the students discussed their responses to questions in small groups. After small group discussions, Glenn had the students write new insights or questions they had on the back of their assignments before turning in the assignment.

Although the short stories were rarely discussed beyond the days when students turned in their responses to the short story questions, students likely did not see the stories as extraneous. Students knew their responses to the story questions would be collected, that they would receive points for completing the questions, and that assessment questions would address the stories. The stories were assigned at times that made sense with the course content and discussed in groups rather than simply turned in. For these reasons, the implementation of the stories in this course is considered to be highly integrated rather than superfluous.

NOS Instruction Not Related to Historical Short Stories

Oftentimes Glenn implicitly addressed NOS in his teaching. When discussing classification systems he noted how various ideas have been used over time and even discussed some of the people behind creating the classification systems. Glenn's words seemed to be chosen carefully on his presentations. Consider how the presentation excerpt below accurately portrays NOS (Exam 4 ppts):

> •Why are flatworms, flukes, and tapeworms placed in the same phylum (Platyhelminthes)?
>
> •Because the available evidence supports the idea that these organisms are more closely related to each other (by their evolutionary history) then they are to other groups, e.g., annelids, basidiomycetes, or chordates…

Glenn could have said that evidence says, or evidence points, but instead used the more accurate, "evidence supports".

Glenn also used language in class that implicitly demonstrated desirable NOS views. When saying, “At this point we do not know of any red algae with flagella” (Field noes, 9/6/07), Glenn implies that scientific knowledge may change in the future. Later he says, “Biologists believe this with the evidence available” (Field notes, 9/6/07) indicating the relative uncertainty of science ideas as well as their basis in evidence.

Only rarely did Glenn’s language not accurately reflect NOS. Once Glenn personified data by saying “Molecular data suggest…” (Field notes, 10/4/07). While this one slip is not of great concern, students may miss the role of human interpretation of data. In another example, Glenn said, “what the fossil record tells us…” (Field notes, 11/29/07) indicating fossils speak rather than need to be interpreted. These two instances do not likely represent Glenn’s misunderstanding, but demonstrate how easily inaccurate NOS language can slip into complex discussions. Because Glenn did not explicitly attend students to his language, minor slips are not of great concern. However, students’ naïve ideas are easily reinforced by inaccuracies in teacher language.

Importantly, Glenn did not rely solely on implicit messages regarding NOS. From the very beginning of class, Glenn explicitly addressed NOS ideas. When introducing biology to the students, Glenn presented a biological worldview by first identifying common assumptions about nature including that the world exists to serve human needs, that species that directly affect human beings are more important, and that scientific knowledge is fixed. Glenn’s next slide was to say these ideas are not congruent with how biologists view the world. He was sure to note that students need not change their worldview, but that understanding how biologists view the world may be beneficial for understanding biology (Exam 1 ppts).

Other than scientific worldviews, Glenn explicitly noted several other NOS ideas. For example, NOS was made explicit when part of the Power Point used to guide the discussion noted, “As we get more data (evidence), we have a more accurate understanding of life on Earth and modify our classification scheme accordingly”. The slide finally mentioned, “conclusions in science are always ‘tentative’…” (Exam 1 ppts).

In a later presentation, the idea of tentativeness was revisited: “For many years plant biologists thought there were two large groups of flowering plants - dicots and monocots. Recent evidence suggests more complexity...” (Exam 2 ppts). When discussing the work of Thomas Hunt Morgan, Glenn noted, “[Morgan] did what scientists do. Changed his mind and accepted the Chromosome Theory of Inheritance, based on the available evidence” (Exam 3 ppts). Glenn revisits tentativeness again later: “As we’ve seen in other groups, classification of organisms is undergoing change due to the availability of new evidence” (Exam 3 ppts).

Related to the tentative nature of science is the notion that scientists disagree. During a discussion of Pogonophorans, the presentation highlighted how scientists disagree. “Some biologists consider these organisms to belong to Phylum Pogonophora, others consider them to be a Class within Phylum Annelida” (Exam 2 ppts). Glenn even noted how some aspects of science are simply considered unknown or “we just don’t know” (Exam 4 ppts).

While several of the above examples illustrate how Glenn discussed NOS while addressing biology content, sometimes Glenn would focus solely on NOS ideas. At one point, Glenn included a short discussion outlining the characteristics of science as (Exam 3 ppts):

- Explanatory by reference to natural law(s)

- Testable against the natural world
- Conclusions are tentative
- It is falsifiable

The presentation went on to differentiate between discovery science and experimental science:

- Discovery Science - mostly focuses on describing nature
- Hypothesis-Based Science - mostly focuses on explaining nature

These slides prefaced upcoming class sessions on evolution. Glenn focused many of his NOS lessons on misconceptions that likely inhibit student acceptance of evolution. NOS misconceptions, such as those related to the term “theory”, may lead people to dismiss the idea of evolution. Glenn pointed out that a theory in science is more than a guess. “I.e., this is a theory that is well supported by data (evidence) and that ‘works’” (Exam 1 ppts).

Glenn attempted to address student misconceptions in creative ways. For example, when introducing “theory” the following slides were used (Exam 1 ppts):

Slide 1:

What do we, in science, mean by the word “theory”?

Slide 2:

There’s a sign on the wall
But she wants to be sure
’cause you know **sometimes words have two meanings**.
In a tree by the brook
There’s a songbird who sings,
Sometimes all of our thoughts are misgiven.
Ooh, it makes me wonder,
Ooh, it really makes me wonder.
There’s a sign on the wall
But she wants to be sure
’cause you know sometimes words have two meanings.
In a tree by the brook
There’s a songbird who sings,
Sometimes all of our thoughts are misgiven.
Ooh, it makes me wonder,

Ooh, it really makes me wonder.

- Led Zeppelin, *Stairway to Heaven*

Slide 3:

Merriam-Webster Definitions of "Theory"

1 : the analysis of a set of facts in their relation to one another
5 : a plausible or scientifically acceptable Glennral principle or body of principles offered to explain phenomena
6b : an unproved assumption

Slide 4:

•*ANYBODY can have an "idea" and call it a "theory"using the "street definition" (~ definition #6b in the Merriam-Webster)*
• *But for an idea to be a scientific theory, it has to be supported by EVIDENCE - LOTS of evidence*
• *You can read more about theories in science on page 24 of your text.*

Slide 5:

In the realm of science…
• "Theory" means an explanation for a natural phenomenon that is well-supported by data and incorporates relevant laws
• The word "theory" can have other meanings in other contexts

The slides continued by comparing and contrasting between facts, hypotheses, theories, and laws. The presentation noted that a scientific law is "a universal relationship describing how the natural world behaves under <u>specific</u> <u>conditions</u>" and that a theory is "an explanation that takes into account, and is consistent with, all known facts and all applicable natural laws" (Exam 1 ppts). This discussion comprised several slides and more than five minutes of class time. Glenn even revisited the definition of theory throughout the course. For example, when introducing evolution, the presentation noted, "Without evidence an idea is…Just an idea, certainly not a "scientific theory" (Exam 3 ppts).

Another aspect of NOS that Glenn touched on was the epistemology of science. Glenn focused on scientists' use of evidence and how they make use of and interpret evidence and the importance of corroborating evidence. Oftentimes Glenn's presentations would go into detail concerning the evidence to support various ideas. For example, he discussed how both radiometric dating and sedimentation can be used as dating evidence (Exam 1 ppts). As another example, Glenn noted how scientists make use of structural comparison as well as DNA/RNA comparison to provide support for classification schemes (Exam 2 ppts). Whenever Glenn introduced a new biological idea (whether it be a relationship or an explanation), he most always noted evidence that supported the idea.

Explicit attention was given to how the ability to get evidence for ideas, or test ideas, helps demarcate science from other ways of knowing. When discussing evolution and intelligent design Glenn's presentation noted, "because intelligent design proposes a mechanism (a supernatural intelligent designer) that is not testable by the methods of science (which seek natural explanations), it is not a science idea, or a scientific theory" (Exam 3 ppts).

To help students understand why scientists seek natural explanations, Glenn had students discuss in pairs, then groups of four, why his truck wouldn't start. After some small group discussion and getting some ideas from the whole class he asked why none of their responses included demons or other supernatural explanations. With some further discussion he attempted to illustrate why supernatural explanations are not useful in science. However, science's adherence to natural explanations does not negate the possibility of supernatural beings (Field notes, 10/30/07).

Some less often noted NOS ideas included the role of serendipity and how science is not a solitary endeavor. Glenn highlighted the role of serendipity when discussion the work of Mendel. "Mendel was Lucky: the genes he studied were on separate chromosomes. He didn't have to deal with the complexity of linked genes in developing his ideas" (Exam 3 ppts). Glenn noted how science is not a lone endeavor when noting Darwin was not solely responsible for evolution. "The development of the theory of evolution is most closely associated with Charles Darwin - but others contributed and had similar ideas" (Exam 3 ppts). While Glenn notes how scientists' ideas build on one another, he did not explicitly draw students' attention to how scientists work collaboratively.

Glenn not only mentioned well-known scientists such as Charles Darwin and Gregor Mendel, he also devoted occasional slides with pictures to scientists whose work was related to topics being discussed that day in class. The scientists and what was mentioned about them are listed below:

- Carl Woese: "Person responsible for first recognizing the fundamental distinction between Bacteria and Archaea" (Exam 1 ppts).
- Lynn Margulis: "Proposed that the ancestors of eukaryotic cells were symbiotic consortiums of prokaryotic cells - The Endosymbiont Theory" (Exam 1 ppts).
- Walter Sutton: "Studied meiosis in grasshopper testes and proposed that Mendel's factors were on chromosomes" (Exam 3 ppts).
- Thomas Hunt Morgan: "Did not accept the Chromosome Theory of Inheritance and thus did what scientists do - tested the theory" (Exam 3 ppts).
- Charles Darwin: "Started out as a "pre-med". Then studied to be a minister but really interested in being a "naturalist". At the age of 22, voyaged around the world on the Beagle. Returned to England in 1836 and spent the next 23 YEARS analyzing and thinking about his specimens and writing a book" (Exam 3 ppts).

- Gregor Mendel: "Austrian (Czech) Monk, studied inheritance in peas, started the field of genetics with a paper published in 1865" (Exam 3 ppts).

Glenn also made "classic papers in genetics" available online. The papers included papers by Sutton (1902), Mendel (1866), and Hardy (1908). While inclusion of these scientists and classic papers does not necessarily indicate strong focus on NOS, Glenn's inclusion of the scientists and their past work demonstrates his desire to humanize science. This desire and his inclusion of accurate NOS ideas in his course are perhaps why Glenn was interested in implementing historical short stories.

Research Question 2

What are the biology instructor's impressions of the short stories after having implemented them in his course?

The instructor of the introductory biology course studied, Glenn, is a faculty member in the Biology Department at the large Midwestern university where the study was conducted. Glenn was interviewed during the summer of 2008 - one semester after the short stories were implemented. This interview was conducted after an initial exploratory discussion between Glenn, the author, and other research team members raised questions about how Glenn viewed the short stories. Major themes drawn from the interview with Glenn concerning the use of the historical short stories in his course are discussed below.

While the interview often explored the nature of science more generally, the discussion reported below is limited to Glenn's view of the short stories and their use in his introductory biology course. The discussion of Glenn's views is organized by providing a summary of Glenn's ideas or thinking related to each theme or sub-theme followed by excerpts from interview transcripts as support for the theme. When possible, larger portions of text are used rather than isolated phrases to provide greater context for Glenn's words. Also, whenever possible, text from multiple portions of the interview is provided as a form of triangulation of Glenn's thinking. Pseudonyms have replaced all names in the interview transcripts and discussion.

Short stories as outsourcing

Glenn viewed the short stories as outsourcing opportunities in that he did not have the time/expertise to create them. Glenn was glad to have the short stories as a resource and noted that he would have never generated the materials on his own. His lack of time and expertise in the history and nature of science would have prevented him from creating the stories. While Glenn's expertise lies with biology content, he would have had to expend tremendous amounts of energy and time to develop historical stories. Furthermore, while he claims to have an intuitive understanding of the nature of science and that his understanding is growing, he admits that he is only comfortable engaging in conversations about deep philosophical issues to a certain extent. He was glad to have a resource to which his students could go for more "digestible" information.

> And to be honest, I don't have the expertise to be able to tell that story in any…it would take me a lot of effort to be able to tell those stories the way I tell stories about biology because there I do have the expertise. There I know that, and when a student asks me a question, I can usually give them some kind of reasonable answer. The short stories have been developed, researched by people, and the folks in history and so forth, who know far more about that aspect than I do. I don't want to have to go to the work of learning that, I'm quite happy to have you guys provide that to me. So,….and it is in this relatively encapsulated, digestible form that I can give to students outside of class. I don't have to burn class time to talk about Darwin's

> historical context or whatever. I think those are the things that I really…..that is why I choose to use those. (Glenn, 1:12:00)
>
> The second part is my level of knowledge and my level of understanding. What do I have a firm grasp on? I think we have talked a little about how I have learned some things along the way, not necessarily from the short stories, but from Todd (Director of the stories project) and deciding that I need to think about this more deeply. Would I really be comfortable trying to explain to students if I decided to use the word "methodological naturalism"? Would I feel like I could really explain that well? Concisely? Accurately? I know what it means, it means that you can't say that God did it. ok, that is fine, but saying that to students is going to do nothing more than alienate them because many of them think that God did do it at some level. Even if it was that God set up evolution. So, could I really…do I have the knowledge base and comfort level to really explain a pretty difficult idea in the nature of science well enough and in a concise enough fashion. (Glenn, 1:20:00)
>
> Just a general comment is that I would have never generated [the stories] on my own, never. I would have been dead three hundred years before that got high enough on the priority list, so I am appreciative, in the sense, both that I wouldn't have had the time and I wouldn't have had the expertise to put them together. So I look at them now as quite useful resources that had been generated with virtually no effort on my part (Glenn, 2:04:15)

Glenn specifically used the outsourcing metaphor when noting that the short stories contained geological content that he did not want to take biology class time to address. Furthermore, he notes that he would not likely have the content expertise to discuss the age of the Earth concept in as great of detail as the stories did. Glenn's value of his instructional time was a consistent theme throughout the interview.

> One is, with the age of the earth short stories, you know, the estimates we have of the age of the earth are really important for a lot of things in biology, a lot of ideas in biology, but this isn't a geology class and I don't want to spend a lot of time doing that. So, I guess I kind of look at those two short stories as a way of out sourcing…getting my students some information about the age of the earth and why we think it is the age that we do and a little bit about the history and the people who were involved, without my spending very much time in class at all on it. In class, I talk about stratigraphy and radiometric dating, but really not much. So I really just kind of outsource those ideas to the short stories. (Glenn, 1:11)

> For those, I think that the content there that I don't want to teach but is useful for them to know about is that this isn't something that just came out of the blue, this is something that people have been talking about for a long time, people had these different ideas, you know, etc, etc. At one time it was 100,000 years old, and why that was wrong. I mean, these are geology topics and in fact those stories were developed for the geology class, but they have very strong connection to and implications for biology and when I'm talking about biological diversity, I'm frequently saying, "well, this group of organisms appears in the fossil record 420 million years ago". I mean I can just throw those numbers out, but what I'm trying to do is provide some context of understanding of where those numbers come from without sacrificing a lot of my time to teach geology, which I couldn't really teach anyway cause I don't really know geology. For me it is a stretch to just understand the principle of radiometric dating, let alone many other details that I'm sure elude my current understanding. (Glenn, 2:10:00)

Glenn also notes that having the stories come from an "outside" source is valuable. Rather than students thinking the stories are just one more thing the professor wants, he hopes the students read them as they would a textbook – with a sense of authority be placed with the stories.

> I think that that is critical. I think that if it was coming from me, it would be just perceived as more of the same. The fact that it is coming from somebody else, who they don't know and who sounds important, I think is probably useful. In fact, at one point we were using versions of the short stories that would have been in the preliminary or pilot thing and it didn't say anything about who had authored it. And I specifically asked Todd (Director of short stories project) to put that on there because I didn't want the students thinking that I had written it for them. I wanted them to look at it in the same way they might look at a text book or a paper that I had…. (Glenn, 1:16:30)

Short stories compliment content instruction

In addition to providing instruction of geology content he did not want to take class time to cover, Glenn noted that the short stories augmented and provided context for the biological content he teaches. While Glenn wants to spend his instructional time covering biological ideas, the stories provide insight as to how the ideas came about and paint a picture of the people behind the ideas. Furthermore, Glenn notes how the stories provide context for the ideas to which he refers.

> The other three short stories that I use, Mendel, Wallace and Darwin, those three individuals are just absolutely central to what we're doing in that course. One of the fundamental themes of that course is genetics and evolution and their connections. So I was using those [short stories] in my view to augment what I was doing in class as opposed to outsourcing and at the same time, bring in something that I wasn't going to do in class. Which was to talk about these people and their particular histories and backgrounds and so forth. From my perspective, that was really the advantage to using those. (Glenn, 3:00)

> Certainly I talk about Mendel and talk a little bit about who he was, but much less than what was in the story. I talk about Darwin, a little bit about who he was, but much less than what was in the story. And Wallace I probably don't talk about really other than just to mention during presentation in class. So I'm really sort of using the short stories to provide an opportunity for the students to have a bigger, broader, more well-developed picture of who these people were than I want to take the time to do in class. What I want to focus on in class is, you know, the ideas that these people had and why they were important for biology and how we use them, those sorts of things. That is how I want to spend my time, but I think it is really useful for the students to have an opportunity to learn more about these individuals as people. (Glenn, 5:40)

> I mean, these are geology topics and in fact those stories were developed for the geology class, but they have very strong connection to and implications for biology and when I'm talking about biological diversity, I'm frequently saying, "well, this group of organisms appears in the fossil record 420 million years ago". I mean I can just throw those numbers out, but what I'm trying to do is provide some context of understanding of where those numbers come from…(Glenn, 2:10:00)

Short stories teach NOS

Considering the short stories were designed for improving student understanding of the nature of science, Glenn's noting the utility of the stories to teach NOS is not surprising. While Glenn, who is likely not familiar with the science education NOS literature, does not discuss specific NOS ideas, he does make clear that he believes the short stories improve student understanding of how science works. He notes that the stories help students realize that science is messy and more complex than many students imagine. Glenn notes that the stories are about real individuals doing real science and that the "lone genius" model for science doesn't hold up for how science ideas are developed or how they are accepted. Science ideas take an unpredictable path to acceptance and the stories make clear that the notion "A leads to B" just doesn't work.

> Well….I think that…These people are, you know, extraordinarily important people in the history and development of biology. There's no argument about that. So I think that just from a historical perspective it is worth it to know something about these people. But I also think that it is useful to get a glimpse of how science really works and how it proceeds and I think that maybe the, you know, the two examples that I'm glad are part of those stories are number one with the Darwin and Wallace thing. You had two people working unbeknownst to each other in terms of what they were doing and what they were thinking and at some point along the line it becomes clear that they were both thinking the same sorts of things. That happens in science a lot. You've got research group A over here working on something and research B working here on something and they may not realize that there is a big connection but they both happen to go to the same meeting or one of them publishes a paper. So, I think that is an important thing. A second thing, with the Mendel story, the fact that his work was lost, buried, unappreciated for, I don't know, 30 or 40 years. I don't know if that would happen today because information is, you know, more readily accessible, but even so, you know, sometimes insights are not appreciated immediately and it takes some further work before that occurs. So I think that both of those are little insights into how science actually works from the perspective of the people who are actually doing science. So, I don't know for sure how much I …I know I talked about how Mendel's work was ignored, you know, it wasn't understood how important it was for a long time. So I think that is some important insight into the process of science. So, that is why I think it is important for them to know more about these people and learn from their stories. (Glenn, 7:00)

> But one of the things that I value about the short stories in this context is I think it helps the students understand that the world is a hell of a lot more complex than they understand. It wasn't just Darwin, inspired by God or the Devil or whoever who came up with this ideas in a blinding flash of light, which is a very easy way to think about it. It was actually part of a whole bigger picture and there were a lot of people who had different pieces of it and who impacted Darwin in various ways. So, I think that what I'm trying to say is that it tries to pry the students away from that "the world is black and white" view and helps move them toward the world is gray view and it is not as simple as "A happened and that led to B". It is a complex interaction. And I think the stories capture some of that complexity. You know, I think the clearest example is Wallace and Darwin, but even the age of the earth stories. The interaction between the various people who were thinking about this and the church and public opinion and with…amongst the group of people who were thinking about the age of

> the earth, it is not a simple story. It is a complicated story. So in a lot of ways, a lot of the student comments could be summed up as, "wow, this was more complicated than I thought it was". I think that is a step forward. I mean, I think that seeing that the world is not a simple place, seeing that the world is complex is a useful step in terms of understanding the world as well as understanding science and how science works. So, to me, that seems like a useful thing…it is a reason that I want to use the short stories. (Glenn, 1:09:30)

> I think it may help alleviate some of those things. I think this is one of Todd's (Director of short stories project) main goals that demonstrating that science is a social activity that it involves other people that the lone genius working on a mountain top is a very inaccurate description of science and that is some of the things that I read when I read student responses. One of the things I notice is that students recognize that "oh gee, I thought science was working in a lab by yourself and it turns out science is interacting with all kinds of people". So, I think that they might attract some people who would otherwise be like, "oh biology, all you're going to be is stuck by yourself working at a microscope". There are some people who do kind of like working on microscopes, but that is really not all that they do. (Glenn, 1:59:00)

Very little NOS instruction time

Using short stories outside of instructional time to illustrate and teach about NOS concepts is of great value to Glenn. While Glenn believes that understanding the NOS is important for his students, he claims to allocate very little direct instructional time to these complex issues. He estimates only one-thirtieth of his time is spent on NOS issues, including time he uses in class to discuss the short stories. For the most part, Glenn's report of how he addresses NOS ideas is accurate, but he seems to underestimate how much attention he pays to NOS ideas in his lectures.

> I spend some time at the beginning of the semester talking about theories and laws, and the like. Then I spend some time in the middle talking about methodological naturalism, although I don't use that phrase, and talking about discovery science vs experimental science. Those are probably only the sort of explicit….we are talking about only 20 – 25 minutes of explicit instruction on the NOS. But along the way in context I try to hit the more tentative NOS by saying "this is what we know now" things like that along the way. (Glenn, 57:00)

Glenn notes that the use of the short stories has increased the total amount of time he spends on the NOS in class. He also speculates on his colleagues' view of including the NOS. Not surprisingly, Glenn believes his colleagues would think anything that distracts from strict biology content instruction does not belong.

> Oh yeah. I don't think there is any question about that. It is still not huge, but I think the fact that I want the students to talk about….and we are taking some discussion time in class to talk about it. I guess I would look at it as it is all part of a system and the fact that we were doing the short stories and thinking about some NOS stuff made me want to take some time to talk about the theory things in more detail and methodological naturalism and discovery science vs. experimental science in more detail…probably reminds me to keep reminding the students about the tentative nature of science. So, I think that it is no one thing in isolation, it is kind of all these things working together that have led to an increase in the amount of time and energy and effort that I am putting in to the students in terms of their understanding of the NOS. But it still is…. sum total is no more than a class period, so it is 1/30 of the time in my class. Do I think that is an appropriate amount of time? I don't know. I'm sure that I have colleagues who would think it was an inappropriate amount of time and that I was spending too much time on it. I guess I look at it and I think, this is probably the bare minimum amount of time that is going to be of any value. If I spend any less than this, I may as well not do it at all because it isn't going to mean anything. Could I spend more time on it? Well I'm not an expert in NOS, I'm sure I could spend more time on it, or I could have guest lecturer. But I'm not sure I want to sacrifice anymore of my content time. (Glenn, 1:15:00)

Not only do the short story discussions themselves increase the time devoted to NOS, the purpose of the short stories has perhaps affected how Glenn constructs his lectures. From working with the short stories Glenn has begun to consider how he might provide more insight into the human side of science and strives to include some information about the people behind the ideas. Glenn does admit that advances in technology have made finding this information easier, but also notes that he may not have thought to include human aspects were it not for the short stories.

> hmmm… Well, in a sense, as funny as this might seem. I think there is an impact right there (Picture of Carl Woese). It is becoming increasingly common for me to include pictures and descriptions of people who were important in the development of

> a particular idea or in the discovery of whatever. It is a little bit conflated in the sense that partly that this is a result of its technologically easier to do that. I mean, I can get onto Google and find a picture of Carl Woese. Twenty years ago when I started teaching, you couldn't have done that. If the textbook I was using happened to have an overhead that had a picture of Carl Woese, or more likely Watson and Crick, I could do that. But today, I can do that for anybody basically who….I have a picture of Kenneth Miller in my presentation, the author of this book they are going to be reading. So the point is, that I think the short stories and the ideas, this humanizing science idea, which is kind of the goal or subtitle of Todd's project has sensitized me to the notion of why just say so and so did this, why not show a picture of them and tell a little bit about them. And let's see if we can't have the pictures we show not be all old white guys. I mean, can there be some women, some diversity. And of course in some ways that is a tough challenge because of course old white guys had more opportunities to make these kinds of contributions, but the point is that I think that has been a real change. It is connected to or conflated with the easy technological access too. But just the idea of doing it, I mean, just because it is easy to do technologically doesn't mean you are going to do it. If you don't have the idea that it might be useful for the students to see that this was a person, is a person, or whatever. That is at least one example. (Glenn, 1:25:00)

Content focus

While Glenn notes that his colleagues would think that any NOS instruction would be too much, he admits that his chief concern is also biology content. Glenn believes that learning about the history and people behind the biology concepts is important, but struggles to rationalize giving up valuable instructional time to discuss these topics. Several times during the interview, Glenn notes that every second he spends on explicit NOS instruction, is a second less of content instruction – "it is a zero sum game".

> I think that most intro bio teachers struggle from the perspective of "how do I fit all of this in?" "All this" being all this incredible amount of information which is what the field of biology currently includes. We know a lot of things and there is no way you can talk about all of it in any kind of sensible way in a semester long or year long introductory biology course. So you are going to have to be prioritizing and deciding what aspects am I going to leave out. And I think most of my colleagues would look at [the short stories] and say this is just one more thing that is going to make me leave out biology and why would I choose to do that. So I think that likely relatively few biology instructors would be interested in incorporating this into their class. I could be wrong about that, but that is my suspicion. (Glenn, 15:00)

> What I want to focus on in class is, you know, the ideas that these people had and why they were important for biology and how we use them, those sorts of things. That is how I want to spend my time, but I think it is really useful for the students to have an opportunity to learn more about these individuals as people. (Glenn, 5:40)
>
> I think there's two. I think I have probably mentioned both of them, but to mention them while your asking, I think the two are obviously, time, it is a zero sum game. Every second that I spend talking explicitly about the NOS is one less second that I spend talking about, sort of, you know, biological discipline ideas. So it becomes a triage or prioritization problem. (Glenn, 1:19:15)

Stories useful in context of content instruction

With Glenn's focus on content, his unwillingness to devote a unit to NOS is not surprising. Glenn notes that he wants the students to learn about the development of the ideas or the people behind the ideas while they are learning about the ideas themselves. Glenn also explains that he believes this contextual instruction would help students better understand NOS concepts.

> I would have never used it as a unit. If what you are telling me is the circumstances I was in was, ok, here is this block of short stories, we want you to spend a week or two weeks going over – I would have never done it. (Glenn, 11:00)
>
> The only way that I was interested in doing this was to interweave it into what I was already planning to do. Adding up front or in the middle somewhere, anywhere, you know, a unit that was specifically "ok we are going to spend the next several class periods talking about the nature of science"…I wouldn't have wanted to spend my time that way. I'm trying to think how I might defend that, you know, what is my rationale for that. I think what it boils down to is I want to have them look at NOS issues sort of in context as we are talking about those things in class in terms of ... beginning of the semester we are talking about the history of life on the planet and the great age of the planet and, you know, when these kinds of organisms were around and so forth. To me, that is the kind of context in which I want the students to know how we come to this conclusion. When we get to the point we are talking about genetics ideas and Mendel and evolutionary ideas and Darwin, that is the point at which I want them to….So what I think it really boils down to is I want to….to me it seems best, and I don't know that I have evidence that would convince me or anyone else, but to me it seems *a priori* best to have the nature of science instruction in

> context with, you know, the biological concepts or ideas that it is related to. I think it is important that they learn about the NOS, but I guess my fear is that if they learn about the nature of science out of context, quote learn about it, if they are exposed to the nature of science out of context that they are not really going to learn it, that they are going to learn it better if it is in context. So that is my rationale, as poorly supported by evidence as it might be. (Glenn, 13:00)

Reduce student resistance to evolution

Throughout the interview Glenn repeatedly indicates that he believes NOS understanding reduces student resistance to biological evolution. This belief is not unfounded (Southerland and Sinatra, 2003) and is a major driving force for Glenn's inclusion of the short stories and explicit NOS instruction. Glenn especially notes the Darwin and Wallace stories as useful in battling student resistance to evolution. He notes that students are largely unaware of Wallace's work and that others, besides Darwin, had been working on the idea of evolution for quite some time. When asked about the short stories' impact on student content understanding, Glenn forcefully notes that all he really cares about is reducing student resistance to evolution. Most all of Glenn's decisions regarding NOS instruction are somehow linked to his concern with student resistance to evolution including his explicit, in-class discussions on the term theory and the concept of methodological naturalism.

> On the other hand, I think there has become, and it is the whole controversy over evolution that has become the flashpoint that is the lightening rod that is leading the charge on this. And I think it is becoming increasingly clear to a broader and broader range of scientists and college level and other level instructors that the public in general does not understand what science is and what it can do and what it cannot do, etc. So I think that maybe, I would still say it is probably a minority, but maybe there is a growing minority of science instructors that recognize that spending all of your time on disciplinary content is not going to get you where you want to go. Where you want to go is real understanding of at least some of that content. And I don't think you can get to real understanding of at least some of that content unless the students have a clearer idea of what science is and how it operates than they typically

have. So, you are going to have to sacrifice in my estimation. Sure I could talk about more groups of invertebrate animals or spend time talking about, you know, whatever, but I have chosen to spend at least some time, both presenting perspectives on the NOS myself, having the students read the [short stories], having them do some discussions in class and so forth. So I'm taking some time to do this, but it is clearly a zero sum game. Whatever time I put into NOS is less time that I will put into biology content and I think a lot of people would be unwilling to give up any. (Glenn, 17:30)

I don't think there is any question in my mind of which I found most useful and like the best – it was the Wallace story. It is the one that I really wanted when we talked about this to begin with. Why? Because evolution and Darwin are so closely tied together. This is an example of the appeal to authority thing, well you believe in Darwin and I believe in God and my authority can beat up your authority… You know what I mean. It really is that sort of simple. So I think that   students have this notion that Darwin, all on his own without any input from anybody, which is hooey because there were people thinking about evolution well before Charles Darwin, they just didn't have a good mechanism and they didn't have enough evidence. Their notion is that he is this authority figure and he stood on the mountain top and bushes burned and he made pronouncements and whatever else needs to happen and therefore all biologists believe this. Well,that's not of course the way it works at all. Darwin's ideas have been modified, expanded, improved upon. It is not like whatever he said is what we still bow down to or anything like that and it is not like he was the only person thinking about it and that is why I think the Wallace story is so powerful, is to see that there was someone else who these students have no knowledge of and I'm sure 99% of them have never heard of Wallace. When they write about this, that is one of the things students comment on that they were surprised that there was somebody else doing this kind of thinking and so that is what I'm trying to get to so I find the Wallace story most helpful because I think it is the most surprising. And it directly erodes away this "Darwin is the authority figure" notion and the story itself is so compelling. I mean this guy had some adventures. (Glenn, 30:00)

By the time we get to evolution, I have used the word theory in several scientific situations. So the red-flag component about theories goes down. (Glenn, 59:00)

Somehow I feel [teaching NOS] decreases the…..resistance to being there, somehow it lowers the level of students being upset, getting up and walking out and confronting me publicly. (Glenn, 1:04:42)

But one of the things that I value about the short stories in this context is I think it helps the students understand that the world is a hell of a lot more complex than they understand. It wasn't just Darwin, inspired by God or the Devil or whoever who came up with this ideas in a blinding flash of light, which is a very easy way to think about it. It was actually part of a whole bigger picture and there were a lot of people

> who had different pieces of it and who impacted Darwin in various ways. So, I think that what I'm trying to say is that it tries to pry the students away from that "the world is black and white" view and helps move them toward the world is gray view and it is not as simple as "A happened and that led to B". It is a complex interaction. And I think the stories capture some of that complexity. You know, I think the clearest example is Wallace and Darwin, but even the age of the earth stories. The interaction between the various people who were thinking about this and the church and public opinion and with…amongst the group of people who were thinking about the age of the earth, it is not a simple story. It is a complicated story. So in a lot of ways, a lot of the student comments could be summed up as, "wow, this was more complicated than I thought it was". I think that is a step forward. I mean, I think that seeing that the world is not a simple place, seeing that the world is complex is a useful step in terms of understanding the world as well as understanding science and how science works. So, to me, that seems like a useful thing…it is a reason that I want to use the short stories. (Glenn, 1:09:30)

> I don't think we ever want to treat the NOS just before evolution, then is seems like evolution is special or different that you have to make excuses for or something. I wanted some time to deal with NOS before we got to evolution. (Glenn, 1:38:00)

> I guess what I am saying is, if [the short stories] had zero impact on their understanding of content, I would still assign them the short stories because of the other reasons I have for assigning the short stories. Does it help them understand the content? I don't know and I'm trying to imagine in the context of evolution, that is, the Darwin and the Wallace stories…. I would be happy with lowering their resistance [to evolution]. (Glenn, 2:07:00)

> My expectations is that maybe it reduces their resistance to learning about evolution a little bit, maybe it gives them a little bit broader understanding of the history of our understanding of the age of the earth, but beyond that I don't care. (Glenn, 2:11:00)

High level of short story implementation

Glenn's implementation of the short stories, while perhaps not as extensive as possible, was extremely high. Glenn had his students read five short stories and complete the embedded questions, held small group discussion based on the short stories, had students reflect in writing on their discussions and took time in addition to short story discussions to address NOS concepts. Of course, this high import placed on the stories and NOS in general begs questions of Glenn's rationale for placing such importance on the stories. Glenn's explanation essentially notes that since he believes the stories are worthwhile, he needs to send that message to his students and encourage them to engage meaningfully with the stories if the students were to receive any benefit.

> Well, I guess it is a trivial reason. I wanted you and Todd (director of short stories project) to be able to have these things tested at some high level rather than a cast off. But I think the real reason is, what would the value be of just having them read it? Zero. Most of them wouldn't read it or wouldn't read it carefully. So, I guess, from my perspective, what it boils down to is how could you have implemented this at any lower level and had the students get anything out of it? Unless there is some kind of expectation that they are going to be held accountable for this, they are just not going to do it. And I don't mean to say that makes them bad people, that is just human nature. So, my job as I see it is to set up an environment where it is to their advantage in some way to actually read it. And I suppose the advantage is not to look bad with their partner when they discuss. Also, there is some contribution to their grade, although they weren't assessed in any way…whatever they wrote they got points for. So, I guess from my perspective, this is about the minimum that could be done and had any expectation that this would be beneficial for the students. If you didn't have them write about it, if you didn't have them discuss it, they just weren't going to do it, they weren't going to read it. And even if they did read it, they wouldn't get as much out of it as if they had actually taken the time to actually write something about it and then discuss some of their writing with a colleague. So, I guess my basic take was, look if I'm going to do this at all, I want the students to benefit from it. This is the thing that is going to help them benefit from it. (Glenn, 1:29:00)

Future use of short stories

Importantly, Glenn intends to continue using all five short stories in his course even though the research project has ended. His intent to continue using the short stories strengthens the interpretation that Glenn saw great value in the short stories and that he believes the stories will help him promote the goals he has for his students.

> I'm in the process of working on 211 for this fall and I'm still planning to use all 5 of those stories even though you guys aren't planning on collecting data as far as I know. So, I found it valuable enough to continue it, I guess. (Glenn, 4:00)

> It is already on my syllabus, they are written in as, I'm calling them assignments basically. I'm going to do for sure those five. It is actually going to be substantial chunk of their grade this year. Let me give you a quick idea. This isn't set in stone, but…..it looks like it will be close to about 10% of their grade. It'll just be that they

> did it, that is basically all it will be. I'll have to look at it again, but some part of the points were for their typed answers and some part for their in class discussion reflection. (1:32:00)

Research Question 3

What are the students' impressions of the short stories and what impact do students report the HSS have on their NOS understanding and interest in pursuing a science career?

Students' General views regarding the historical short stories

Students were given an in-class questionnaire consisting of Likert-scale items, rank order items, and open-ended items. The questionnaire was given after all short story assignments had been completed. The questionnaire was used to investigate students' impressions of the short stories and to what extent they felt the stories helped them learn about NOS. The full questionnaire is found in Appendix A.

When students responded to the Likert-scale item concerning how interesting they found the short stories as a whole, the mean score was 2.88 with a 95% confidence interval of [2.73, 3.02] (p = .084, N = 153, SD = 0.88). This result was not significantly different from a mean score of 3 (neutral interest in short stories as a whole). Frequencies of student responses are reported in table 1.

Table 1. Frequency of students' response concerning interest in the short stories as a whole.

Value	Label	Frequency	Percent
1	Very Interesting	6	3.9
2		47	30.7
3	Neutral	65	42.5
4		30	19.6
5	Very Uninteresting	5	3.3

To investigate students' perceptions of individual stories, the questionnaire asked students to rank order the stories from most interesting to least interesting, leaving blank stories they did not read (average rank is reported in Table 2). On average, students seemed to perceive the stories about specific scientists such as Mendel, Darwin and Wallace more interesting than the stories that did not focus on a central character. However, this result could also be explained by the fact that the biology course studied would have a natural bias toward biology content such as Darwin, Mendel and Wallace and students would be less interested in the two age of the Earth stories since the content is more geological in nature.

Table 2. Average student ranking of the short stories based on interest.

Story	**N**	**Mean**	**Standard Deviation**
Early Efforts	143	3.80	1.19
Deep Question	142	3.18	1.50
Mendel	144	2.84	1.38
Darwin	143	2.07	1.14
Wallace	141	3.04	1.25

Students were also asked how many of these short stories they would like to have if the stories replaced other homework (frequencies are reported in Table 3). The highest category for student preference was in the 3-4 story range (41.3%). Interestingly, very few students suggested that stories not be included in the course.

Table 3. Frequency of response concerning number of short stories students would like.

Number of stories	**Frequency**	**Percent**
None	12	7.7
1-2	48	31.0
3-4	64	41.3
5+	31	20.0

To further explore students' general views of the stories, the survey asked for additional comments students have about the short stories. Since most students commented on the stories more generally, the results of analyzing the students' comments will be discussed here rather than in the next section pertaining to student learning of NOS.

Student comments were read and grouped into similar themes through constant comparison with developing themes. Once initial themes or categories were created, they were grouped into larger, more inclusive themes. When an initial category could not be grouped with other categories it remained its own category.

Several themes were developed from student comments. While some comments were vague, other comments were specific and provide insight into how the students viewed the short stories and ways they would like the stories to be improved. Although student enjoyment of the stories is not the top priority of the stories, investigating students' views provides insight into what frustrations or concerns students have with the stories, and what might be done with the stories to make them more effective.

The total number of students who responded to the open-ended item "Additional comments you have would be very much appreciated. Thanks!" was 72. Some students' responses contributed to multiple themes resulting in a higher total than 72. Themes generated from students' written responses and the numbers of students categorized within the theme are presented in table 4. More detailed discussion and representative examples of student views follows.

Table 4: Themes developed from student open-ended responses concerning views of historical short stories.

Student Views	**# of students**
Positive Views	**30**
• *Generally interested or enjoyed the stories*	12
• *Stories provide varied learning opportunity and encouraged new thinking*	8
• *Stories supplemented class well*	3
• *Enjoyed learning about history of science and/or how science works*	5
• *Enjoyed aspects concerning science & religion*	2
• *Learned that scientists take years to reach conclusions*	1
Negative Views	**35**
• *Generally disliked the stories or found them boring*	4
• *Stories disconnected from class*	2
• *Wanted stories to be shorter*	4
• *Stories too much work*	3
• *Found embedded question confusing*	12
• *Stories were common sense*	3
• *Found stories to be similar or redundant*	12
Made Suggestions for Improving Stories	**5**
• *Specific suggestions for improving short stories or their implementation*	2
• *Desired class discussion about stories*	3
Generally ambiguous views of stories	**2**

Positive Views

Generally interested or enjoyed the stories (N = 12)

Several students claimed positive views toward the historical short stories, but did not provide enough detail to understand why they liked the stories. Many of the students in this category simply said "They were interesting". Some students in this theme noted that the stories were "easy points" and "since they were short, I was more motivated to read them". These students didn't provide any attributes about the stories that were of interest other than they were short or easy. One student noted the stories were "worthwhile as long as they seem interesting to the majority of the students".

Stories provide varied learning opportunity and encouraged new thinking (N = 8)

A subset of student who held favorable views of the stories noted that the stories got them "to think about science". These students commonly noted that the stories required a "type of thought process [that] is more beneficial then lectures and 'BASIC' worksheets". These students saw the stories as "a nice homework alternative" that got them "to look at topics in a new way" or "helped me understand [science] in a new way". Students in this group saw the embedded questions as "deep, thought provoking, and complex".

Stories supplemented class well (N = 3)

These three students simply noted that the stories "went along with what we were learning in class". They felt the stories were a "good supplement to the by-the-book teaching common in class" and that the stories were "a good way to provide more information that wasn't covered in class, or in the textbook".

Enjoyed learning about history of science and/or how science works (N = 5)

This group of students saw value in learning about the history of science. They claimed, "it was good to read about past scientists that everyone knows". One student noted how the stories "add a bit of background on biology" while another student simply claims the stories "help inform on the history of science". One student highlighted how the stories "talked about individual scientists and their work" rather than just science content.

Enjoyed aspects concerning science & religion (N = 2)

Somewhat surprisingly, the only mention of science and religion was in a positive light. One student claimed "history of science and religion interaction [was] very interesting". The second student explained in greater detail why they enjoyed the stories' attention to science and religion:

> I like how some of the stories dealt with struggles with religion, because that is one of my main beefs with science: some things we learn conflict with my views religiously.

While the student doesn't go into detail about how the stories helped or hindered the "conflict" between science and religion, the fact that they liked the stories because of their inclusion of religion and science is an indication that the students' views of science and religion became more able to coexist rather then in greater opposition to one another.

Learned that scientists take years to reach conclusions (N = 1)

This student claimed, "the most important idea I learned was that scientists take years to find great conclusions – very important to aspiring scientists".

Negative Views

Generally disliked the stories or found them boring (N = 4)

These students did not provide much detail, just simply stated that they "didn't enjoy reading the short stories". The students claimed the "stories were really boring" or "not very helpful". While these ideas reflect their personal impressions, their lack of explanation is not very helpful for improving the stories.

Stories disconnected from class (N =2)

Previously, some students saw the stories as a nice supplement to class. These two students felt the opposite way. One student claimed, the stories "didn't relate as much as they could to class discussions". The other students "saw no connection between the short stories and the rest of class".

Wanted stories to be shorter (N = 4)

This group felt the description of the stories as "short" was misleading. One student simply said, "They aren't really that short". Another student felt the stories "may be more effective if they were more concise". This student felt the stories "seemed to go on and on". This sentiment was echoed by another student who said, "the stories are long and drag sometimes".

Stories too much work (N = 3)

Similar to the desire for the stories to be shorter, this group felt the stories were "way too much work for the amount of points given for the assignment". One student wanted "the stories assigned more spread out" and felt assigning two short stories at a time was unreasonable.

Found embedded question confusing (N = 12)

One of the more common criticisms of the short stories concerned confusion with the embedded questions. While some students said, "the questions with the stories were a little confusing", others felt "the questions didn't seem relevant to the reading". One student even thought the questions needed to "relate more to the stories [rather] than personal thought". While many in this group thought the questions were "wordy and strange" a couple students noted they were not "sure what my professor was looking for in my answers". The open-ended nature of the questions seemed to bother these students who are likely used to expecting answers to either be right or wrong rather than contextual. Alternately, these students might be used to finding clear answers in the reading rather than having to reflect on ideas.

Stories were common sense (N = 3)

A small group of students claimed to not have learned anything from the short stories. "What wasn't plain statistics was paragraph upon paragraph of common sense!" While the statistics aspect of this students' view is confusing, their view of the stories as common sense was supported by another student, "I feel [the stories] are very common sense based". While these students might find NOS ideas to be common sense, later analysis of student responses will demonstrate that many students do not find these ideas to be straightforward.

Found stories to be similar or redundant (N = 12)

Another more common negative review of the stories was redundancy. Admittedly, the stories do touch on common themes and some questions are similar. These students explicitly noted this repetition as negative. "The stories all asked the same question about scientists being creative, I got sick of answering it." Another student "felt like there was so much repetition between the stories sometimes". Other students asked to "have a wider variety of stories".

Made Suggestions for Improving Stories

Specific suggestions for improving short stories or their implementation (N = 2)

Two students made specific requests regarding the stories that did not fit with other themes. The first student noted, "more short stories on natural biological phenomena would be pretty cool" meaning they seemed to enjoy the stories clearly related to biology content.

The other student suggested “an online quiz about the stories might be a good idea after reading each story.

Desired class discussion about stories (N = 3)

Some students wanted to more thoroughly discuss the stories in class. One student wanted to discuss them so they “knew exactly what you wanted us to get from the readings”. This desire relates to students’ frustrations with the open-ended questions. Many students seem to struggle with ambiguity. However, another student noted that discussing the stories in class would help her “understand [the story] in more depth”.

Generally ambiguous views of stories

Generally ambiguous views of stories (N =2)

Lastly, two students provided additional comments but seemed to be “on the fence” about the stories. These students noted that the stories were both good and bad, boring and interesting. “They were interesting, yet bland at the same time. Learning, yet boredom.”

Reported influence of historical short stories on NOS understanding

The questionnaire described previously also asked the students to what extent the short stories taught them something new about how science works. The mean response for this question was 2.57 (N = 156, SD = .88) with a 95% confidence interval of [2.43, 2.71] indicating that, on average, students felt the stories taught them slightly above “somewhat” new ideas regarding how science works. Frequencies and percentages are reported in Table 4.

Table 5a: Frequency of students' response when asked to what extent HSS's taught them something new about how science works.

Value	Label	Frequency	Percent
1	Very Much	15	9.6
2		59	37.8
3	Somewhat	64	41.0
4		14	9.0
5	Not at all	4	2.6

Students were also asked to indicate on a 1-5 Likert scale to what extent the short stories changed their views of how science works (frequencies reported in table 5). The average student response was 2.96 (N = 156, SD = .90) with a 95% confidence interval of [2.81, 3.10] indicating somewhat of a change. The largest percentage of students chose number 3 indicating that the stories *somewhat* changed their views regarding how science works. This "somewhat" response is not surprising considering that these students are mostly science majors so their views of science ought be more established then the general public.

Table 5b: Frequency of students' response when asked to what extent HSS's changed their views about how science works.

Value	Label	Frequency	Percent
1	Very Much	8	5.1
2		36	23.1
3	Somewhat	74	47.4
4		31	19.9
5	Not at all	7	4.5

Student interest in science careers

A separate questionnaire asked for students to report how the short stories affected their interest in a science career using a Likert-scale item and through open-ended response. On average, students indicated that the short stories increased their interest in pursuing a science career. The Likert-scale item asked students to circle between numbers one and five: five indicating great increase, and one being great decrease, with three indicating that there was no change in the student's interest in pursuing a science career. The mean score was 2.65 ($p<.001$, $N = 156$, $SD = .71$) with a 95% confidence interval of [2.54, 2.77]. This average was statistically different from 3, no change in interest, demonstrating that, on average, students claimed the stories increased their interest in pursuing a science career. This result is particularly impressive considering that this population of students is already highly interested in science. This already high interest might explain why more than half of the students claimed the stories caused no change in their interest in science as a career. Descriptive themes developed from student comments are discussed in greater depth below.

Table 6: Frequency of students' response concerning the HSS's affect on their interest in science as a career.

Value	Label	Frequency	Percent
5	Decreased Interest	3	1.9
4		5	3.2
3	No Change	90	57.7
2		51	32.7
1	Increased Interest	7	4.5

The discussion of student comments below is meant to be descriptive in nature. Student views are organized first by indication of increase, decrease, or no change in interest in science as a career and then sub-themes are explored with reference to actual student comments.

Increased interest in science careers

Many students who indicated that the short stories increased their interest in science as a career and made additional comments indicated that they learned something from the stories. Much of what the students claimed to have learned that increased their interest was closely tied to nature of science understanding.

> [The stories] showed me that science is not only done in a lab which was nice so there are more opportunities.
>
> The cooperation and social aspect of science is something I knew little about, and it makes the career seem much more attractive to me.
>
> It encouraged me to know that scientists work together.
>
> Encouraging to see that science is made up of small contributions.

Other students claimed to have learned something more generally or increased their interest in learning about science.

> [The stories] give me a new insight to issues in science.
>
> I really liked to read them because I learned a lot.
>
> I thought they added a lot of interest to learning about science
>
> Looking forward to learning more.

Some students identified specific topics or individual short stories of interest. Students seemed to enjoy the stories concerning evolution and genetics more than the age of the Earth stories. Perhaps this difference is due to greater perceived connection to course content.

> I was interested in Darwin.
>
> I really enjoyed the Darwin one.
>
> I was interested to read the story of Mendel. That was my favorite.
>
> A couple of the stories increased my interest. I enjoyed evolution and genetics – so those had an impact. The others were extremely boring and almost decreased my interest.

Although more common with students who claimed no change in interest, some students who claimed increased interest noted that their interest in science as a career was already set. For students in the increased interest group, they often noted that the stories added to or reinforced their interest.

> I already have my career field decided, but the stories heightened my interest in science.
>
> I was already interested in science as a career.
>
> I wouldn't say it had a huge impact on my interest in science, but it definitely helped a little.

No change in interest in science careers

Some students indicating that the stories did not affect their interest in science as a career claimed that they learned from the stories.

> I felt like I gained knowledge, but it had no effect on my interest.
>
> I was already interested so it helped answer questions.
>
> I still want to pursue a career in science regardless of how long the process is.

Most students in this category who left comments noted that they were already interested in science at a high level, so the stories did not affect their interest. Considering this class has a large population of science majors, high initial interest in science is not surprising.

> I have, for many years, wanted to pursue a career in science (engineering), so these stories did not really have an effect.
>
> I have a very clear and thought out career plan and it would take more than short stories to change that.
>
> I am already interested in a science career.
>
> My rating is not to say I have no interest, but my interest was already high and did not need to increase.

Other students specifically noted that they found the stories interesting, but did not increase their interest in science as a career.

> The stories were interesting, but it didn't influence me on what I'd like to go into.
>
> They were interesting, and easy points, but not really an effect on my interests.

They were nice to read but it didn't make me any more interested in science.

A few students noted that the stories did not pertain to their specific interests or to their specific career interests.

They were interesting, but they aren't about what I am interested in.

The stories didn't pertain to the scientific career I am pursuing.

The stories were not about any scientific career I'm interested in.

Decreased interest in science careers

Only eight students claimed that the short stories decreased their interest in science as a career. Of those eight, only three left comments. The student comments are not surprising.

Made me hate science even more than I have this whole semester.

They were very boring

I changed majors.

While these students' views are extremely negative, they represent only a small fraction of students in the course.

Research Question 4

To what extent and in what ways do students' misinterpret the historical short stories?

While many students made the intended sense of the short stories, some students demonstrated inaccurate or problematic responses to embedded questions. Some of the students seem to have misinterpreted some of the questions while others seem to have misinterpreted the text of the short story. Still other students may be continuing to hold onto their naïve views regarding NOS despite the stories explicit mention of desirable portrayals of NOS.

To better understand students' struggles to accurately respond to embedded short story questions, students' problematic responses were identified and organized into common categories/themes. These themes of students' problematic responses are presented below. Importantly, one student response may end up in multiple problematic categories as the response might contain various misconceptions or problems. For this reason, numbers are reported as instances rather than students.

Problematic responses included: NOS misconceptions, content misconceptions, incomplete responses, and/or unintelligible responses. While some problematic responses did not necessarily constitute NOS misconception, the students' inattention to some aspect of the question or other misconception might indicate need to modify the question to more explicitly encourage students to wrestle with the multifaceted nature of NOS.

Extensive student writing is provided to help illustrate themes developed for each question. All student quotes are verbatim with grammar and spelling errors kept in tact.

Story 1 - Early Efforts to Understand the Earth's Age: Naturalists and Chronologists

The first story students were assigned addressed the age of Earth. The story highlights several geological principles such as catastrophism and uniformitarianism as well as several NOS ideas. The story notes how early scientists are "straddling two worlds" – one of religious faith and one of science. The story tries to make clear that science and religion are not mutually exclusive. Other NOS ideas include: origins of science, the social nature of science, and the interpretive nature of data analysis.

Results obtained from analyzing students' responses of each question are reported in tables 7, 8, 9, and 10. More detailed descriptions of themes developed from student problematic responses are provided after each corresponding table.

"Naturalists and Chronologists" – Question 1

The first question from this story was:

> Those who are investigating the natural world at this time have either the personal financial resources or the financial support from others to conduct their work. The word "scholar" comes from the Latin word "scholee" which means "leisure time". Today we hardly think of conducting scholarly work as "leisure". Why do you suppose that in the past, leisure time was associated with doing science and other forms of scholarship?

The number of acceptable and problematic student responses is reported in Table 7. Additionally, Table 7 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

This question's high number of problematic responses seems to step from students view that science was fundamentally different in the past than it is today. While the top category stems from student misunderstanding of "leisure time" the next top three categories indicate students believe science was different or viewed differently in the past. Kolsto (2008) notes that students may dismiss historical examples as not reflecting contemporary science. His suggestion to have students compare contemporary and historical science episodes may address many of the problematic responses to this question.

Table 7: Student responses to question 1 of "Early Efforts to Understand the Earth's Age: Naturalists and Chronologists".

Response Category	**Number of instances**
Acceptable	**62**
Problematic	**100**
Specific Problematic Response Themes *Misinterpret language of question* • Interpret leisure as "after work" time *NOS related problematic response* • Science was not important • Science was easier because less was known • Back then there were not as many options for entertainment so people entertained selves with science • Science is easier now because of technology advances • Religious beliefs pushed science toward leisure only activity	29 25 24 24 5 9

Acceptable responses (N = 62)

Acceptable responses noted how cultural influences of the time affected who was able to do science and that the freedom to explore curiosities was reserved for the wealthy because they did not have to eke out a living.

> In the past those who were considered scientists and investigated the natural world had financial resources and/or support to spend their "leisure time" making scientific advances. The other perhaps under class man and women didn't have the funds, time, or support to work in the science field. (DA, NC1)
>
> Leisure time was probably associated with doing science because only the upper class would be able to do it. To the working class people looking at things, writing about common occurrences and other things that were not physical in nature appeared to be leisure to the common person. (AL, NC1).

Problematic responses (N = 100)

Most commonly, problematic responses focused too intently on how the past was different instead of why science was associated with leisure time.

Back then there were not as many options for entertainment so people entertained selves with science (N = 24)

Rather than considering how scientists might find scientific investigations to be inherently interesting, these students saw science as an only alternative for entertainment. These responses claim that there was not as much to do "back then" and science was an only outlet for fun. These students do not focus on how economic systems of the past affected who was able to do science or how scientists are driven by curiosity.

> The reason that I think that in the past many people's leisure time is because back then people did have a lot of other activities to do. (KM, NC1)
>
> In my opinion the reason people don't do "scholarly" work anymore is because there are so many other opportunities in today's world. Such as: taking your children to soccer practice, watching television, emailing your friend who lives far away, going to a sporting event, going to a movie and the list goes on and on. (NL, NC1)

Science is easier now because of technology advances (N = 5)

> In the past, they did not have the technology that we have today to help them with their discovery. This takes a lot of patience and leisure time, "inspecting the nooks and crannies of the earth". (LH, NC1)

Science was easier because less was known (N = 24)

These responses claim that science was easier in the past and now science has become tedious work so is no longer associated with "leisure time".

> I believe science was seen as a leisurely experience because there was so much to discover and it was more mysterious. In current times people know a lot about science and there is much more to do these days, so people do not see learning as a leisurely task. (MM, NC1)

Science was not important (N = 25)

Some students claimed that science's importance is related to its status as a leisure activity. That is, in the past science was not important so relegated to "free time" activities.

> I believe that in the past scholarly work was done as a hobby unlike today where it is a profession. In the past, scientific discovery was not as big of a deal as it is today. (GH, NC1)

> Many people did not think what happens around them is very important. These men were doing something that is for fun, and it was not taken seriously. (MD, NC1)

Religious beliefs pushed science toward leisure only activity (N = 9)

While the question makes no connection to religious beliefs, some students believe religious influences kept science as merely a hobby.

> I think that in the past leisure time was associated with doing science at the time because science was still widely considered a joke to theologists and was not being taken seriously. (CG, NC1)

> People did not accept science in the time period of circa instead they believed in religion. Science was a leisure activity for some people but not actual laboring work. (PK, NC1)

Interpret leisure as "after work" time (N = 29)

While leisure time certainly is "after work" time, these students made no connection to how class structures affected who was able to do science.

> They had to worry about where their food cam from and how to protect themselves from neighboring cities or armies. Only in your free time you would have been able to be a scholar. (ZK, NC1).

> Because scientists had to fund their own studies, they probably had another job or career to help fund their studies. Therefore they only had time to do their research in their free time. (SB, NC1)

"Naturalists and Chronologists" – Question 2

The second question from this story was:

> Consider how scientists' many associations likely influence and nurture 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?

The number of acceptable and problematic student responses is reported in Table 8.

Additionally, Table 8 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

Most students made the intended sense of this question. The majority of problematic responses seems to be most related to student misinterpretation of the word social in the context of science being social or they focus only on how science is social to share ideas rather than social in a collaborative sense.

Table 8: Student responses to question 2 of “Early Efforts to Understand the Earth’s Age: Naturalists and Chronologists”.

Response Category	**Number of instances**
Acceptable	**115**
Problematic	**47**
Specific Problematic Response Themes	
Misinterpretation of question language	
• Misunderstand Social	20
o *Social means travel a lot*	*3*
o *Social means multidisciplinary*	*9*
o *Social is simply competitive*	*2*
o *Social means to “hang out” or have friends*	*6*
• Science only social to gain followers or share ideas	13
NOS related problematic responses	
• Science and Religion mutually exclusive	6
• Science and Religion ought be integrated	5

Acceptable Responses (N = 115)

Most students were able to articulate how the scientists in the story are working together and building off each other’s work. Some students even brought in other examples to illustrate how science is not done by “lone geniuses”.

> This story illustrates the social aspect of science by showing the large community of thinkers from multiple disciplines that all are connected by the common thread of wanting to understand more and helping each other to advance our collective knowledge. (CN, NC2)

> Being a scientist is not necessarily a solitary profession, as most think. Scientists often get ideas from each other and work together, such as Watson and Crick. (YR, NC2)

> Hutton's friends "provided" an environment that nurtured progressive ideas. Science is definitely a social endeavor and the input and critique of others can be essential to a successful scientific undertaking. (ZV, NC2).

Problematic Responses (N = 47)

Science and Religion mutually exclusive (N = 6)

Although the question does not target religious issues, a few students note how arguments might break out between believers and non-believers. While the arguments might illustrate a social aspect of science, the students imply that science and religion are necessarily at odds with one another.

> Science is very controversial and people take their beliefs very seriously. If a scientists strongly believes in evolution, and you don't; the verbal battle between the two of you can get very bloody. (MM, NC2)

Science and Religion ought be integrated (N = 5)

Other students also noted how science and religion interact. However, these students implied that science and religion ought to be reconciled and that the two ways of knowing ought to be brought to bear on each other instead of noting how the two are different ways of knowing.

> De Luc and Hutton were able to research their own theories and tie in their religious beliefs with the scientific evidence they found. They allowed their beliefs to influence the scientific evidence they studied and they had many colleagues that interpreted their findings in the same way. (SJ, NC2)

Misunderstand Social (N= 20)

As will be seen with many other questions, some students seemingly misunderstand key words in the question. For this question, some students misunderstand the notion of "social" and do not note how scientists work with others or how their ideas build on each other. Instead these students focus on travel, multidisciplinary aspects, competition, and that scientists have friends.

Social means travel a lot (N = 3)

Traveling is social and the research is being done outside a lab. (SW, NC2).

Social means multidisciplinary (N =9)

> Science is social because it involves more than one aspect of itself. All are interconnected and help support each others ideas and theories. (LH, NC2).
>
> Science is a social endeavor because when studying science, one cannot just study one specific type. All science is tied together in many ways. For instance, in biology when we want to determine the age of a fossil we use carbon dating. Carbon dating is more chemistry then biology. (GH, NC2)

Social is simply competitive (N = 2)

> Scientists seem to almost compete with one another to try to uncover facts and more quality research better than the other scientists. This is the reason science can be considered to be a social endeavor, in that competition through research is a way of motivation for many scientists. Therefore, science can in this way be compared to other social and competitive activities, such as athletics, which many consider a popular career choice. (JH, NC2)

Social means to "hang out" or have friends (N = 6)

> The story illustrates that science is a social endeavor by showing how the scientists enjoyed it. They also had fellow scientists' friends, which I think would make a science career a little more interesting. Since having friends in the same career area would make it more enjoyable and you would be able to work together. (NK, NC2)

Science only social to gain followers or share ideas (N = 13)

Some responses focus on the peer review process and that scientists want others to agree with their ideas. While this is an aspect of science, these students focus on sharing of ideas as the social part of science and pay less attention to the social context in which ideas are generated.

> Once a theory is thought up it must be shared with society which cannot be done solitarily. (MK, NC2)
>
> Science is very much a social endeavor because there is no point to making discoveries if you are unable or unwilling to share them with others. (JF, NC2).

"Naturalists and Chronologists" – Question 3

The third question from this story was:

> 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 number of acceptable and problematic student responses is reported in Table 9. Additionally, Table 9 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

As with other questions, many students misinterpret the question. Many students did not discuss how data does not tell, but focused on scientists need to explain their thinking. Unlike other questions, many students demonstrated NOS related problematic responses. Most prominent was students' holding onto the notion that data *does* tell scientists what to think.

Acceptable responses (N = 67)

Acceptable responses make clear the role of scientists in data interpretation. Rather than data collection being an end of science investigation, these students recognize that making meaning of the data is an important, and human, aspect of science.

> It tells us that data can be interpreted in several different ways. Every scientist is different and has his or her own opinion so the data cannot "show or tell" anyone what to think because every one has a certain way of seeing the situation. (WS, NC3)

> Data doesn't *show* you answers. Scientists have to take the results they got from the data and come up with a theory themselves. They have to interpret the data. (HM, NC1).

Table 9: Student responses to question 3 of "Early Efforts to Understand the Earth's Age: Naturalists and Chronologists".

Response Category	**Number of instances**
Acceptable	**67**
Problematic	**95**
Specific Problematic Response Themes *NOS related problematic responses* • Imply that data does tell • Prove/True • Science ideas do not rely on evidence *Misinterpret question language* • Misunderstand question to focus on scientists' need to tell/explain their ideas	 60 11 6 34

Problematic responses (N = 95)

Prove/True (N = 11)

These students indicate or imply that science is capable of arriving at proven truth or that "right" answers exist and scientist need only locate them. These students often note that data, if collected or interpreted correctly, lead to "proven" ideas rather than well-supported ideas.

> Many things are still up in the air and data just helps bring us closer to finding the real answer. (LE, NC3).

> The uncertainty and ambiguity of data interpretations are what I believe led to the necessity of hypothesis based science rather than simply discovery based science. That led towards more concrete facts, proven by science, and not to ideas spread by opinion or belief. (BK, NC3)

Science ideas do not rely on evidence (N = 6)

These students seem to have shifted to another extreme regarding the role of data in science. While some students believe data is self-evident, these students seem to think data has little connection to scientists' ideas.

> Sometimes data can't be collected right away and the results can take many years so scientists have their own theories of what they think happened or what is true. (CH, NC3).

> What it tells us is what Hutton chose to interpret it as saying, however educated, this was still just a guess. (TD, NC3)

Misunderstand question to focus on scientists' need to tell/explain their ideas (N = 34)

These students' views about the role of data are unclear because they focus on scientists' need to clearly articulate their ideas to others. Rather than asking about data's inability to tell, these students seem to think the question is asking about scientist's ability to tell or clearly articulate their ideas. While these students' ideas are not necessarily inaccurate, they ignore the question. Perhaps instead of asking how Hutton's need to convince others demonstrates that data doesn't tell the question could simply ask students to use the story to illustrate that scientists have to figure out what data means. By removing the part of the question focusing on Hutton's need to convince, these students might not ignore the role of interpretation in data analysis.

> Convincing other people that their interpretation is very likely to be factual is completely different from telling or showing someone that a theory is true with the support of data. (JK, NC3)

> Scientists try and convince people that their observations are meaningful and important by publishing their findings and telling everyone what they have learned in the hopes that someone else will believe what they say. Scientists must be very persuasive in order to get people to take their work seriously. (SB, NC3).

> Hutton needs to tell the people what exactly he saw and needs to explain his ideas. (JY, NC3).

Imply that data does tell (N = 60)

Although the question attempts to make clear that data do not show or tell scientists what to think, many students either explicitly or implicitly claim data does tell scientists what to think. For many of these students, they claim that while data doesn't tell scientists what to think, observations do. These students seem to see data as sets of numbers and observations as something different. This question may need to be reworded to explicitly note that data and observation are both types of evidence and evidence must be interpreted.

> Data does show and tell scientist an observation, an explanation, or an idea about their research, but each scientist can take what they've obtain and believe or do whatever they want pertaining to their research (DA, NC3).
>
> Today, the meaning of data is to show or tell us about something and to prove a fact or a theory. (CM, NC3)
>
> Data is just a table of information that doesn't necessarily mean anything to you personally, but it's when you see it for yourself does it takes meaning. (NL, NC3)
>
> It is through observation that tells us what is happening and what to believe data is just a record (MD, NC3)

"Naturalists and Chronologists" – Question 4

The final question from this story was:

> How does this story illustrate that science versus religion is not an accurate description of efforts to understand the age of the earth?

The number of acceptable and problematic student responses is reported in Table 10. Additionally, Table10 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

Most students were able to make the intended sense of this question. Those students who demonstrated problematic responses seemed to want to claim that either science and religion are incompatible or that they ought integrate rather than the view promoted by the story that individuals can accept both science and religion as different ways of knowing.

Table 10: Student responses to question 4 of "Early Efforts to Understand the Earth's Age: Naturalists and Chronologists".

Response Category	**Number of instances**
Acceptable	**120**
Problematic	**42**
Specific Problematic Response Themes *NOS related problematic response* • Science vs. Religion • Science and religion ought integrate • Science ideas are proven truth • Theory/Law • Scientists can and should be objective	 16 13 12 5 3

Acceptable responses (N = 120)

Most students were able to draw from the story to explain how science and religion are not necessarily enemies. These students might note how the scientists in the story were religious or note that the scientists were clearly not trying to simply disprove religion.

> It shows that many of the scientists tried to explain it while staying within religious boundaries, and that most information is based on the most relevant evidence rather than worrying about if it is or is not in conflict with religious views. (MK, NC4).

> It shows that scientists are not trying to say that religion is wrong but that they are trying to have a better understanding of our world. Also, some chronologists have looked into biblical writings to try to understand when people started living by compiling a list of ancestry. (WP, NC4).

Problematic responses (N = 42)

Theory/Law (N = 5)

Although the question does not ask about theories and laws, several students demonstrate the naïve belief that scientific theories are simply educated guesses.

> Every offered theory of the age of earth and how it started is only a theory, therefore there is no conclusive proof for a scientific theory to disprove a creationalist theory or vice versa. (SN, NC4)

Science ideas are proven truth (N = 12)

As in a previous question, the students imply that science is capable of arriving at proven truth. These students often use this view to claim science is an inherently better way of knowing rather than a way of knowing in a particular context.

> Without absolute, factual evidence to support one theory, there will be controversy within the science vs. religion debate. (RR, NC4).

> Religion is but a book of beliefs in it, not true evidence. Unlike science which is the study of what really happened by studying the earth and finding facts of what happened. (KA, NC4).

Scientists can and should be objective (N =3)

Related to science's ability to arrive at proven truth is scientists' ability to be objective. These few students claimed that scientists need to be objective and not let their religious beliefs affect their thinking.

> When performing true science you're supposed to look at everything with a non-bias even if it contradicts your beliefs or religion. (WW, NC4)

Science vs. Religion (N =16)

Despite the question's explicit claim that science vs. religion is not accurate, these students imply an adversarial relationship between science and religion.

> Science is fact. Religion is belief. (MB, NC4)

> Religion uses myths to discover the unknown reality we face. Science goes to lengths to finding out the real story. So I have to agree that religion is not accurate in defining the existence of earth or the universe. (LS, NC4).

> Science and religion do not mix. Science is trying to find proofs and religion is relying on faith. Science and religion is always going against each other, trying to prove which is right or which is wrong. (CS, NC4).

Science and religion ought integrate (N = 13)

As seen with other questions, these students seem to have shifted to the other extreme regarding science and religion. Instead of seeing the two as adversaries, these students believe science and religion should to build on each other and that both are useful for similar questions. These students likely do not understand the important and utility of methodological naturalism.

> Science, on its own, doesn't have all the answers scientists are looking for, as is the same way with religion. However, perhaps using both techniques will provide better results and understanding for scientists (JH, NC4).

> Science and religion is really more of a collaborative then anything else. (RA, NC4).

> This story does say a little about how in the earlier years, that is what many people focused on: science vs religion. Now-a-days, scientists incorporate the two to get that much closer to a more solid theory. (BK, NC4).

Story 2 - A Very Deep Question: Just How Old is the Earth?

The second story students read also addressed the age of the Earth. This story focused on how various scientists took different approaches to estimate the Earth's age. Because the story focused on different methods and the meaning scientists made of various kinds of data, the NOS ideas drawn out by embedded questions included: how scientific knowledge and process are intertwined, how both methods and data interpretation require creativity, and how scientists expect ideas from varied disciplines to cohere. Additionally, the story asked students to calculate a scientist's estimated age of the Earth based on the estimated rate of erosion and height of geologic columns. Results obtained from analyzing students' responses of each question are reported in tables 11, 12, 13 and 14. More detailed descriptions of themes developed from student problematic responses are provided after each corresponding table.

"A Very Deep Question" – Question 1

The first question from this story was:

> 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, calculate the approximate age of the earth he came to.

The number of acceptable and problematic students' responses is reported in Table 11. Additionally, Table 11 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

Most students were able to accurately perform the calculation. Any problematic responses seemed to be miscalculations.

Table 11: Student responses to question 1 of "A Very Deep Question: Just How Old is the Earth?".

Response Category	**Number of instances**
Acceptable	**152**
Problematic	**12**
Specific Problematic Response Themes	
• Mislabeled incorrect number (54.14 billion or million)	4
• Simply used the estimate in the story (38-300 million years)	2
• Mislabeled the correct number (96,760,000 billion years)	1
• Incorrect number (54.1 years)	1
• Incorrect number (147 million)	1
• Incorrect number (1,149,120,000 years)	1
• Claimed problem is nonsensical	1

Accurate responses (N = 152)

Almost all students were able to accurately respond to this question. To correctly answer this question, students needed to multiply the two numbers given in the problem: 1,330 years/foot x 72,000 feet = 95,760,000 years. Many students noted that this number falls with the 38 – 300 million-year estimate noted in the story and is close to the 100 million years that other scientists had determined.

Problematic responses (N = 12)

Simply used the estimate in the story (N = 2).

These students did no calculation. The story notes that scientists were making estimates between 38 and 300 million years for Earth's age. Rather than calculate using the numbers in the problem, the students just repeated the estimates.

Mislabeled the correct number (95,760,000 billion years) (N = 1)

This student accurately calculated the number, but added the label "billion years" to their calculated number. This addition likely stems from how often very large numbers referring to the age of fossils or the Earth are followed by "billion years". This student may have meant to write "95 million years".

Mislabeled incorrect number (54.14 billion or million yrs) (N = 4)

These four students likely divided the two numbers instead of multiplying them to arrive at 54.14. Recognizing the problem with the Earth being only 54 years old, the students added either million or billion to the number.

Incorrect number (54.1 years) (N = 1).

This student seems to have made the same mistake as those above, but did not recognize the problem with a 54 year old Earth. This student gives new meaning to the label "young Earth creationist".

Incorrect number (147 million) (N = 1).

Using the two numbers given in the problem to reach 147 million is not possible without additional numbers or other calculations. For some reason, this student subtracted 2007 from the year John Phillip used the idea of sedimentation. The student claims the answer is reasonable since the number fits with the accepted estimates of the time.

> I calculated that the earth was approximately 147 million years old according to John Phillip's data. I reached this conclusion by subtracting today's year from the year John Phillip discovered the idea of sedimentation. This estimate seems somewhat correct because the valued ranged from 38-300 million year old (ST, DQ1).

Incorrect number (1,149,120,000 years) (N = 1).

This student added a factor of 12 to the equation. This student likely thought months in the year needed to be accounted for resulting in 72,000 x 12 x 1,330 = 1,149,120,000 years.

Claimed problem is nonsensical (N = 1)

Lastly, one student claimed the problem to be unanswerable with the given information:

> From John Phillips theory on sedimentation the age of the earth cannot really be determined and the numbers cannot be mathematically put together to form a number on the earth. (SB, DQ1).

"A Very Deep Question" – Question 2

The second question from this story was:

> Note that how scientific research is conducted (the processes of science) is intertwined with prevailing ideas about natural phenomena. This, in turn, affects new thinking about the natural world. Use information from this short story to explain how scientific knowledge and scientific process are intertwined.

The number of acceptable and problematic students' responses is reported in Table 12. Additionally, Table 12 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

While the number of problematic responses seems high for this question, the most frequent categories were not related to NOS misconceptions. The most common problematic response was that students did not attend to how process and knowledge affect *each other*. Instead, many students simply talked about how either process affects knowledge or knowledge affects process.

Table 12: Student responses to question 2 of "A Very Deep Question: Just How Old is the Earth?".

Response Category	**Number of instances**
Acceptable	**93**
Problematic	**71**
Specific Problematic Response Themes	
Only attend to one direction of effect	
• Note only how scientific process affects scientific knowledge. Usually how process leads to knowledge	31
• Note only how scientific knowledge affect scientific process. Not as problematic since for most part process affect on knowledge is somewhat obvious and perhaps inferred	21
General NOS problematic response	
• Note only how prior knowledge affects new knowledge	14
• Scientific Method	2
General problematic response	
• Nonsense answers or did not answer question	5

Acceptable responses (N = 93)

Acceptable responses to this question noted the two-way street between scientific process and scientific knowledge. That is, current scientific knowledge will affect new science investigations and new scientific investigations will affect the current state of scientific knowledge.

> Scientific experiments are based on previously known theories and laws. If one of the basic principles research is based on is false, than the resulting theory is also incorrect. Kelvin's dating by energy is one such case. His theory was accurate until the nature of radioactive elements was discovered. (AK, DQ2).

> This story illustrates how scientific knowledge and scientific processes are intertwined. Kelvin used his knowledge about heat and how it transfers to theorize about the earth's age, while Joly applied the ideas of sediment to the salinity of the ocean to calculate the earth's age. Both of these scientists applied scientific knowledge to come up with a process to calculate the earth's age. Scientific knowledge and processes are interrelated because they build on each other and evolve from each other. (LM, DQ2).

Problematic responses (N = 71)

While the number of students who held problematic responses seems high, the students typically were able to note how either process affects knowledge or how knowledge affects process. By not including both directions, the students did not fully articulate how intertwined process and knowledge are. To encourage students to more fully articulate and think about the complex nature in which process and knowledge affect *each other*, the questions might be modified so that the co-effects are more explicitly noted. For example, modifying the question to say, "Explain how science investigation is affected by current science knowledge and how science knowledge is affected by science investigation" may encourage students to explicitly note the two-way street between process and knowledge.

Note only how scientific process affects scientific knowledge. Usually how process leads to knowledge (N = 31)

These students did not explicitly note how knowledge affects the process of science. The students simply noted how different processes might lead to different knowledge.

> Scientific knowledge and process are intertwined in that their knowledge is obtained through scientific process. The scientists did research in many ways. In the story, some did research on sedimentation and some on heat loss. Both ways produced different estimates on the age of the earth. The research led to the results, and different ways of researching led to different results. (LB, DQ2)

> Scientific knowledge is based on what is known or has been interpreted form previous experiments. It is knowledge that needs to be addressed when researching a certain subject or in trying to figure out a certain experiment. Scientific process is intertwined with this because it is used to gain the scientific knowledge needed in research. The process is done to gain the information we need to know. (JK, DQ2).

> When trying to figure out the age of the earth scientists used many different methods. Kelvin used thermodynamics to estimate the age of the earth, while geologist John Joly used the salinity of the oceans. Even though they did not come up with the answers anywhere close to each other they both still used their own individual processes to gain scientific knowledge to come to a better understanding with the question they imposed. (RT, DQ2).

Note only how scientific knowledge affect scientific process (N = 21).

Slightly fewer students focused solely on how knowledge affects the process of science. This view does not seem as problematic as when students only note how process affects knowledge. Oftentimes the notion that scientific process affects science knowledge was implied in student responses, but not made explicit.

> Scientific knowledge is integral for scientific process. In Kelvin's case, he used his knowledge of the earth and temperature to come of with a process that would work for his experiment. He had to use his knowledge of previous experiments done by him as well as other to come up with an appropriate scientific approach. (LH, DQ1)

> In order to figure out the scientific processes you need scientific knowledge. To determine the different processes you need to know what you are talking about. (KA, DQ2)

> Scientific knowledge and scientific process are intertwined because processes come from the knowledge one holds. In order to think or devise a way to find out how or why, there must be knowledge of how other things work or of how to break down problems. (DS, DQ2).

Note only how prior knowledge affects new knowledge (N = 14)

Some students did not attend to the role of scientific processes at all. While their notion that new knowledge is affected by previous knowledge is accurate, simply saying this does not fully address the question. These students may not understand what the question means by the word “process” and may think the question is referring to natural processes (i.e. the water cycle) so using the word “investigations” rather than “process” might better draw students attention to the way process and knowledge are intertwined.

> People form theories and beliefs based on what they know. If there knowledge is incomplete or faulty, they will come to erroneous conclusions. (IF, DQ2).

> Scientists can take ideas from already existing theories and use it to prove or refute a hypothesis of their own. By intertwining the different scientific thoughts, they will work together and won’t end up contradicting the other point. (KN, DQ2).

Scientific Method (N = 2)

Since the question asks about scientists’ processes, a few students claim that scientists use the scientific method. Importantly, only two students exhibit this view. This low number provides hope that students’ naïve views regarding the scientific method are being modified.

> All of the scientists were using the scientific method. They were both doing things that they thought was valid. Thought that research they came to extremely different answers even though they all used an empirical approach. (AL, DQ2).

Nonsense answers or did not answer question (N = 5)

A few students’ responses did not make sense or did not address the question. These student’s ideas weren’t necessarily inaccurate, but may have been so unclear that assessing their views was impossible.

> John Joly clearly made the poor assumptions that water has always been a part of the Earth. Earth existed for an extremely long time before water, and Joly probably never even thought a thought that would lead him to this thought. (VP, DQ2).
>
> At the beginning of the 1850s had provide convincing evidence to the most scientists by the 1950s, that helped them work hard to earned a new knowledge on how to interpret data. (EZ, DQ2).

"A Very Deep Question" – Question 3

The third question from this story was:

> Many students today choose not to pursue science careers, thinking that science is a dull and unimaginative process. Using this historical episode, explain how both the methods scientists use and the sense they make of data illustrate that science is a creative endeavor.

The number of acceptable and problematic responses by students is reported in Table 13. Additionally, this Table highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

As with previous questions, the high number of problematic responses may be misleading. However, none of the problematic responses are related directly to NOS misconceptions. Most commonly students note how either methods or data interpretation requires creativity rather than how *both* require creativity. Beyond leaving out an aspect of the question, some students misunderstand the question with most of these responses taking on the task of convincing their readers that science is interesting.

Table 13: Student responses to question 3 of "A Very Deep Question: Just How Old is the Earth?"

Response Category	**Number of instances**
Acceptable	**78**
Problematic	**85**
Specific Problematic Response Themes	
Only attend to one aspect of question	
• Note only how methods scientists use are creative	36
• Note only how data interpretation/ideas are creative	21
Misinterpret language or does not clearly address question	
• May vaguely note science is creative, but focus on convincing reader that science is interesting	24
• Misunderstood question in some way related to creativity or what aspect is creative.	6
o *Data presentation takes creativity*	*3*
o *Creative mean determined*	*1*
o *Creative because so much is unknown*	*1*

Acceptable responses (N = 78)

Acceptable responses for this question needed to address how creativity is required for interpreting data *and* for designing new ways to collect data or test ideas.

> Scientists have to be completely creative in order to be successful. They have to create their own methods to discover things in science and they then have to think of creative ways to interpret that knowledge and make meaning of things (AG, DQ3)
>
> It takes creativity to make sense out of data one has before them. This data is meaningless without interpretation, and that interpretation requires creativity to be found. The same goes for the method. And experiment would be useless if it weren't well designed, and it takes creativity to come up with a good one (BB, DQ3).

Problematic responses (N = 86)

The high number of problematic responses may be misleading. Most all of the students were able to articulate some ways in which science is creative, but did not fully address all aspects of the question, only vaguely note science is creative, or overstate the creative freedom scientists have. This question, as others, has two parts: 1) What role does creativity play in designing new research methods? and 2) What role does creativity play in data interpretation? If the question more clearly separated out the two parts, students may attend to each part more thoroughly.

Note only how methods scientists use are creative (N = 36)

While these students note that science is creative they only note how the methods scientists use are creative and ignore how data interpretation requires creativity. This response is problematic because students may naively believe that if scientists create the right test, the data will "tell" scientists what to think. Of course these students may understand the role of creativity in data interpretation, but they have not explicitly noted as much.

> Well before either of these scientists's performed these experiments, experiments like these had never been done. Scientists have to be creative everyday to come up with new processes and experiments. (LR, DQ3)
>
> In using both methods, scientists have to come up with ways of developing different results to make sure their data is correct. If the new results contradict the old results they have to find out why they differ. Using creative methods scientists can then determine the reason for the differences. Then plugging in those new factors into the original process may come out with better results. (JY, DQ3).
>
> Science is not dull or boring. There were many interesting and creative methods used to determine the age of the Earth. For example; one scientist measured the heat lost by the earth and another scientist determined the amount of sediment that had accumulated; both to determine the age of the earth, but both of their methods were creative and interesting. This proves that science is not dull and/or boring. (BH, DQ3).

Note only how data interpretation/ideas are creative (N = 21)

These students focus solely on how creativity is required to make sense of data. While students may understand the role of creativity in designing research investigations, they have not explicitly noted so. Believing creativity is only required in data analysis may indicate students think designing investigations is straightforward or even prescriptive as in "the scientific method".

> Science in its entire essence is creative. When confronted with new data, researchers have to create an entirely new hypothesis to fit the results. Science is also one of the most groundbreaking fields to work in. Current research is always producing new data that makes scientists completely rework their preexisting paradigms. (AK, DQ3)

> There is a reason that everyone is not a scientist. Everyone assumes it is a dull boring career, but that is not the case. In order for the scientists to come up with all the ideas and discoveries that they do they must be very creative. They must also be creative to interpret the data that they come up with. (KA, DQ3).

> Science is a creative process because scientists have to explain different things in nature. They often try to come up with new ideas and think out of the box. (YR, DQ3).

May vaguely note science is creative, but focus on convincing reader that science is interesting (N = 24)

Students in this category often note that science is creative, but do not go into any detail on how either the methods or the interpretation of data require creativity. These students tend to focus their writing on convincing the reader that science is indeed interesting. These students have focused most intently on the question's introduction that states, "Many students today choose not to pursue science careers, thinking that science is a dull and unimaginative process."

> Scientists observe nature around them to find things to explain or help them explain another aspect of nature. Many exciting things happen in nature such as volcanoes, hurricanes, and even tides. Science is a hands on career that is only as boring as the way you conduct experiments. Kelvin played with ice and Pierre and Marie Curie did radioactive testing (AS, DQ3).

> The life of science is far from dull. James Hutton used stratigraphy to estimate how old the earth was. Stratigraphy is the study of the rock layering. Kelvin used his theory that in every interaction energy is released. Basically this means, that ever since the beginning of the earth and sun, they have been losing heat. So, Kelvin

> tested the remaining heat left and estimated the time from that. Studying rocks from the earth and testing how hot the earth is, this is fun. (KS, DQ3).

> How can science not be a creative endeavor? Science is the unknown. Science holds mysteries that are barely imagined. Science is understanding what many cannot and striving to find the truth. Some methods and data can be dull but when you look at the bigger picture it's fascinating. (DA, DQ3).

Misunderstood question in some way related to creativity or what aspect is creative. (N = 6)

This theme is composed of several students seemingly misunderstanding the use of the word "creative" or what aspect of science the question refers to being creative. Instead of noting how methods and data interpretation require creativity, students noted data presentation requires creativity, creative means determined, or scientists must be creative because so much is unknown.

Data presentation takes creativity (N = 3)

> It is easy to understand how some students find science to be dull because they have a lack of interest in it, which makes it hard to comprehend something if they have no desire to. Scientists do a good job of providing data of their findings and stating their ideas by putting it in journals, magazines, or text books. They understand also that they have to break it down into simpler terms for the average person to understand it by showing graphs or diagrams of information. Science is a very creative endeavor if you give it a chance and not just dismiss it right off the bat. (KA, DQ3).

Creative means determined (N =1)

> Neither Kelvin nor Joly could have come up with their ideas and conclusions about what they were studying if they had just sat at home and did nothing. Kelvin had to go into the deepest, darkest, and hottest places to get the data he needed to draw the conclusions about how heat and the earth's age were intertwined. Joly couldn't have gotten the information he needed if he had not gone to the ocean to collect data on how much salt the ocean contained or how much it once contained. Both scientists did not just do science that was dull and an unimaginative process. These two scientists were living examples of how science is a creative endeavor. (TW, DQ3).

Creative because so much is unknown (N =1)

> Science is a creative endeavor because there are still a lot of things to be explained and there is even more to prove such as how old the earth is. (SB, DQ3).

Overstate creative freedom (N = 1)

One student overstates the role of creativity in an "anything goes" view. While science does require creativity, the role of evidence prevents scientists from saying anything they want.

> They can make whatever they want out of the data they collect but have to remember to put it in a mind set that everyone will understand (BK, DQ3).

"A Very Deep Question" – Question 4

The final question from this story was:

> 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?

The number of acceptable and problematic responses from students is reported in Table 14. Additionally, Table 14 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

Very few students exhibited problematic responses for this question. Of those that were exhibited, only ten instances were related to NOS misconceptions. The other problematic responses seem to be caused by student misunderstanding of the usage of "cohere".

Table 14: Student responses to question 4 of "A Very Deep Question: Just How Old is the Earth?"

Response Category	**Number of instances**
Acceptable	**144**
Problematic	**20**
Specific Problematic Response Themes *NOS related problematic responses* • Scientists don't seek coherence • Scientists simply don't want to be wrong *Misunderstand question language* • Misunderstand meaning of "cohere" o *Cohere means that scientists agree rather than ideas fit together* o *Cohere means that scientists want to be sure to receive credit* o *Each discipline should be used in investigations* o *Thought coherence referred to science and religion*	 2 7 7 *3* *4* *3* *1*

Acceptable responses (N = 144)

This question targets a fairly sophisticated notion of NOS: coherence theory of justification. This notion is based on the fact that scientists are studying one natural world and ideas that explain this world ought to fit together. That is, nature does not likely work in wildly different ways at different times and places, so conclusions concerning a specific phenomenon ought to fit together. If our ideas about a particular phenomenon do not fit, something must be wrong. If the ideas do fit together, our confidence in the ideas increases.

Acceptable responses noted how scientists have more confidence in their ideas if they fit together or that our ideas are more likely to be accurate if multiple scientists are coming to similar conclusions using different methods.

> Scientists want their ideas to cohere because the basis of science is to understand our world. If ideas do not cohere with each other, that means that our world does not cohere with itself. Theories and ideas must cohere to form a more complete view of the world. (JC, DQ4).

> Ideas that don't cohere make science difficult because science doesn't work in one way at one time an in different ways at other times. Ideas that fit together work and support each others claims. (AM, DQ4)

> If scientists come up with the same conclusions by doing experiments differently, it means that their answers have more of a chance at being accurate. I personally trust something more if lots of people come up with the same answer versus if everyone ended up at completely different conclusions. (LR, DQ4).

Problematic responses (N = 20)

Not many students struggled with this question. Admittedly, the question is very open-ended so a wide range of responses is acceptable. While modification to this question is likely not necessary, perhaps removing the last piece noting "even if these ideas come from different disciplines" will help students focus on ideas cohering rather that scientists agreeing or making use of all disciplines.

Scientists don't seek coherence (N = 2)

Two students flatly claimed scientists do not like coherence or do not find value in ideas fitting together.

> Scientists do not care if their ideas fit together with ideas that come from different science disciplines because all science subjects are tied together. You cannot learn about the age of the earth if you use only one type of science subject. You would not gain all the information needed to find an answer. (HM, DQ4)

Scientists simply don't want to be wrong (N = 7)

Rather than focusing on coherence, this group of students focused on scientists desire to be "right". While coherence may indicate greater levels of "correctness", these students did not make the connection explicit.

> Scientists are all about twisting things around as long as their ideas coincide with each other because they study certain things for large amounts of time. It's imaginable for scientists to believe what they are putting their hearts and souls into could fail. (SG, DQ4).

> No one likes to be wrong. Scientists spend a lot of time coming up with their ideas and testing them. They don't want all the time they put into finding their prediction to be wasted. Also they want to get the glory for finding something out and have their work published. (RR, DQ4).

Misunderstand meaning of "cohere" (N = 7)

Some students misunderstood the question. A few believed the coherence was referring to scientists agreeing rather than ideas fitting together. Other students placed significant emphasis on scientists' desire to receive credit for their work. While receiving credit may be a concern of scientists, this question does not address the issue of receiving credit.

Cohere means that scientists agree rather than ideas fit together (N = 3)

> It is very important for all science to cohere. If not it may not make sense to everyone. Thinking of taxonomy, if all the names weren't the same all over the world a person calling a species one thing could be wrong to someone somewhere else. (AB, DQ4).

Cohere means that scientists want to be sure to receive credit (N = 4)

> I think that scientists want to be the only one with an idea for a topic. On the other hand, they want to have to best idea, the one that is used for year to come. Therefore, I think that scientists would want their ideas to be similar in some way. So that their idea is the one that "wins." (LW, DQ4).

Each discipline should be used in investigations (N = 3)

This small group of students thought the coherence of ideas means that all scientific disciplines need to be involved in all investigations.

> Each of the different science disciplines has a little part in any scientific experiments. Even if they are from different kinds of science, they are still important when they are put together. (CS, DQ4)

Thought coherence referred to science and religion (N =1)

One student confused coherence of science ideas with coherence of non-science with science.

> Religion versus science will not accomplish much. Until the religious groups can compromise a bit and perhaps listen to a bit of logic and the scientific groups can do the same and possibly think a little more religiously, not much will be done. These groups working together can make a much better effort to find the answer to the Earth's age. (BH, DQ4).

Story 3 - Creativity and Discovery: The Work of Gregor Mendel

This story highlighted the role of creativity to move scientific knowledge forward both in creating new ideas and coming up with new ways to investigate old questions. The story highlighted new ideas and methods by illustrating how science has a subjective nature and past thinking influences current research. Rather than a complete break from former ways of thinking, the story illustrates how Mendel's ideas were revolutionary, but also heavily influenced by prior scientific knowledge.

Results obtained from analyzing students' responses of each question are reported in tables 14, 16, 17 and 18. More detailed descriptions of themes developed from student problematic responses are provided after each corresponding table.

"Creativity and Discovery" – Question 1

The first question from this story was:

> Explain how Mendel's thinking shows both a gradual progression from prior ideas regarding heredity and also a break from those prior ideas.

The number of acceptable and problematic students' responses is reported in Table 15. Additionally, Table 15 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

The number of problematic responses for this question is concerning. However, the number of responses directly tied to NOS misconceptions is only five. The remaining problematic responses seem to be tied to incomplete answering of the question or not accurately recalling or noting a detail of the story.

Table 15: Student responses to question 1 of "Creativity and Discovery: The Work of Gregor Mendel".

Response Category	**Number of instances**
Acceptable	**38**
Problematic	**87**
Specific Problematic Response Themes *Problematic responses not clearly related to NOS*	
• Miss the NOS idea of how ideas are both evolutionary and revolutionary – little note of how the thinking shows gradual progression and break from prior ideas.	58
o *Describe the old ideas that influenced Mendel and his idea of factors*	*15*
o *Note the influence of old ideas and that Mendel had new ideas, but one or other is extremely vague*	*23*
o *Only describe or note influence of old ideas*	*19*
o *Only describe new ideas*	*1*
• Credit Mendel with ideas he didn't come up with that were mentioned in the story	20
• Mis-identify the break from prior ideas	4
NOS related problematic responses	
• Factors/genes were discovered/found	5

Acceptable responses (N = 38)

Acceptable responses noted how Mendel's thinking was influenced by past ideas and how he contributed novel ideas to the study of heredity.

> While Mendel continued his education, other scholars like Darwin, Buffon, and Linnaeus were also pondering the mystery of genetics. It was known that plants could procreate that and offspring had both male and female genes from their parents. It was also known that if u mated two different species, you could develop a sterile hybrid. Mendel broke away from these ideas when he hypothesized that a number of different forms would result from a random fertilization of two kinds of "egg cells" by two kinds of pollen grains. He proposed there were "factors" for every characteristic. He use old ideas to create a new way of thinking and new ideas about heredity. (LG, M1)
>
> Mendel coined the term of "factors," something no one had thought of before. He formulated a way to obtain the probability a trait would occur. This was unlike anything anyone had done, especially with pea plants. His gradual progression was due to what he had learned regarding heredity. The ideas that influenced him were: 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 mail and the female. With these ideas in mind, he started his experiment. As he continued his work, these ideas evolved into new ones. (MB, M1).

Problematic responses (N = 87)

Like with other multifaceted questions many of the students attended to only one or another aspect of the question. In this case, the students either noted how Mendel was influenced by prior ideas or how his ideas were new. To remedy this problem, the question may need to be broken down into two parts: A) In what way did Mendel build on the work of others? and B) In what way did Mendel revolutionize the approach to heredity?

Miss the NOS idea of how ideas are both evolutionary and revolutionary – little note of how the thinking shows gradual progression and break from prior ideas. (N = 58)

Most students did not clearly note how Mendel was both influence by past ideas and how his ideas broke from old ideas. Some students simply described the progression of ideas as a linear process from old ideas to new ones rather than noting how Mendel's thinking was revolutionary in nature. Other students were so vague in their description of how Mendel used prior ideas and broke away from those ideas that ascertaining their understanding was too difficult. Lastly, some students focused on only the role of old ideas or Mendel's new ideas and did not connect the two.

Describe the old ideas that influenced Mendel and his idea of factors (n = 15)

> Mendel was influenced by the previous ideas held by other scientists. Some of these would include that new "species" can appear in the form of hybrids, that they didn't quite know why hybrids gave rise to new hybrids, and however heredity worked, it involved male and female specimens. During his teaching, Mendel did experiments with pea plants and concluded his thought that there were "factors" for each characteristic and those characteristics are responsible for different variations of a trait in different sex cells. (LB, M1)

> Mendel like the past scientists believed that new species might have resulted from procreation. He also believe that hybrids could produce offspring, and that the mechanism of heredity involved both male and females. However, where Mendel's thinking is different form the prior scientists ideas is that, Mendel believed that instead of being two kinds of "egg cell", there were two kinds of "pollen grain." He believed that there were different factors responsible for the traits of the offspring, but that these factors could not occur in the same sex cell. (BH, M1)

> Mendel already knew from prior studies that had been done that two parent plants could make plants that looked like the parent plants and also could make plants that were a new species. Mendel used this knowledge and then went on further to say that there were different factors for each characteristic and these characteristics could not occur in the same sex cell. (KN, M1)

Note the influence of old ideas and that Mendel had new ideas, but one or other is extremely vague (n = 23)

> At the beginning of his career he followed what other people were doing and what they believed. He finally began to gain his own point when he graduated from the University of Vienna. When this happened he began to take on his own thinking and beliefs of how heredity works. (BA, M1)

> He used the ideas from previous scientists such as Charles Darwin and Joseph Koelreuter. He then looked into them more and eventually came up with ideas of his own. (KA, M1)

> Mendel's ideas started out very simple and then grew to be more complex with the more that he learned as he researched. He started with the idea that humans can cause the different types of plants with the thought of hybrids. To the idea that there are

> different parts of the plants that determine the genetic makeup of the new plants. (SC, M1)
>
> Prior ideas didn't explain the exact relationship that both parents have on the outcome of the offsprings traits. They knew that the parents had something to do with it but Mendel went further and explained how exactly it works. (AG, M1)

Only describe or note influence of old ideas (n = 19)

> The idea that Koelreuter had was that when humans tampered with plants unnatural crosses are formed, then it was thought that blueprints are passed from the parent plant to the next generation thorugh miniature replicas within the sperm and ovule cells. Mandel used these ideas to influenced is ideas that a new "species" can appear in the form of hybrids, it's difficult to explain why these hybrids are formed, and hereditary involves both male and female plants. (LA, M1)
>
> Mendel graduated at the time where there were new ideas being put forth, so he had to put them together with his own thoughts. He used these ideas (1 new 'species' can appear in the form of hybrids, 2 great difficulty existed I explaining why these hybrids gave rise to new hybrids, and 3 whatever the mechanism of heredity, it involved both the male and female) to help influence his work, in the end making them his own. (AB, M1)
>
> Mendel's thinking progressed from his early experimentation at the monastery, this was likely due to his broader range of studies at the University of Vienna. With influence from Carl Linnaeus and Joseph Koelreuter, Mendel was inspired to further his knowledge of hybrids producing new species, and heredity in the male and female. (RC, M1)

Only describe new ideas (n = 1)

> Mendel wanted to test the purity of type. He wanted to go beyond just the first generation out come. He went to discover the out come of the 2nd and 3rd generations. He showed how recessive and dominant genes determine the out come of the generations. (CK, M1)

Credit Mendel with ideas he didn't come up with that were mentioned in the story (n = 20)

These students credited "new" ideas to Mendel that were not actually his ideas. While this problem does not relate to the question asked, the problem may be indicative of student struggles to understand the storyline.

> …[Mendel] started developing his own original ideas when he came up with hybrid plants. (HA, M1)

> …Mendel also looked more at the heredity and the fertility of the new hybrids. (OD, M1)

> Mendel used his previous college experience, knowledge gained from professors and other scientific minds like Koelreuter to compile the ideas that he outlined; 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 female. These ideas were revolutionary however, they were a compilation of others' thoughts as well as Mendels. Thanks to the revolutionary thinking of Darwin, Linneaus and Koelreuter Mendel was able to create and develop these three key concepts. (SF, M1)

> …However Mendel did not believe that hybrids were only derived from human influence, he claimed that variations could arise in natural populations. (AG, M1)

> He breaks away from those prior ideas by investigating hybrids and realizing that heredity specifically involves the male and the female. (VG, M1)

> Mendel's thinking differs from that of earlier ideas mainly because Mendel uses plants to study hereditary traits instead of the traditionally used animals that earlier men had used. (BH, M1)

Mis-identify the break from prior ideas (n = 4)

These four students misplace the ways in which Mendel's ideas broke from prior ideas.

> [His thinking] broke from his prior thinking when he went to study at the university; he learned a mass number of things and also the basic principles of physics. (SB, M1)

> Mendel's work showed a progression of earlier ideas in the sense that he found out how much probability had to do with heredity;… (OD, M1)

> Mendel thought that plants did reproduce and that it had a genetic component. Other scientists thought that God would not let plants have a shameful whoredom of reproduction. Many thought that while during intercourse if the man thought about himself the offspring would be male and if the man thought about his wife then the offspring would be female. Mendel would prove this wrong with the growing of hybrid pea plants and the dominant genes that would be seen in the offspring. Many

> scientists thought that God made species the way they are supposed to be and if humans interfered with the process the offspring would be unnatural. (SF, M1)

Factors/genes were discovered/found (n = 5)

This problematic response indicates a much deeper misconception about NOS. Rather than viewing factors as a way to explain data, the students believe Mendel discovered or found these factors.

> …This includes how he actually counted every new species that was created when he crossed the peas as well as the discovery of dominant and recessive genes. (KA, M1)

> …Mendel found that traits were combined in a different way and not just an entire part comes from the mom and another part comes from the dad. Mendel discovered completely new concepts about traits. (MB, M1)

> [Mendel] found "factors" that are responsible for the variations of traits. (EH, M1)

"Creativity and Discovery" – Question 2

The second question from this story was:

> How does Mendel's work illustrate that observation and data analysis is not objective (i.e. scientists "see" through the lens of their theoretical commitments)?

The number of acceptable and problematic students' responses is reported in Table 16. Additionally, Table 16 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

Despite the question asking how scientists are not objective, many students claim that scientists can be unbiased. Some students shift to the opposite extreme by overstating the subjective nature of science. As with other questions, many students misinterpret some aspect of the question's language.

Table 16: Student responses to question 2 of "Creativity and Discovery: The Work of Gregor Mendel".

Response Category	**Number of instances**
Acceptable	**55**
Problematic	**70**
Specific Problematic Response Themes *NOS related problematic responses* • Claim that scientists can be unbiased o *Explicitly claim that Mendel and other scientists are or can be unbiased* o *Implicitly claims that Mendel or other scientists are unbiased* o *Data Tells* o *Increased data leads to greater objectivity* • Overstate Subjectivity *Misinterpretation of question language or do not answer question* • Did not understand "objective" • Don't answer questions o *Simply describe Mendel's work* o *Only note that Mendel's work was not straight-forward*	 28 *6* *14* *4* 4 15 14 18 10 8

Acceptable responses (N = 55)

Acceptable responses often noted how Mendel's numbers did not show a true 3:1 ratio, but Mendel made sense of the data by inferring a 3:1 ratio. More advanced responses might additionally note how Mendel's view of factors might have led him to believe a 3:1 ratio ought to be observed.

> Data interpretation's subjectivity is illustrated by the fact that not all the crosses were exactly 3:1, but Mendel made sense of the data by interpreting 3:1 to be what is happening with some outliers that are statistically insignificant. (CN, M2).

> Mendel illustrates that science is subjective rather than objective, because he has to interpret his data. The numbers will not tell a scientist what he needs to know, but they will lead him in the right (or wrong) direction. Mendel inferred, and rightfully so, from his numbers that a 3:1 ratio should exist. However, he never achieved a perfect 3:1 ratio. One also has to remember that genetics have a lot to do with probability, and probability is rarely exact. (MZ, M2).

Problematic responses: 70

Problematic responses varied greatly for this question. Most common and perhaps most problematic were students' views that scientists can achieve objectivity. Because so many maintained an objective view of science and others clearly misinterpreted the concept objectivity, the question might be better worded by asking students how the story illustrates scientists are biased and influence by their expectations. Simplifying the question's language may help students better attend to NOS ideas being promoted. A possible problem would be that students would then shift too far and think that subjectivity in science cannot be significantly reduced.

Claim that scientists can be unbiased (N = 28)

These responses indicate that students believe individual scientists can be objective. Some explicitly say science can be objective, but most only imply scientists' objectivity. A few students believe that data tells scientists what to think indicating that scientists' biases would have little impact on conclusions. Similarly, other students claim that increased data leads to increased objectivity.

Explicitly claim that Mendel and other scientists are or can be unbiased (N = 6)

> Mendel's work is physical, concrete evidence. He followed all the steps of proper scientific research and has actual plants that he takes his observations on. Mendel, as well as any scientists, is simply a liason between scientific evidence and the general population. Scientists simply observe and write down, adding in their own spin on things but generally keeping their findings unbiased. (JM, M2).

> He plans an experiment, sets the conditions of the experiement so little, if any, error is attained, and follows through with his experiment to see the ending result. My calculating the conditions in his experiment it is considered that the result is not influenced. Thereby what is observed ultimately confirms or doesn't confirm prior predictions. (NF, M2).

> …it shows that he took the time to collect the accurate data and it may not be exactly 3, but he did not try to cover it up which shows that his results are not biased by his own beliefs. (KA, M2).

> He does not have biased experiments and claims that are based on former beliefs. (ZK, M2)

Implicitly claims that Mendel or other scientists are unbiased (N = 14).

> His data is not always "perfect" for his claims. He admits that the ratio in his data is not always three to one, which would be the best ratio to prove his hypothesis. He did not see the data the way he wanted to see it, or pick out the data that best proved his point; he analyzed all the results that he collected, whether or not they fully supported his claims. (LG, M2).

> Mendel's experiment is essentially based on observation in which he derives his data from. It is a combination of data and mathematical probability. (KB, M2).

> As Mendel did his work, he changed his ideas to go with the data that he was observing. He didn't change his data to fit his ideas. (RR, M2).

> Mendel went into his experiment not really knowing what he was going to find…there wasn't any way that Mendel only saw what he wanted to see… (EE, M2).

Data Tells (N = 4).

> Even though Mendel's data had flaws he was able to find a general trend with in the plants, thus leading him to the 2/3 to 1/3 of the hybrid to dominant and recessive traits. (LM, M2).

> It takes a lot of understanding of the material to be able to go through it and find what the data is telling you. (HM, M2).

Increased data leads to greater objectivity (N = 4)

> Observations and data might not fit the calculated answer, but the results may show a different trend. Scientists have to test more thoroughly to get exact results. (JY, M2).

> Sometimes there needs to be more experiments and more individuals in the experiment to get better numbers. Scientists sometimes need to perform extra experiments to see if their hypothesis is correct of if it is incorrect (PK, M2).

Did not understand "objective" (N = 14).

Several students clearly did not understand what is meant by objective. Some of the students say Mendel was not objective but go on to note how open minded he was and that he did not let outside influences affect him.

> Mendel's data analysis and observation is not objective because he wasn't ignoring the other information that he didn't publish. He simply published the majority of his information that happened to coincide with his hypothesis. He was showing the public how much data supported his ideas. (AR, M2).

> Mendel's work was definitely not objective. He was a very hands on scientists and was always excepting of new ideas and discoveries. He was always creating new hybrid plants and new discoveries were welcomed. (CM, M2).

> I'm not really sure what objective means in this particular questions. Does it mean that the results are actual results and not tampered with or persuaded to make one type of offspring over the next? (MS, M2).

> Mendel's work with the plants, his observations and data analysis, were not objective because he almost "stumbled" upon these results before actually realizing the significance… (JN, M2).

Overstate Subjectivity (N = 15)

These responses jump to far on the continuum between subjectivity and objectivity and claim that Mendel was simply guessing or that scientists can use data to support any idea they may have.

> His experiments were complex and involved a lot of guessing as to the causes of the different F2 generations. He guessed based on his own ideas. These ideas may or may not have been right. (AL, M2).

> Inconvenient data can simply be ignored and support for pretty much any idea can be found as long as one ignores the contradicting data. (VG, M2).

> It is not a proven fact and therefore can be interpreted anyway you want to. (EE, M2).

Don't answer questions (N = 18).

As with most of the questions, several students did not answer the question or discussed ideas not clearly related to the question. Some of the students just describe Mendel's work while other just note that Mendel's work contained inherent ambiguity rather than how Mendel's work illustrated a lack of objectivity.

Simply describe Mendel's work (N = 10).

> Mendel's work illustrates that observation and data analysis is not objective because Mendel crossed the two different plants of the same species. After crossing he found out that the species had one dominant and recessive genes which led to modern world's theory about the heredity in plants. When Mendel crossed his pea plants with different length of stems and different colors which helped him decide the nature of the resultant plants ie. The hybrid of the two plants. (SN, M2).

Only note that Mendel's work was not straightforward (N = 8)

> His work isn't definite. When he uses a large number of plants the outcome is different than if he were to use a small number of plants. Experimental results always come out differently and may include some error. (MB, M2).

> Mendel's work illustrates that observation and data analysis are not objective because his ratios are not the perfect even number he predicted. Mendel recorded what he observed and statistical randomness is present in these observations. (BE, M2).

"Creativity and Discovery" – Question 3

The third question from this story was:

> 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?

The number of acceptable and problematic students' responses is reported in Table 17. Additionally, Table 17 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

While the number of problematic responses seems high, very few are directly related to NOS misconceptions. Even of those related to NOS misconceptions, most of the problematic responses were problematic because the response was too vague rather than inaccurate. Most students simply did not address all parts of the question and only noted how one aspect of science requires creativity.

Table 17: Student responses to question 3 of "Creativity and Discovery: The Work of Gregor Mendel".

Response Category	**Number of instances**
Acceptable	**60**
Problematic	**65**
Specific Problematic Response Themes	
NOS related problematic responses	
• Accurate but vague	11
• Noted that Mendel is creative, but hinted that other science is not	2
Misunderstood language or incomplete answer	
• Limited creativity to one aspect of science	43
o *Focused solely on creative ideas*	*27*
o *Focused solely on design of investigations*	*14*
o *Focused solely on data analysis*	*1*
o *Focused on scientists' presentation of data*	*1*
• Misunderstood creativity	11
o *Creativity is determination*	*10*
o *Creativity is fun*	*1*

Acceptable responses (N = 60)

This question identified three areas of scientific research that require creativity: creating ideas, creating ways to test ideas, and data interpretation. If students accurately addressed how creativity is used in at least two of these areas their view was consider acceptable. Essentially, acceptable responses needed to note how creativity is required both in idea generation and creating ways to investigate nature.

> To be a scientist, you must be creative. Mendel had to take a new approach on why the hybrids were how they were. To think up reasoning for that and then come up with an experiment took lots of new ideas that had not been seen before. Mendel also had to figure out why the data was expressed as it was by thinking outside the box. Scientists have to be creative, since they have to think of new approaches to everyday problems. Mendel's experiment shows that from start to finish with his new ideas and ways to come up with everything (AL, M3).

> He showed creativity by being able to come up with a new idea, an experiment to test that idea, and the ability to interpret the data so that the idea worked. (BB, M3).

Problematic responses (N = 65)

As with other questions, the most prevalent problem with student responses is their attention to only one aspect of science requiring creativity. Because the question asks for how various aspects of science require creativity, student responses that did not address several aspects were considered problematic. While most all students recognize the creativity inherent in science, if they see science as only creative in one aspect, they likely do not fully grasp the nature of science investigations. Separating the question into parts might more forcefully draw students' attention to how creativity is required in the different aspects of science investigations. Instead of asking, "How does Mendel's original idea, approach to testing that idea, and his analysis of data illustrate that science is a creative endeavor?" the question might be broken down to ask, "How does each of the following demonstrate that science is creative? A) Mendel's original idea, B) Mendel's approach to testing his ideas, and C) The manner in which Mendel analyzed his data."

Accurate but vague (N = 11)

While these responses note that science is creative, they are so vague that ascertaining students real views or how they would explain the role of creativity in science is difficult.

> It takes a very creative mind to reject a well accepted theory and explore the possibility of an alternate solution. Mendel took the information of his time and used pea plants to revolutionize the scientific theory of heredity. That is pretty creative! (RC, M3).

> Mendel had great creativity in his work because no one else had done his research or in the chosen manner. (LM, M3).

Limited creativity to one aspect of science, didn't explicitly say not in other aspects, but did not include although question asked about (N = 43)

While these students note ways in which science is creative, they focus only on one aspect of science despite the question's explicit attention to multiple aspects of science.

Focused solely on creative ideas (N = 27)

> Again, Mendel had no clue as to why plants produced the plants that they did. He merely knew, from his data, observations, and analysis that it was so. He had to speculate that this production was due to heredity and dominant genes, no one was there to tell him that this explanation was right or wrong because no one had ever thought to study heredity in this way before (CG, M3)

> Mendel's approach to science illustrates that science is a creative endeavor because he had to formulate his own idea in his head because there was no information out there about gene types and other characteristics of genes. (TW, M3).

> With his data, Mendel had to creatively create an explanation for what he had discovered. (EG, M3).

> Mendel had to take what little knowledge he had and then from there figure out that there was a certain trait that was overpowered and had to figure out which hybrids had dominant and recessive traits and would breed easily together. All of these things show that science is a creative endeavor. (KN, M3).

Focused solely on design of investigations (N = 14).

> Mendel proved that science is a creative endeavor in the process he went through to determine dominant and recessive traits. He was creative in deciding the approach to take in determining how he was going to investigate the traits, having the plants use self fertilization. This was a very creative process considering the time and what he was trying to discover. (RM, M3).

> Mendel's work illustrates that science is a creative endeavor because he thought outside of the box, so to speak. He crossed not only regular plants, but also their

> hybrids in countless combinations that had never been tried before. He had to come up with a creative way to solve a mystery. (YR. M3).

Focused solely on data analysis (N = 1).

> Mendel's work proves that science is a creative endeavor because he is creative in how he interprets his results. Without a creative mind scientists would not be able to draw conclusions from the work. Creativity is what spurs them on to find solutions and make connections. Mendel had a very creative mind and we can see that his intensive work with peas and hybrids (KK, M3).

Focused on scientists' presentation of data (N = 1).

> Mendel's original idea, approach to testing that idea, and his analysis of data illustrated that science is a creative endeavor because in order to prove his idea he has to come up with a way that would persuade other scientists to accept his idea. His data had to illustrate that his idea was indeed correct. (KN, M3).

Misunderstood creativity (N =11)

Surprisingly, some students misunderstand the term "creativity" or do not talk about creativity in their answer. Several students only talk about Mendel's determination and another students equates creativity and fun.

Creativity is determination (N = 10)

> They have to be extremely determined to take their lone idea usually not supported by the public, in fact usually denounced by the public, and come up with empirical evidence to support it. They must have creative insight that only truly creative minds must possess. (WW, M3).

> The sciences are one of the greatest institutions of creative thinking. Sciences require an open mind and an ever-growing hunger for knowledge. Mendel showed how one person can take an idea and, through rigorous experimentation, turn it into a widely accepted truth. (KH, M3).

Creativity is fun (N = 1)

> Many people believe that research is boring, but I think because Mendel grew plants that matured quickly and could yield very visible results he enabled his research to be more fun and less tedious. (SN, M3).

Noted that Mendel is creative, but hinted that other science is not (N = 2)

Some students admitted that Mendel had to be creative, but imply that he is not like most scientists or that other science is not creative.

> If Mendel would have done what other scientists did we probably wouldn't know who he is today. Because of his creativity he created a new plan and explored new ideas that led to new discoveries. (NS, M3).

> Mendel had to be creative to be a scientist at this time. Many people would put down his ideas, but because he was creative, he formed an in-depth hypothesis in which he traced through generations, introducing something new to science. (AB, M3).

"Creativity and Discovery" – Question 4

The final question from this story was:

> Consider that Mendel's ideas involved "factors" for particular traits, and the application of mathematics and probability to biological systems. Why might scientists in Mendel's time have found each of these ideas difficult to accept?

The number of acceptable and problematic students' responses is reported in Table 18. Additionally, Table 18 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

A wide variety of NOS misconceptions were demonstrated in student responses for this question. Some students viewed Mendel's work as not very well supported with several students noting his ideas were note "proven". Some students believed others were not as smart as Mendel. While Mendel's intelligence may have been high, these students seem to support a "lone genius" model for science. Additionally, even though Mendel was himself a priest, some students maintain that science and religion must be at odds.

Table 18: Student responses to question 4 of "Creativity and Discovery: The Work of Gregor Mendel".

Response Category	**Number of instances**
Acceptable	**81**
Problematic	**44**
Specific Problematic Response Themes	
• Mendel's research wasn't well supported	19
o *Didn't have absolute proof*	*7*
o *Mendel didn't have enough evidence*	*6*
o *Not enough technology to support ideas*	*2*
o *Mendel wasn't a "good" scientist*	*4*
• Despite Mendel being a priest, many students claimed the "religion vs science" to be the reason others didn't accept his ideas	19
• Other scientists were simply not as smart as Mendel, support "lone genius"?	7

Acceptable responses (N = 81)

Acceptable answers discussed how prior ways of thinking might interfere with scientists accepting Mendel's ideas. Most students focused on how mathematics had not been previously used in biology so scientists had trouble accepting that biological phenomenon might be related to probability. Also, acceptable responses may have included how other scientists may not have easily accepted Mendel's notion of factors since they were unobservable entities.

> Scientists in Mendel's time might have found his ideas hard to accept because it was the first time that "factors," probability, and mathematics had been tied to heredity. The scientists were not used to this connection, and were likely not ready to accept the idea after only one set of experiments. (CR, M4).
>
> At this time, many scientists doubted Mendel's thought on "factors", since he could offer no explanation on what they were or how they were transmitted. Some Naturalists also thought that plants could not reproduce sexually, removing the possibility of factor exchange at all. (AK, M4).

Problematic responses (N = 44)

Three main themes were observed as problematic responses. Some students explained that other scientists did not accept Mendel's ideas because his research was not well supported. Some students thought other scientists were not as smart as Mendel. A few students even claimed the issue was related to science and religious conflict despite Mendel being a priest.

Mendel's research wasn't well supported (N = 19)

Several reasons were put forth when claiming Mendel's research was not well supported. Some students demonstrated a common misconception that science requires or is capable of absolute proof. Other students claimed Mendel did not have enough evidence or was not a trustworthy scientist. Some even claimed that scientists did not have enough technology to provide enough support for Mendel's ideas.

Didn't have absolute proof (N = 7)

> Scientists' might have found Mendel's ideas difficult to accept because his data was not totally clear and accurate. Scientists want totally prove of an idea, not just a sketch, which Mendel supplied them with. (KN, M4).

> Scientists at his time would find it hard to except both of these ideas because neither of these ideas were proven so his ideas had a lot that could go wrong with them. (RT, M4).

> They might have felt them hard to accept because there was no conclusive proof other than the data Mendel had to support his theory. It's hard to believe something without proof. (SN, M4).

Mendel didn't have enough evidence (N = 6).

> Other scientists may have had trouble accepting some of these ideas because they were probably not very developed. There wasn't very much information supporting them. (KA, M4).

Not enough technology to support ideas (N = 2)

> There weren't any technological advances to go even further with Mendels experiments. (LS, M4).
>
> The technology during this time was not as advanced so scientists could have thought that it was difficult to determine the various factors needed to produce various cross-breeding results. (AL, M4).

Mendel wasn't a "good" scientist (N = 4)

> His failures on exams made it hard for other scientists to believe Mendel's work was efficient and correct. Mendel's nerves also go to him as well, so for other scientists Mendel's ideas just didn't seem stable and level-headed. (SG, M4).
>
> They might have thought that he manipulated his numbers to get a figure he wanted and be become famous. They also did not know how he was able to come up with his numbers in the experiment which could make some scientists disbelievers. (BA, M4).

Other scientists were simply not as smart as Mendel, support "lone genius" (N = 7).

This group of students claimed that other scientists were not as smart as Mendel. The other scientists did not accept Mendel's ideas because they simply did not understand the ideas.

> Scientists may have found Mendel's ideas hard to except because to them his ideas may have been too abstract or advance at that point in time and it may have been hard for them to grasp the concept and understand it fully like Mendel and a few of his fellow scientists could. (KA, M4).
>
> Mendel's ideas were very advanced for his time and were very far fetched and creative compared to what most other scientists of his time could even comprehend. The statistics and reasoning put behind the conclusions Mendel drew were very advanced and out of the understanding of any other scientists. (SB, M4).

Despite Mendel being a priest, many students claimed the "religion vs. science" to be the reason others didn't accept his ideas (N = 19).

Although Mendel was a priest, some students attributed scientists not accepting his ideas to a perceived conflict between science and religion. The Mendel short story made little mention of the interaction between science and religion, but students seem to be applying their knowledge from popular culture or even from wrongly applying historical episodes related to science and religion.

> Scientists didn't really have much knowledge of how probability worked in relation to life. The popular belief was that things were created by a higher being. People just had a hard time accepting the idea of mathematical equations being responsible for how life or genetics worked. (EE, M4).
>
> Scientists of that time were not very scientific to today's standards. They relied fairly heavily on beliefs and faith and chose to ignore certain facts if it was necessary (JM, M4).
>
> The time that Mendel lived was full of "science vs. religion". For someone to step forward ad say that the only reason plants were the way they were was because of mathematical probabilities and patterns was social suicide. (TD, M4).
>
> I think that at the time the prevalent idea was something along the lines that God made the world to be exact and that there was no probability. (BB, M4).

Story 4 - Charles Darwin: A Gentle Revolutionary

The story about the work of Charles Darwin was assigned to students in conjunction with the story about Alfred Wallace. The Darwin story highlighted Darwin's travels as well as his efforts to make sense of his observations. The story drew attention to ways our culture affects popular views of science as well as how culture affects science itself. The story directly addressed ideas like methodological naturalism, the scientific method, and the role of both experimental and observational science. The story also detailed Darwin's personal struggles including his illness, the death of his daughter and his understanding of the cultural implications of his idea.

Results obtained from analyzing students' responses of each question are reported in tables 19, 20, 21 and 22. More detailed descriptions of themes developed from student problematic responses are provided after each corresponding table.

"Charles Darwin" – Question 1

The first question from this story was:

> Summarize the evidence and reasoning Darwin uses to support the view that species change to become adapted to their environment rather than having been uniquely created for that environment.

The number of acceptable and problematic students' responses is reported in Table 19 Additionally, Table 19 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

Table 19: Student responses to question 1 of "Charles Darwin: A Gentle Revolutionary".

Response Category	**Number of instances**
Acceptable	**122**
Problematic	**32**
Specific Problematic Response Themes	
• Human involvement in evolution	5
• Lamarckian Evolution	8
• Creationism	7
• Limit to Microevolution	3
• Misperceive Darwin's role/purpose	3
• Extraneous reasoning/evidence	2
• General Confusion	6

Acceptable responses (N = 122)

As with other content-oriented questions, most students did not struggle with summarizing the evidence and reasoning of Darwin. Students were able to highlight how Darwin's observation of species that were geographically separated informed his thoughts on how these species might have come to be.

> Because species in nearby locales, yet completely separate, were similar, Darwin hypothesized that species had been transported somehow and adapted to their environment and were not simply placed there. During his adventure to the Americas

> and the Galapagos Archipelago, Darwin noticed that the species were very similar. Again in Cape de Verde Islands, the species were related to those in Africa, (CG, D1).
>
> Darwin thinks that it is highly unreasonable for a Creator to "visit" every inch of land on the Earth and make unique species of animals for every different place. He thinks that the animals originated from mainland and then were transported to places, like islands, and adapted to the different climates. (AR, D1).

Problematic responses (N = 32)

While most students seemed to understand Darwin's ideas well, some still demonstrated misconceptions related to biological evolution. While NOS misconceptions may hinder students' acceptance of evolution, no NOS misconceptions were identified in student responses when explaining Darwin's reasoning. This absence of NOS misconception may indicate that NOS misconceptions mainly affect students' *acceptance* and *deep understanding* of evolution, but not their ability to engage with the reasoning and evidence to support biological evolution.

While content questions such as this one are more straightforward, students still interpret the questions in interesting ways. Some students interpret the question correctly, but use past experience/thinking to interpret the message of the story in ways other than intended. Other students seem to latch on to an historical idea (ie: Lamarckian evolution) and incorrectly believe the historical idea to be the current views.

Human involvement in evolution (n = 5)

These students believe that the relocation of species is due to human influence. That is, humans separate species and then the species evolve into different species. These students likely do not fully understand that deep time necessary for evolutionary processes. While the story does make a connection to geologic time via Darwin's thinking, no explicit connection is made between geologic time and evolutionary time prior to question one in this short story. While only five students explicitly indicated this misconception regarding human transportation of species, many more may hold this view as the question did not ask students to discuss how evolution happens, only the evidence and reasoning Darwin used to support evolution.

Some students leaning toward human control of evolution were implicit, using language such as “shipped” to indicate the species were transported via human transportation.

> …there was only one species of each kind of organism that were shipped to different parts of the world that had to change and adapt to be able to survive. (LG, D1)

Other students were more forceful in their language regarding the role of humans in evolution.

> …leading Darwin to believe that they had been introduced to islands and other with them and mutants that eventually came about creating new species. (SN, D1).

This misconception of human interference has possible links to other misconceptions regarding evolution. If humans control evolution, students will wrongly believe evolution to be a short process. Furthermore, the notion of controlling evolutionary change borders on Lamarckian views that organisms change as result of effort rather than through natural selection.

Lamarckian Evolution (N = 8)

While the story does mention Lamark and explains his ideas regarding evolution, the passage makes clear that Darwin’s ideas varied from Lamark’s. Unfortunately, some students seemed to have used the reading to support the misconception that organisms evolve due to effort or desire – ideas that might make intuitive sense, but do not accurately describe accepted ideas regarding natural selection.

> For their attempts at adaptation they might attain certain physical properties and in turn making them a new species of their former selves (HA, D1)

> He (Darwin) thought about the use and disuse of limbs and organs. He thought of the giraffe and how it reached for food and the neck could have gotten longer and longer. (SP, D1).

Creationism (n = 7).

Several students exhibited creationist views regarding evolution. Most of these views were minor, but do not represent ideas found in the story.

> …instead of species being created for the specific island that they were created probably on the mainland, and then adapted to their new environment on the island. (KD, D1).

> He (Darwin) believed that they must have been created in one place and then must have somehow been transported to other places in the world. (BH, D1)

> One explanation is that a few primitive species were created, moved to other environments and adapted to match the environment. (MJ, D1)

Other students seem to have reversed the examples of the story and come to the conclusion that Darwin became more of a creationist throughout his journey on the Beagle.

> Then, he (Darwin) began to read books about others ideas, including castrophism and uniformism (that everything was created from one area). Doubting these, he set off on an excursion around the country in a ship known as the *Beagle*. On this excursion, he saw animals that were fitted especially to their surroundings and unique differences in their make up and features from one part of an island to another. That's when he began questioning the idea of genetic evolution. (JO, D1)

> All this led him (Darwin) to think that the currently held beliefs were inaccurate and that a different set of organisms was created for each place. (CN, D1)

Limit to Microevolution (n = 3)

While none of these students explicitly indicate acceptance of microevolution and rejection of macroevolution. The students' responses seem to indicate that they understand evolution to be concerning only within species changes as opposed to change resulting in new species. While microevolution does occur, if students believe only microevolution occurs they do not fully understand the breadth of explanatory power in evolutionary theory.

> He (Darwin) saw that many of the animals came from the mainland and changed to their new environment. (LL, D1)
>
> The reasoning behind Darwin's theory that animals adapt to their environment is supported and proved through the differences in the same species relative to their environment. There are differences between members of the same species just based on where they live. (RT, D1)
>
> The same species of bird from two different areas have different types of beaks, which are for specific uses in each environment. (LS, D1)

Misperceive Darwin's role/purpose (n =3)

Some students seem to have misconstrued Darwin's intent. One student seems to think Darwin set out to disprove creation.

> He (Darwin) did not agree with the logic he was presented and, therefore, set out to disprove that logic (independent creation) with factual evidence.

While the student may claim the story supports their thinking, the story took great pains to make clear that Darwin was not anti-creation and that at one time he intended to become a priest. This students' phrasing also seems to elevate "factual evidence" above other kinds of thinking. This student seems to believe science is above religion as "factual" rather than thinking science and religion each have a role. Furthermore, the student does not seem to understand the role imagination and creativity play in interpreting evidence, that evidence is not self-evident.

Two other students seem to misconstrue Darwin's role in the evolution idea. While natural selection was an important addition, the story made clear that the idea of organisms changing over time was not novel. Yet, these students (and the previous student) see Darwin as a wild revolutionary coming up with all of his ideas completely independent of anyone else.

> He finally came up with the idea that when they change environments, that they themselves change, thus evolution. (SR, D1)

> He came to disagree with the then accepted independent creation and formed his own opinions. (AK, D1)

Extraneous reasoning/evidence (n = 2)

These responses brought in reasoning or evidence not discussed within the story. While this is not problematic, the notion that students are answering the question with information beyond that included in the story indicates how students bring prior thinking with them and use that prior thinking/experience to interpret the story and the questions.

> All he had to do was look at fossils and compare them to species today (TH, D1).

> He used a lot of fossil records that he had gathered and that there was no other evidence of these animals anywhere else on earth. (ZD, D1)

General Confusion (n =6)

Three students seem to have confused Darwin's thinking/reasoning. One student seemed to miss that Darwin thought the species on different islands were linked to each other, but still different.

> Darwin realized that the species he studied on each island were unique to it. (AL, D1)

Another student noted that similar environments had similar organisms, rather than Darwin's observation of the opposite.

> He noticed similarities between the two environments and similarities between the animals. (AP, D1)

The third student simply stopped at Darwin's questioning of unique creation and makes no reference to Darwin's explanation.

> He noticed that they were similar to other birds off the island of the Galapagos, but their beaks were different. He couldn't understand why they would be created differently. (NS, D1)

Two other students confused climate issues, thinking that the climates were the same when the story talked about climates being different.

> Darwin couldn't figure out why the birds on the Galapagos were only slightly different from those of the mainland, even though their climates were very similar. (KN, D1)

> The best example that is given is the difference between the Galapagos finches and the finches on Chili. These two finches lived in the exact same climate. (AL, D1)

"Charles Darwin" – Question 2

The second question from this story was:

> Scientists are human beings and part of society. Like all humans, their work is influenced by the culture in which they exist. a) What cultural factors are influencing scientists' thinking that adaptation must follow some sort of plan? b) How does Darwin's struggles and anxiety indicate he is wrestling with those same cultural influences?

The number of acceptable and problematic students' responses is reported in Table 20 Additionally, Table 20 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

While some students demonstrated problematic responses related to content, most of the problematic responses were related to students' misunderstanding of the phrase "cultural factors". Some students did exhibit NOS misconceptions with scientific method being the most common.

Table 20: Student responses to question 2 of "Charles Darwin: A Gentle Revolutionary".

Response Category	Number of instances
Acceptable	**108**
Problematic	**41**
Specific Problematic Response Themes	
• Problematic interpretation related to NOS	
o *Misunderstanding of phrase "cultural factors"*	
▪ Miscellaneous	8
▪ Cultural factors = population increases	4
▪ Answered questions noting human or cultural evolution	4
▪ Ignore culture and discuss evolutionary factors	5
o *General NOS misconceptions*	
▪ Scientific method	18
▪ Science ideas must be proven	1
▪ Science ideas are discovered or found	9
▪ Evidence interprets self	2
▪ Science & religion at odds	1
o *Past cultural effects on science not same as today*	5
• Problematic interpretations related to content	
o *Ladder of progression was Darwin's idea*	1
o *Misunderstanding of evolution*	2

Acceptable responses (N = 108)

Acceptable responses addressed both how cultural influences affect scientists and how Darwin is being influenced. Most students identify the dominant religious views of the time to be the cultural factor affecting scientists and note that Darwin is concerned about how his ideas will be accepted and interpreted by both the scientific and religious communities.

> Cultural influences can affect scientists' thinking, as well as followers of a certain faith like Christianity. Darwin wasn't sure about his data, but he knew he didn't agree with some of the earlier opinions on adaptation. It was hard for him to publish his paper without knowing a mechanisms responsible for adaptation. (EE, D2)
>
> The main cultural factor that is influencing scientists thinking and adaptation is religion. Since God has a plan for us all, then adaptation has to be apart of that plan. Darwin's fear of being dubbed an atheist or materialist shows that this was as true yesterday as it is today. (BK, D2).

Problematic responses (N = 41)

Problematic responses for this question were divided into two groups: those related to NOS ideas and those related to science content ideas.

Problematic interpretation related to NOS

Misunderstanding of phrase "cultural factors" (n = 21)

These students misunderstand what the question means by cultural factors. Some students simply misunderstood the term cultural factors while others simply discuss the ideas Darwin had regarding evolution.

Miscellaneous (n = 8)

> [Darwin] was in so many different regions and cultures that he didn't have one that he wanted to focus on right away or one that he wanted to figure out first. (ZD, D2)
>
> Darwin needed a plan or he could not communicate with others his views on evolution. Lamarck and Chambers had a plan for people to understand why evolution happened. (JY, D2)
>
> Some of the factors that might be influencing scientists' into thinking that adaptation might be following some type of plan by how many kids people have, certain diseases that people may obtain, or even certain lifestyle choices. (KA, D2)
>
> Since certain animals have the process of natural selection where they do not select their mates according to certain traits they prefer, but however in the human species, we do. The traits that we choose may be transferred to our offspring. (MN, D2)

> The idea that one eventually dies when they get old, or if they caught some sort of disease which would lead to a probability of death is a cultural factor influencing scientist' thinking that adaptation must follow some sort of plan. (AW, D2)

> The cultural factors back then may have been that to keep your good credibility as a scientist: you couldn't just publish something that you couldn't' prove and couldn't find the reason behind it. (DA, D2)

Cultural factors = population increases (n = 4)

> The people are experiencing problems with population and probably having health problems. Darwin needs to get away from all the growth and the population to deal with his anxiety. (WP, D2)

> The increase in population, would in time accumulate and result in an organism becoming incompatible with its ancestors. (CS, D2)

Answered questions noting human or cultural evolution (n = 4)

> Scientists have a hard time thinking that other beings adapt differently than their culture has. … Because [Darwin's] western culture stated that that culture alone was the only one to civilized standards, he labeled other cultures as undeveloped. He assumed that the other cultures had just not gotten to the point in high development that his had, when in reality that was not the case. (HA, D2)

> …which could lead to the adaptation plan since people in the countryside live differently than people from the city. (KA, D2)

> Some of these cultural factors are things such as a change in local population wouldn't change people instantly in adaptations, however over time it would accumulate and result in an unchanged organism being incompatible with the rest of its local population. … Future generation may grow adapted to the things that Darwin and many others had to go through. (SB, D2)

> Some cultural factors that are influencing scientists' thinking that adaptation must follow some sort of plan might be because as the world changes, we change and need to adapt to the change. If the world gets colder, we find a way to get warmer, the world gets warmer, and we find how to cool off. There is always a plan on how to improve. (DS, D2)

Ignore culture and discuss evolutionary factors (n = 5)

> The idea on "struggle for existence" explains that some species had advantages over others. This helps explain the variety of species. They use the example of the wars between the Asiatic tribes. (EH, D2)

> Darwin talked about the small changes of local populations and how in time they accumulate and result in an organism being incompatible with its ancestors. This idea was related to the trouble that naturalists had determining separate species. (CH, D2)

> Cultural factors that may be influencing scientists thinking that adaptation must follow some sort of plan are whether an animal's factors or characteristics are an advantage or disadvantage to their environment. (ST, D2)

General NOS misconceptions (N = 18)

These students' responses indicated NOS misconceptions not tied directly to cultural influences including: scientific method, absolute proof, data interpretation, and science vs. religion.

Scientific method (n = 1)

> Also, the scientific method follows a set of steps and order is easier to understand and explain. (SJ, D2)

Science ideas must be proven (n = 9)

> [Darwin] realized that his ideas could not be proved so they would be hard for society to accept. Darwin dealt with the pressures of what he believed was correct and being able to prove them. (AL, D2)

> Scientists can be inhibited by culture because what they publish can be absolutely, scientifically correct, but if it goes against some deeply held belief of the public it is less likely to be accepted (CN, D2)

> Darwin struggled because he hadn't yet found a way to prove his adaptation idea. (SR, D2)

> …because he had nothing to prove the idea of why the adaptations were occurring in species. (MB, D2)

> [Darwin] wanted to make sure he could absolutely prove it and support it before he released his ideas. (GH, D2)

Science ideas are discovered or found (n = 2)

> [Darwin] wrote his work but wouldn't publish it until he found a mechanism. (RR, D2)

Evidence interprets self (n = 1)

> [Darwin struggles because he wants to believe one thing, but is kind of forced to believe otherwise, what his evidence suggests. (BA, D2)

Science & religion at odds (n = 5)

> Those that believe that there was a creator and people and animals follow that creators plan for them because that is their culture, they don't believe in evolution and adaptation, they believe that God created all. (AP, D2)
>
> The science versus religion factor may also be added in. (SR, D2)
>
> Some people believe the idea that we came from monkeys and others believe the idea of creationism that god created everything. (MB, D2)
>
> Darwin also struggle from this factors because he is of Christianity and the beliefs are against evolution. (CS, D2)

Past cultural effects on science not same as today (n =9)

While these students' ideas might be accurate, they either explicitly or implicitly claim the cultural factors of the past do not necessarily impact science today. These students would likely benefit from explicitly drawing connections between the historical short stories and more contemporary science episodes.

> Religion was certainly a powerful concept back then and it influenced the way scientists thought. (DL, D2)
>
> Science was governed by religion in Darwin's day… (LS, D2)
>
> In the culture of the scientists of Darwin's day it was probably unacceptable to think and believe things that had not already been proven. (BH, D2)
>
> The factor that affected them was this was a very religious time… (AW, D2)
>
> [The Church] was still quite prevalent in life at that time. It still had an influence on everyday life, as well as thinking. (BB, D2)
>
> There was a very strong religious aspect to culture during this time period. (JF, D2)

Problematic interpretations related to content

A few students note misconceptions related to evolution or what ideas Darwin created.

Ladder of progression was Darwin's idea (n = 1)

> Darwin felt that there might have been a ladder of progression instead that would explain the change occurring in a species. (JN, D2)

Misunderstanding of evolution (n = 2)

> Some believe that all humans evolved from apes. (KS, D2)

> Some people believe the idea that we came from monkeys… (MB, D2)

"Charles Darwin" – Question 3

The third question from this story was:

> Nobel prize winning scientist Percy Bridgeman once stated that science is "doing one's damndest with one's mind, no holds barred." He was expressing that doing science research demands creativity and that scientists will use most any method that will help them understand the natural world. 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 defy investigation by means of a controlled experiment. a) How might you account for the prevalence of these two significant misconceptions regarding how science research is done? b) How might the public's adherence to these misconceptions cause them to reject biological evolution?

The number of acceptable and problematic students' responses is reported in Table 21 Additionally, Table 21 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

Although this question highlights two myths of science, the scientific method and the need for controlled experience, many different NOS misconceptions were observed in student responses. Some students seem to have ignored the question's introduction and claim that science does follow a method and that controlled experiments are necessary or better. Other students note other general misconceptions including proven truth, status of theories, and ability to empirically support evolution. Still other students brought religion into their answer despite the question not addressing the relationship of science and religion.

Table 21: Student responses to question 3 of "Charles Darwin: A Gentle Revolutionary".

Response Category	**Number of instances**
Acceptable	**81**
Problematic	**73**
Specific Problematic Response Themes	
NOS related problematic responses	
• General NOS misconceptions	46
o *Science arrives at proven truth*	*10*
o *Scientists follow the scientific method:*	*22*
o *Controlled experiments are better science*	*20*
o *Theories are not well supported*	*4*
• No way to test or get evidence for evolution	15
Do not answer question as asked	
• Use religion to explain not accepting evolution rather than scientific method or controlled experiment misconceptions	12

Acceptable responses (N = 81)

Acceptable responses to this question provided reasonable origins for the misconceptions related to the scientific method and observational science. The responses also needed to explicitly link these misconceptions to the rejection of evolution. Most students identified both school and popular media as sources of the misconceptions and noted that people might dismiss evolution since it cannot be tested in a laboratory or because Darwin's work did not follow a step-by-step scientific method.

> a. This is probably because it's what is normally presented. How many times have you seen on TV the scientist portrayed as a lone man, surrounded by a Rube Goldberg-esque collection of glassware and tubes and alarmingly bright colored

> liquids? b. Because it would seem to the casual observer that evolution can't be tested in a lab and therefore can't be tested at all. (BB, D3)
>
> a. Perhaps these claims originate from the rigid form that we, as students, learn to make lab reports while growing up. We are told that all hypotheses must be in the "if, then" format and every lab is in the same format. b. Since the public adheres to these two misconceptions, it would be hard to accept that something like evolution, a process that supposedly occurs over millions of years, could be tested. (MP, D3).

Problematic responses (N = 73)

As in the previous question, many students demonstrated specific NOS misconceptions such as: proven truth, the scientific method, and theories become laws. These students often implied that good science does follow the scientific method and/or that the best science is experimental in nature. For these students, the set up to the questions seems to be unclear or at least unconvincing. This question might be reworded to help students understand why the scientific method is myth rather than simply saying so. Perhaps the question could include, "If we look at what scientists actually do, their approaches are so different that a single scientific method cannot possibly exist." Additionally, the question might be better targeted to explaining why "the scientific method" is a myth rather than asking students to reflect on the source of this misconception.

General NOS misconceptions (N = 46)

Science arrives at proven truth (N = 10)

> Scientists create theories that sometimes may be proved right by controlled experiments, but at other times, different outcomes denying the theory may be the case (EG, D3).

Scientists follow the scientific method: (N = 22)

> Although research is usually performed step by step and follows certain guidelines, scientists must use creativity to be able to discover new things (CM, D3)

Controlled experiments are better science (N = 20)

> Because there are no data available that can be seen with naked eyes, i.e. no controlled experiments to support the theory, it becomes very difficult for the scientist to believe the ideas and observations. (SN, D3).

Theories are not well supported (N = 4)

> People may not want to believe something that they can't see in front of their eyes with a factual explanation. This could have been the problem for Darwin because evolution doesn't have a factual explanation. It is a theory and people don't want scientists saying that they think something unless they can prove it (GH, D3)

No way to test or get evidence for evolution (N = 15)

Some students used the ideas the question explicitly notes as misconceptions to answer the question. Clearly, these students did not understand the question "set up". The question as written now asks students to comment on both the origin and application of misconceptions – fairly high-level tasks. Perhaps the question ought more forcefully target the misconceptions themselves and ask students to reflect on how the story illustrates that science is more than a simple step-by-step process or a series of experiments.

> Although Darwin had many ideas about the world around him that would support his idea of adaptation that later led others to hypothesize evolution, there was no experimental test that could prove it to be so. There is no experiment to test the theory. (CG, D3)

Use religion to explain not accepting evolution rather than scientific method or controlled experiment misconceptions (N = 12)

While these students note how misconceptions might inhibit acceptance of evolution, the misconceptions they cite are related to science and religion rather than the scientific method or experimental science.

> The public thinking that science is discovered and performed in step by step controlled manner may cause them to reject biological evolution because of what they have been taught by religion, what others expect them to believe, they're willingness

> to expand their own horizons, and that sometimes, you can't know everything about something. (JG, D3)
>
> A belief in something as strong as religion can keep a person going each day but if a scientist tells you that is wrong then what you fundamentally believe in will be altered forever. (KK, D3).

"Charles Darwin" – Question 4

The final question from this story was:

> Science's approach to explaining events in the universe without reference to the supernatural is called "methodological naturalism". Individual science, researchers must provide natural rather than supernatural explanations for phenomena. This approach has undeniably been successful and has provided useful scientific explanations for phenomena that in the past were attributed solely to supernatural intervention. How would permitting supernatural explanations in science interfere with the quest to develop explanations humans can understand and use?

The number of acceptable and problematic students' responses is reported in Table 22 Additionally, Table 22 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

The high number of problematic responses seems to be the result of students simply attacking supernatural ideas rather than noting how supernatural ideas hinder science progress. While these students' ideas might be accurate critiques, they do not address why science does not make use of supernatural ideas. Instead, the students response simply dismiss the ideas rather than engage with how the ideas are different from science ideas.

Table 22: Student responses to question 4 of "Charles Darwin: A Gentle Revolutionary".

Response Category	**Number of instances**
Acceptable	**84**
Problematic	**70**
Specific Problematic Response Themes	
• *Focus on problems with supernatural explanations rather than how these explanations interfere with the quest to develop useful explanations*	44
o Supernatural ideas cannot be proven, implying that science ideas somehow generally better than supernatural ideas rather than different	25
o Supernatural ideas do not have evidence	4
o Too much variation among supernatural ideas	16
• *Supernatural ideas cannot be proven*	9
• *Supernatural ideas would interfere with acceptance, but not development of idea.*	2
• *Misconception regarding the relationship between science and religion.*	14
o Science or religion dichotomy	6
o Combination of science and religion	5
o Methodological naturalism taken to metaphysical materialism.	3
• *Science does not study supernatural phenomena*	2
• *Underestimate society's view of the supernatural*	9

Acceptable responses (N = 84)

Acceptable responses note how supernatural explanations are of little use for providing useful ideas explaining how nature works. That is, supernatural ideas cannot be connected to other scientific ideas and do not explain phenomena in ways in which human beings can use. These responses often note that supernatural explanations would not meet the evidentiary requirements of science ideas.

> Supernatural explanations have, by definition, no limit. They transcend human cognition and cannot be supported by natural observations and analysis. Thus, supernatural explanations are scientifically bulletproof. If such explanations were used in science, natural explanations would be replaced by those that humans cannot understand, and the initiative to discover natural causes and explanation would be destroyed. (MJ, D4).

> Allowing supernatural explanations would allow for any made up explanation to be a possible contender for the true explanation, and there is no way to disprove supernatural explanations. (MK, D4).
>
> Allowing supernatural explanations would greatly hinder scientific progress since anything that wouldn't be explained would be labeled as being supernatural instead of being investigated further and finding a scientific explanation. (BE, D4)

Problematic responses (N = 70)

Focus on problems with supernatural explanations rather than how these explanations interfere with the quest to develop useful explanations. (n = 44)

These students' focus on problems with supernatural ideas may lead to thinking religious ideas are irrational or of inherently less value than scientific ideas. This view would contribute to the polarization of science and religion rather than the notion that people can accept both science and religion (Gould, 1999).

Supernatural ideas cannot be proven, implying that science ideas somehow generally better than supernatural ideas rather than different. (n = 25)

> Scientists look for answers with things that they can prove which makes the two ideas collide between one with evidence and the other with ideas that will never be proven. (AM, D4)
>
> Supernatural conclusions cannot be proven and therefore are not acceptable for scientific understanding of the natural world. People will want evidence of why things are the way they are so they can understand the learn from these scientific ideas. (SJ, D4)
>
> Humans want some proof about an occurrence. They aren't going to believe that an alien is the explanation for why nature is doing something crazy. (MB, D4)
>
> The idea of science is to come up with factual reasons to many wonders; any person can make up a tall tail and call it fact, but to test it and prove it true is science. (HA, D4)
>
> Many people need to see it to believe it, and in the case of a supernatural being this can't be done. (NS, D4)

Supernatural ideas do not have evidence. (n = 4)

While these students might be correct in saying supernatural ideas have no *scientific* evidence, they go too far in saying supernatural ideas have no rational basis. Furthermore, religious beliefs adhere to their own rules of evidence. While what counts as evidence is different, religious scholars are not allowed to simply create ideas. Theologians, like scientists, are held to particular standards. Instead of using the natural world as a source of evidence, theologians use sacred text.

> There is no strong evidence to support supernatural beings so it is even harder to accept an ideology that is based on supernatural forces. (JK, D4)

> Without some sort of evidence there is not way to make supernatural ideas believable. (JM, D4)

Too much variation among supernatural ideas (n = 16)

Some students rightfully note that supernatural ideas are extremely varied. However, they do not note any problem with the supernatural ideas themselves, only that there are so many. This same argument could be applied to most any legitimate science ideas early in a research program.

> This would interfere with the development of an explanation because not everyone believe in a "supernatural being" because there are so many different types of religion, and it would be really hard to convince someone from an entirely different religion that did not believe in a higher power that there was in fact one. (KA, D4)

> It would confuse people everywhere because there are so many different religions in the world today that there would have to be the same number of explanations for every experiment done, just to satisfy everyone's needs. (TH, D4)

> If we allowed supernatural explanations, there would be multiple explanations for the natural phenomena. Not everyone believes in the same thing, so the beliefs or the supernatural may differe due to geographic locations. (EG, D4)

> Different people have different religious beliefs so not everyone would accept the supernatural explanations involving a religion other than their own. (SB, D4)

Supernatural ideas cannot be proven (n = 9)

These students do make a connection to how supernatural explanations may interfere with development of scientific ideas, but also claim science ideas can be proven.

> Permitting supernatural explanations in science would definitely interfere with the quest to develop explanations because science is based on facts, and bringing in supernatural explanation would also bring in religion and so forth, and this give endless possibilities… (AW, D4)

> If supernatural explanations were accepted in science, there would be little chance to prove virtually anything. Scientists like Darwin could collect a more than substantial amount of evidence, but there would still be doubt because of the change that some supernatural force or being was causing everything to occur, not science. (JK, D4)

> Natural reasons give us plain proof of our ideas. Supernatural could not fully explain science because supernatural we cannot touch or prove anything. … (LR, D4)

> Supernatural explanations can interfere with science because it cannot be proven. If scientist can't prove it then they can't explain to people why it happened. (JY, D4)

> It is impossible to prove a supernatural occurrence. … Humans have to have facts to be able to use to explain different things. Using supernatural explanations would not allow humans to explain anything since there would not be any fact of proof. (AL, D4)

Supernatural ideas would interfere with acceptance, but not development of ideas.(n = 2)

These two students believe people are unwilling to accept supernatural explanations. Unfortunately, their views are likely opposite of reality.

> …humans want to know the natural scientific explanations for things. Using a supernatural explanations will only cause the humans to reject the ideas… (CK, D4)

> …because humans will be more prone to believe a scientist who has scientific evidence on what he believes in, rather than just supernatural explanations they cannot fully understand. (KN, D4)

Misconception regarding the relationship between science and religion. (n = 14)

Some students in this category believed science and religion are mutually exclusive while others believe science and religion should be combined. Both of these views miss the complexities of how science and religion are different. A small group of students misinterpret methodological naturalism as metaphysical materialism and believe the ability of science to explain natural phenomenon negates the need for other kinds of thinking.

Science or religion dichotomy (n = 6)

> Allowing supernatural explanations to coexist with science will interfere with the quest to develop human understanding of the natural world because often times supernatural ideas clash with any theories or understanding of existing scientific discoveries. Also, supernatural phenomena are almost in a whole category of it's own, and it would bring about more conflict and confusion than helping the quest for understanding our environment. (JN, D4)

> People usually do not use supernatural and science in the same sentence. People believe in supernatural or they believe in evolution, not both. (LW, D4)

> Believing in supernatural explanations for science would interfere with scientific reasoning because it would cause a dissonance with the person and they would probably just come up with a justification to believe the supernatural explanation over the scientific reasoning. (AR, D4)

> Either you believe in a supernatural being or you believe in the theory of evolution. They often interfere with each other rather than coincide with each other. (JP, D4)

Combination of science and religion (n = 5)

> Therefore, scientists have to have a theory that not only supports an explanation that people will understand and believe, but also one that might explain a "supernatural being". (AL, D4)

> I think scientists should do what they need to do to find answers to the worlds questions. Even if they are off the wall new ideas that no one would ever think of. This is how we discover new ideas. (NL, D4)

> Although there may be some truth to [the existence of higher powers], it has not yet been proven through science alone. (LA, D4)

> It is best to find a scientific reason for a phenomenon, and then if needed, provide a supernatural hypothesis too. (MZ, D4)

Methodological naturalism taken to metaphysical materialism. (n = 3)

> Many people believe in God and that he made all the animals. With evolution they all evolved from other species. This makes it hard for people to believe if some other power made these species. In the science part there is all natural explanation so people might start to wonder what happened to God and higher powers. (LL, D4)
>
> …everything can be explained with natural explanations and supernatural is not necessary. (CP, D4)

Science does not study supernatural phenomena (n = 2)

These students focused on why science ought not study supernatural events or beings. They ignore how supernatural explanations get in the way of creating naturalistic explanations for natural events.

> Some humans find it difficult to understand some of the experiments that scientists have performed on everyday materials. So many humans would not be able to comprehend the complex explanation it would take to explain a supernatural phenomenon. (SC, D4)
>
> There is no real explanation for the supernatural events of earth, and science is intended to explain the ways of the world. (KG, D4)

Underestimate society's view of the supernatural (n = 9)

These students believe most people will easily reject supernatural explanations. While these students may have adopted a scientific worldview, they underestimate the greater population's views regarding science and religion.

> Humans want some prove about an occurrence. They aren't going to believe that an alien is the explanation for why nature is doing something crazy (MB, D4)
>
> …humans want to know the natural scientific explanations for things. Using a supernatural explanations will only cause the humans to reject the ideas… (CK, D4)
>
> Also, there is the fact that the supernatural isn't believe by everyone, whereas science is a socially accepted subject and what it entails, like organisms, is present on Earth to be studied. (KS, D4)

> People want to hear humanistic and real explanations. We would not want to hear a ghosts story. Supernatural theories would not be accepted by society. (SF, D4)
>
> …people would have trouble believing/understanding something that was described as occurring supernaturally. People are more apt to understand something that is described by a more natural process. (TS, D4)
>
> Because you cannot prove supernatural phenomena. Natural explanations make the society feel better about accepting a concept versus accepting something that is not proven. (LR, D4)

Story 5 - Adversity and Perseverance: Alfred Russel Wallace

While this story is most focused on the work and mishaps of Alfred Wallace, the story gives significant attention to the interactions between Darwin and Wallace. While Wallace and Darwin came to similar conclusions their work differed most prominently in the amount of evidence and their ideas differed in subtle ways illustrating the role of evidence and the need for evidence to be interpreted. The tentative and social natures of science were also addressed by embedded questions within the story.

Results obtained from analyzing students' responses of each question are reported in tables 23, 24, 25 and 26. More detailed descriptions of themes developed from student problematic responses are provided after each corresponding table.

"Alfred Russel Wallace" – Question 1

The first question from this story was:

> Both Darwin and Wallace developed the same theory to account for their interpretations of the data they had observed. How can you account for Wallace's view that his putting forth the theory of evolution would have been seen as simply an "ingenious speculation" rather than the revolutionary effect of Darwin's *Origin of Species*?

The number of acceptable and problematic students' responses is reported in Table 23 Additionally, Table 23 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

The high number of problematic responses is mostly a result of students not attending to the role of evidence in the acceptance of Darwin's ideas. While the role of evidence is important, just because students did not attend to the role of evidence does not necessarily mean they do not understand the role of evidence.

Table 23: Student responses to question 1 of "Adversity and Perseverance: Alfred Russel Wallace".

Response Category	Number of instances
Acceptable	**66**
Problematic	**80**
Specific Problematic Response Themes	
• Ignore evidentiary argument for Darwin's prominence and create/focus on other reasons	60
o *Focus on Darwin's Priority*	27
o *Darwin worked longer/harder*	19
o *Darwin's ideas were more detailed/well thought out*	16
o *Darwin was older/more experienced/better known*	18
o *Wallace published in journal, Darwin in book*	1
o *Darwin was smarter than Wallace*	1
o *Wallace's paper paved way for Darwin*	2
o *Wallace had less money than Darwin*	3
• Wallace had essentially no evidence	2
• Wallace and Darwin had different ideas	1
• Wallace did not take credit	3
• General NOS misconceptions	10
o *Prove/True*	4
o *Discover/find*	1
o *Theory/Law*	1
o *Less Technology*	3
o *Observations not as good as experiments*	1
• Focus on Wallace and Darwin's feelings	2
• Completely off	5

Acceptable responses (N = 66)

Acceptable responses noted the tremendous support Darwin had for his ideas. While Wallace and Darwin had very similar ideas, Darwin's extensive supporting evidence roots his ideas in the natural world.

> To have revolutionary effects, Wallace's ideas needed evidence to back them up. What was different between Darwin and Wallace was not necessarily their ideas but their support for their ideas. (AM, W1)

> Wallace did not have the evidence or all the species to back up his theory like Darwin did. Also Darwin's paper was much more detailed due to the fact that he had been studying species for 20 years to the shorter time of Wallace. (PK, W1)

Problematic responses (N = 80)

Although the answer to this question is fairly straightforward, many students ignore the role of Darwin's extensive evidence. To draw students' attention to this idea, the question might be reworded to ask, "Darwin had extensive evidence to support his ideas regarding evolution. Why do you think Wallace's ideas might have been seen as "ingenious speculation" rather than revolutionary as Darwin's ideas were viewed?"

Ignore evidentiary argument for Darwin's prominence and create/focus on other reasons (n = 60)

Some of these students seem to think the question asks why Darwin was given credit, rather than why Darwin's ideas were more accepted or had more clout. The students did give multiple, and largely inaccurate, reasons for why Darwin was given credit as outlined below.

Focus on Darwin's Priority (n = 27)

> He was the second to come up with the theory, so people would have thought that he was just reiterating what Darwin had already explained in great detail that Wallace had never thought of. (CL, W1)

> Wallace was seen as an "ingenious speculator" because people saw his ideas as just reinforcing the idea that was already discovered by Darwin. (LM, W1)
>
> Wallace was seen as a person who went off of what Darwin sai to produce a new idea. He was not seen as a "revolutionist" in this field because he was not believe to be the first to come up with the idea.
>
> Because Darwin had come up with his theory twenty years earlier. Wallace's was just backing Darwin's theory up. (LS, W1)
>
> Wallace didn't even think of the theory that Darwin worked out until years after. So he thought that he would come out second in the whole thing since Darwin started working on it first. (DS, W1)

Darwin worked longer/harder (n = 19)

> Because Darwin had researched and examined many aspects of his theory, and the fact that he studied it for a long time, whereas Wallace took only a short amount of time in developing his similar theory, is why it may be seen as "ingenious speculation". (KG, W1)
>
> He hadn't worked on it as seriously as Darwin. Also, this was a very creative process, which is determined by the indivitual. (HH, W1)
>
> Wallace's view would be considered as only an "ingenious speculation" because of the time that Wallace spent doing his research compared to Darwin. Darwin put in many years with plenty of journals to account for it, while Wallace's journals were sunken and proof of his research was limited. (MN, W1)
>
> Darwin had been working on his theory for twenty years prior to publishing his ideas while Wallace had claimed to have only spent two days. Many people would regard Wallace's short time spent compared to Darwin's ideas as simply another idea. Also, Darwin's family had a history of working with evolutionary ideas. (WP, W1)

Darwin's ideas were more detailed/well thought out (n = 16)

> One can account for Wallace's view that putting forth the theory of evolution as an "ingenious speculation" rather than the revolutionary effect of Darwin's Origin of Species because Darwin's theory was so well thought out and had things that Wallace had not thought of. (TS, W1)
>
> …because Darwin was able to delve further into the theory of Natural Selection. Also, Wallace had admitted to not having as detailed information as Darwin, and Darwin was able to develop ideas Wallace had not yet thought of. (JN, W1)

> The reason is because he didn't go into that same kind of details that Darwin did. Wallace would have just made other scientists curious to go see for themselves. (AW, W1)

> Wallace's ideas weren't as fully developed as Darwin's. Darwin had thought more of each different component and Wallace's idea was somewhat of an outline, waiting to be written into a full developed paper. (MD, W1)

Darwin was older/more experienced/better known (n = 18)

> Darwin was well respected and a very renowned scientist at the time. Wallace just found himself relieved to have come to the same conclusion as Darwin. … (KD, W1)

> Darwin had already made a name for himself. He had written many stories aout his accounts, and his view on what was happening. People knew is name already. Wallace was still young in the running; he wouldn't have gotten the same fame. (AB, W1)

> Wallace was not as esteemed as Darwin and gave all credit to Darwin. (CB, W1)

> Wallace had spent less time working on his findings and was younger and less known than Darwin even though their work was quite similar. (AG, W1)

Wallace published in journal, Darwin in book (n = 1)

> Wallace may have felt that his effort to explain his interpretations was inferior to Darwin's because it was published in a journal/newspaper. Darwin spent years and years on his book. Wallace's also came first, so he introduced his ideas to the public. Darwin then went second, where some of the topics were already introduced so the public may have been more willing to accept his ideas. (EG, W1)

Darwin was smarter than Wallace (n = 1)

> Wallace saw Darwin as a much more intelligent scientist than himself, therefore calling his theory an "ingenious speculation". (AT, W1)

Wallace's paper paved way for Darwin (n = 2)

> Wallace may have felt that his effort to explain his interpretations was inferior to Darwin's because it was published in a journal/newspaper. Darwin spent years and years on his book. Wallace's also came first, so he introduced his ideas to the public. Darwin then went second, where some of the topics were already introduced so the public may have been more willing to accept his ideas. (EG, W1)

Wallace had less money than Darwin (n = 3)

> Wallace was not as big as a society man as Darwin was. He did not come from money and could almost not even afford his adventure to South America. Therefore, people would be less likely to believe him. (SN, W1)

> …Wallace was not as popular as the great Darwin. Wallace also had little money for his journeys and research while Darwin was very well off. (BH, W1)

Wallace had essentially no evidence (n = 2)

Some students overstate Wallace's lack of evidence. These students seem to hold the misconception that scientists can create whatever ideas they want with no reference to the natural world.

> Wallace's theory was made without observations to back up his idea. He made his conclusion and wrote his paper within a few days. … (SJ, W1)

> …because he came up with his theory through a thought process. [Wallace] did not go on to collect data to support his idea, instead he sent it to other scientists to verify. (LM, W1)

Wallace and Darwin had different ideas (n = 1)

> Darwin and Wallace both thought differently so in retrospect, they would want to do things differently. (LR, W1)

Wallace did not take credit (n = 3)

These students believe Darwin received credit because Wallace did not take credit or gave Darwin the credit. These responses do not note the role of Darwin's evidence.

> Wallace gave Darwin credit for coming up with the idea showing that Darwin was the one to revolutionize the science, while Wallace seemed to say that he ws only speculation on Darwin's work and improving it. (MK, W1)

> Wallace in a sense made room for Darwin to be the big revolutionist. He gave all the fame to Darwin, so Darwin could take credit for the theory of evolution. (BK, W1)

General NOS misconceptions (n = 10)

Several more general NOS misconceptions were observed in student responses. Although these ideas were not explicitly addressed by the question, their presence illustrates how interconnected NOS ideas are.

Prove/True (n = 4)

> It would have been seen only as a speculation because he could not prove it without Darwin. (TH, W1)
>
> If Wallace would have waited until everything was correct for sure his ideas would be more popular like Darwin. (NL, W1)

Discover/find (n = 1)

> The public would consider Darwin as the only person to truly discover evolution. (JY, W1)

Theory/Law (n =1)

> …there is no way to prove it, it is just a theory. (LR, W1)

Less Technology (n = 3)

> …Darwin's book and his theories were only valued until genetics came to existence. (SN, W1)
>
> Because at the time there weren't the technology that there is now. (EH, W1)

Observations not as good as experiments (n = 1)

> At the time it was fair for Wallace to state that the theory of evolution was just an "ingenious speculation". This is mostly due to the fact that it was only an observation at the time; there was not DNA testing or anything on the microscopic level that could be proved. It was a notable theory by Darwin that Wallace commended, but was right in saying all it was at the time was an observation due to the seer fact that there was no scientific proof of it (DNA testing). (HA, W1)

Focus on Wallace and Darwin's feelings (n = 2)

These two students did not address why Darwin's work would be seen as more robust. Instead, they focus on how Darwin and/or Wallace felt about the ideas.

> Wallace was very clever by sending Darwin a letter of his observations. In fact, it even made Darwin a little scared and rushed to publish his work. However, when he did Wallace did not show any anguish, just gratitude that he arrived at the same conclusion as infamous Charles Darwin. (JP, W1)

> Wallace's observations were very clear when he sent his letter to Darwin. I think it made Darwin a little nervous and he rushed to publish his works. Wallace was not upset he was just happy when he arrived with the same conclusion as Darwin. (LW, W1)

Completely off (n = 5)

A few students either claim to not understand the question or clearly do not answer the question as intended.

> Wallace talked a lot about how the human struggle might of lead to a change of our own species. This would of infuriated many people who wanted to keep the human race above the laws of nature. (AL, W1)

> I am sorry but I do not even understand the question. (MS, W1)

Other students claim Wallace's ideas were more robust than Darwin's. They seem to have interpreted the "ingenious speculation" as prominence over Darwin.

> Wallace's view as an ingenious speculation because his theory of evolution adaptation showed evidence. Wallace mentioned why the macaw, being a strong flyer, locate themselves in one place instead of being widespread. It was do to where their food is located. As time change so does the surrounding organisms. Wallace explained that fossils found in the location of a current organism are almost similar, showing that species had "changed" over time. (CS, W1)

> Wallace chose to go further than Darwin did with this topic. Wallace showed the intellect of the species along with the physical adaptations that Darwin showed. (CK, W1)

"Alfred Russel Wallace" – Question 2

The second question from this story was:

> Data does not tell scientists what to think! However, what does the above illustrate about the importance of data in science?

The number of acceptable and problematic students' responses is reported in Table 24 Additionally, Table 24 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

Table 24: Student responses to question 2 of "Adversity and Perseverance: Alfred Russel Wallace".

Response Category	**Number of instances**
Acceptable	**80**
Problematic	**66**
Specific Problematic Response Themes	
NOS related problematic response	
• Data does tell (points, explains, develops, steers)	26
o *Naïve view*	9
o *Transitional*	17
o *Backed up thinking by noting Darwin and Wallace arrived at similar ideas*	5
o *Data "tells" if organized appropriately*	1
• General NOS misconceptions	9
o *Science = Technology*	1
o *Science arrives at Truth*	5
o *Scientific method/hypothesis testing*	2
o *Theory/Law*	1
Misinterpreted question or focused on extraneous aspect	
• Ignored importance of data and focused on importance of some other part of knowledge generation	20
o *Who/how data is presented*	4
o *Interpretation of data overemphasized*	14
o *How data obtained*	1
o *Role of collaborative work*	1
• Misunderstand what question means by "data"	10
o *Data is not the same as evidence or observation*	5
o *Having data to give credit to appropriate party*	5
• Wallace had essentially no evidence	2
• Completely misunderstood question	3

Acceptable (N = 80)

Acceptable responses discuss how data and evidence are used to support ideas rather than thinking ideas can be generated without reference to the natural world. The responses also make clear that data is insufficient for scientific ideas to be developed.

> It agrees that data doesn't tell you exactly what to think, but if you want your information to seem credible and mean something to everyone else, then you must have data and evidence to support it. (BA, W2)

> Data plays a large part in what a scientist believes. The scientist must take the data into account when forming beliefs. Just the data cannot form the belief; the scientist must interpret the data and use some creativity and outside-the-box thinking to form that belief. (CB, W2).

Problematic (N = 66)

Data does tell (points, explains, develops, steers) (n = 26)

Despite the question's explicit statement that data does not tell scientists what to think, many students still personified data to imply that data does tell. The question may need to more clearly note that data is incapable of thought or that data is not an explanation.

Naïve view (n = 9)

> Data does not tell scientists what to think, however, data does give rise to the ideas scientists turn into theories. (SS, W2)

> Data can show you everything. It doesn't tell you what to think but it can show you a new idea to think about. (EE, W2)

> Data can help point scientists in a general direction and put them in the right train of thought. (KB, W2)

Transitional (n = 17)

> Data is needed to support a theory, and although the data doesn't' tell the scientists what to think, it is needed to point them in the right direction. Without the data, the scientists couldn't prove that their idea was substantial. (EE, W2)

> Data does not tell scientists what to think, however data does play an important role in science by illustrating new ideas and thoughts about a certain situation. Data helps develop theories and relationships between different subjects so that scientists can correlate known information with unknown data. (JN, W2)

> Data offers explanations to happenings in the field of science, and in the world. Data is a crucial part of explaining what goes on and how it happens. However, how data is interpreted is the crucial aspect of the field of science. (KG, W2)

> Data is very important to back up what one thinks. Sure everyone can interpret data different but it guides us in the right direction. If one things read eyes in fruit flies is dominate but more offspring have brown eyes then the data proves it wrong. (LR, W2)

Backed up thinking by noting Darwin and Wallace arrived at similar ideas (n = 5)

> Data steers scientists in similar directions just as how Darwin and Wallace came to the same conclusions after studying the same topics. (SJ, W2)

Data "tells" if organized appropriately (n = 1)

> Data can be organized in such a way as to point to the most obvious conclusion. (WW, W2)

General NOS misconceptions

As with other questions, more general NOS misconceptions show up in student responses even though the question does not ask about many of the ideas.

Science = Technology (n = 1)

> … Slowly but surely almost all sci-fi technology becomes a reality. (WW, W2)

Science arrives at Truth (n = 5)

> Without data, scientists would never be able to prove anything. It would all be based on pure speculation. (CG, W2)

> Darwin had much more data than Wallace and in turn was able to come to better conclusions. If you didn't have data, there wouldn't be any evidence and how would you prove your theory to be true? (LE, W2)

> It illustrates that data must always be backed up with evidence in order to convince people that it is indeed fact, and not just speculation. (SN, W2)

Scientific method/hypothesis testing (n = 2)

> Instead of telling scientist what to think, it supports the ideas that they already had. The scientist had set up a hypothesis; the data collected and observed helps to back up that beginning hypothesis. (AB, W2)

Theory/Law (n = 1)

> …it can never be proven if is a theory. (SR, W2)

Ignored importance of data and focused on importance of some other part of knowledge generation (n = 20)

While many of the ideas in this category are accurate, the response ignores why data itself is important in science. Instead of focusing on the role data plays in the generation or acceptance of science ideas, these students focused on other aspects of the knowledge generation/acceptance process.

Who/how data is presented (n = 4)

> Data can be interrupted [interpreted] in many different ways, so how you distribute your data and how you present it will make a huge impact on the receiver. (DA, W2)

> It is important to have data presented in different ways. (EG, W2)

> Whoever is interpreting the data is usually the strong influence in how the data is received to the world. (KG, W2)

> Data is definitely important, but more importantly, I think how the data is conveyed and put "out there" is more important. (AR, W2)

Interpretation of data overemphasized (n = 14)

> This passage shows us that data can be interpreted in many different ways. Darwin and Wallace had pretty much the same ideas but they interpreted wht they had slightly different. Scientists can see things differently than others an this leaves science open to different interpretations. There is not one answer to everything in science and these two scientists proved that. (GH, W2)

> Other scientists interpretations of data lead to theories that they may with to test themselves. (CG, W2)

> Data does not tell what scientists have to think, scientists have to interpret the data in their own view. Interpreting data is what science is, interpreting how the fossils explained evolution was the big breakthrough in the theory of evolution. (JY, W2)

> Darwin and Wallace had the same theory but the way they arrived at the theory is different. It is not the way the data is used that is important; it is the overall interpretation of the data. (LW, W2)

How data obtained (n = 1)

> The way data is obtained has a lot to do with the way other scientists view it. While both Wallace and Darwin both came to the same conclusion about evolution, Darwin became a household name because of the effort and energy he put into his work. (TD, W2)

Role of collaborative work (n = 1)

> It is important to work together and guess and check. If Darwin and Wallace wouldn't have exchanged ideas Wallace would not be completely finished and Darwin probably wouldn't of publicly shared his information. (NL, W2)

Misunderstand what question means by "data"

Data is not the same as evidence or observation (n = 5)

> Data helps build evidence for an idea. (MD, W2)

Having data to give credit to appropriate party (n = 5)

> Data, in the case of this story, was very important in proving that Darwin had established his theory first. (CM, W2)

> …writing down our data is key so that you can get credit for the work that you have done. (KM, W2)

Wallace had essentially no evidence (n = 2)

> Darwin actually had data to back his theory up. Wallace had come up with the same idea but only through speculation. (BB, W2)

Completely misunderstood question (n = 3)

> It tells that, different species exhibit different environment. Science require critical thinking. By accepting some details while others been modified or rejected. (MA, W2)

> Wallace had spent a lot of time on two islands and realized how different they were. They were so close together but had completely different flora and fauna. He then wondered why would a creator make two such simlar islands with such different sets of animals. (AW, W2)

"Alfred Russel Wallace" – Question 3

The third question from this story was:

> Today, the scientific community has rejected Darwin's view regarding the relative intelligence of races. So while his overarching theory and many of its details are still accepted, other notions have been modified or rejected. How does this illustrate that the scientific community is more willing to revise their thinking regarding biological evolution than many critics assert?

The number of acceptable and problematic students' responses is reported in Table 25 Additionally, Table 25 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

Table 25: Student responses to question 3 of "Adversity and Perseverance: Alfred Russel Wallace".

Response Category	Number of instances
Acceptable	**95**
Problematic	**50**
Specific Problematic Response Themes	
• Focused on something besides revision of ideas.	
o *Note science's care in acceptance/rejection of ideas*	21
o *Only focused on strengthening of ideas.*	1
• General NOS misconceptions	
o *Evidence tells*	3
o *Theory*	4
o *Proven truth (science seeks Truth)*	3
o *Scientists are objective*	2
o *Overstate technology's role in developing knowledge*	4
• Overstate characteristics of scientists (ie: scientists more open-minded)	4
• Overstate influence of greater society	3
• Ideas revised so not lost	1
• General Confusion	5

Acceptable responses (N = 95)

Acceptable responses note that scientists do revise their thinking, but do not go so far to say that science ideas change whimsically.

> This shows that the scientific community is trying to come up with the best explanation for biological evolution, based on the information that is available to them. The scientific community is willing to revise their thinking, but not until an explanation arises that explains a phenomenon better than the previously held notion (CR, W3)

> It shows that science is not a constant but is instead in a state of constant flux. By rejecting some ideas and keeping others, science changes, unlike what some might want you to believe. (BB, W3)

> Scientists modify, reject and accept theories. If an experiment or an idea doesn't quite work out, they modify or reject the idea and look for new ways or new ideas. Critics may just reject everything all together. (DS, W3).

Problematic responses (N = 50)

Focused on something besides revision of ideas. (n = 22)

The responses in this category may be accurate notions of how science works, but do not address the question and scientists' willingness to modify their ideas.

Note science's care in acceptance/rejection of ideas (n = 21)

While these students note that science ideas are not easily dismissed or accepted, they do not pay any attention to the fact that scientists *revise* their thinking.

> It shows that scientists don't just blindly accept things proposed by other scientists. They take in to account what is likely to be real and what is likely to just be speculation. (SN, W3)

> The scientific community has been extremely willing to hear ideas. Not all theories are accepted. Darwin had a lot of theories, some were accepted and some were not. (HM, W3)

> Because they didn't just completely throw away is theory instead they took parts of it to agree with it an other they modified it so that it could be accepted; however, other parts they did just throw out, but at least accepted parts of it. (CN, W3)

> The fact that not all of Darwin's ideas have become accepted illustrates the fact that when new ideas are presented they are carefully evaluated and not passively accepted as fact without further testing. (CN, W3)

Only focused on strengthening of ideas. (n =1)

> These areas that Darwin did not have strong evidence for, scientists have been able to find stronger evidence that supports the biological evolution theory. (RM, W3)

General NOS misconceptions

As with other questions, students articulated seemingly unrelated NOS misconceptions when answering this question.

Evidence tells (n =3)

> Since new evidence came forth that led the scientific community to reject the idea of relative intelligence of races, this is evidence that the community is willing to revise their thinking on evolution as evidence dictates. (BE, W3)

Theory (n = 4)

> I believe that the scientific community accepts that proposed theories such as Darwin's theory of evolution are in fact, "theories" and are not concrete explanations….(AG, W3)

> A theory is always changing. That is why it is not considered to be factual. (SV, W3)

Proven truth (science seeks Truth) (n = 3)

> The scientific community is based on hard facts. … The ultimate goal is truth, and science will mold to fit the facts (RH, W3)

Scientists are objective (n = 2)

> All scientists have to maintain an open mind about their work or else they will lose the required objectivness needed to make unbiased claims. (WW, W3)

Overstate technology's role in developing knowledge (n = 4)

> Yet scientist's views can change. The number one reason that I think this occurs is because of technology that has taken over the scientific industry in recent years. (SR, W3)

> They have altered what Darwin thought because of the true findings with more technology that he did not have back then. (LB, W3)

Overstate characteristics of scientists (ie: scientists more open-minded)(n = 4)

This small group of students seems to have shifted to the opposite extreme regarding scientists' willingness to change their views. These students seem to think scientists are very open-minded rather than entrenched in their own thinking. While expecting scientists to be very open-minded is desirable, the reality is that scientists do not easily change their minds.

> …because many people that do not understand biological reasoning may not think that we have to change ways of living that would not be influence in their lives. When looking at the scientific community, they are more well adapted in changes because they undergo concepts and theories that they understand. (ST, W3)

> Scientists are more willing to revise their thinking than most other people. … (KA, W3)

Overstate influence of greater society (n = 3)

> This shows that the scientific world adapts to different theories and ideas. The world changes and so does the way that people think. The scientific world has to bend and mold in order to keep up with the world and the people who live in it. (BK, W3)

> Because of this, many theories are accepted initially, but then revised to fit what culture is willing to accept at that time. (LG, W3)

Ideas revised so not lost (n = 1)

> Many people may look down on evolution but the scientists believe that at least part of it is still true. That is why the scientists revise the theory as opposed to completely throwing it out. (MB, W3)

General Confusion (n = 5)

> Darwin and Wallace disagreed on human intellect and their ideas of evolution and that's why many people today disagree with either of them. The scientific

> community bases their ideas on what they already know and what information is available. (CH, W3)
>
> Because of the fact that certain of the ideas that Darwin had regarding biological evolution are still plausible today, this illustrates the fact that the scientific community is more than willing to revise their thinking regarding biological evolution. Some of Darwin's points are seen today to be just as likely as they were when Darwin first proposed his theory (AL, W3)

"Alfred Russel Wallace" – Question 4

The final question from this story was:

> While science is often portrayed as being done by lone geniuses, what does this historical narrative illustrate about the social nature of science? How do science textbooks' emphasis on individual scientists distort how science really works?

The number of acceptable and problematic students' responses is reported in Table 26 Additionally, Table 26 highlights themes developed from students' problematic responses and how many students held the problematic views. More detail and student quotes are provided below to provide greater insight into student problematic responses.

While the number of problematic responses seems great, as with other questions very few of the problematic responses are the result of clear NOS misconceptions. Instead, most of the problematic responses are based on students not attending to an aspect of the question. While many students did not fully explain their response or ignored aspects of the question, only seven responses were identified as demonstrating clear NOS misconceptions.

Table 26: Student responses to question 4 of "Adversity and Perseverance: Alfred Russel Wallace".

Response Category	Number of instances
Acceptable	**84**
Problematic	**61**
Specific Problematic Response Themes	
Leave out aspects of the question or misinterpret question/story	
• Note that multiple individuals involved, but did not note collaborative nature	22
o *Work of individuals is additive and ignore collaboration*	16
o *Scientists only work together to evaluate ideas & gain support*	6
• Response did not address distortion of textbook accounts	25
• Response notes that people don't have to be geniuses or that the scientists are not that special. They seem to focus on the "genius" rather than "lone"	3
• Short story is fictional	1
• ????	5
NOS related problematic response	
• Lone genius model or the textbooks are accurate	2
• Prominent individuals or ideas are more important or insightful, so given rightful place at lead	4
• Proven truth	1

Acceptable responses (N = 84)

Acceptable responses make clear that science is a social endeavor and that the "lone genius" model does not fit with how real science works. Acceptable responses also note that textbooks' focus on individual scientists paints an individualistic picture of science rather than a social and collaborative picture.

> You usually grow up thinking that scientists do all their work by themselves, but they don't. They use the help of all the other scientists to better their findings to try and come up with what the correct conclusion is. They are not hermits and they look for the help and criticism from other scientists if they have reason (LB, W4).

> The historical narrative between Darwin and Wallace illustrates that science is often a collaborative endeavor between fellow scientists. Textbooks often only emphasis one scientist, creating the illusion that science is a lonely field. (BE, W4).

Problematic responses (N = 61)

Note that multiple individuals involved, but did not note collaborative nature (n = 22)

Work of individuals is additive and ignore collaboration (n = 16)

Some students noted that contemporary ideas influence scientists and that there might be multiple people working on the same ideas and their ideas are "put together", but they do not note the collaborative process and hint that the ideas are developed in private then magically put together by the community. Other students noted how ideas add to past work, but again do not explicitly note the collaborative nature of idea generation.

> The story of Alfred Russel Wallace and Darwin shows that different paths can lead to the same conclusion, and even that conclusion can be use in different ways. (AW, W4)

> Scientists read each other's work and come up with ideas that branch off of previous works and ideas. (SB, W4)

> A majority of Science's ideas are not just one person alone. The ideas of one scientist is built on many other and if not for the first, the others would not have come up with the conclusion that they did. (LE, W4)

> Science has never been solved by single geniuses rather it has been a collection of many scientists' works. All scientists base their work off of the previous people who studied before them. (JM, W4)

> Scientific discoveries are often the result of the compilation of several researchers' theories. One scientist may find the evidence of another's ideas to be logical, but incomplete. They could experiment and develop a new idea building off of the information that was previously unavailable to them **without the help of fellow scientists.** Many scientists were able to demonstrate their ideas through a means of gathering socially in hopes that if their theories were reasonable but incomplete. This would provide the opportunity that someone else might be able to find additional evidence supporting their idea or an idea spawning off theirs. Science textbooks often cite discoveries as the work of an individual. This distorts how science really

> works because it shows little about the efforts of scientists and their contribution through discoveries prior to the findings of the stated scientist. (JK, W4)

Scientists only work together to evaluate ideas & gain support (n = 6)

Some students noted that scientists are social to share ideas and gain support, but mention nothing about collaboration to develop the ideas.

> Because it takes multiple people to accept an idea before society will accept it. If everything was done alone, it would take a much longer period of time to accept things. (LR, W4)

> You take what you have found and observed and compare it to the work of others, to get a truer look on what your hypothesis originally was. (AB, W4)

Response did not address distortion of textbook accounts (n = 25)

While these students addressed the social nature of science, they did not attend to the second question regarding how textbook accounts of scientists distort how science works. While the second question could be superfluous, asking students to critically examine popular images of science encourages them to more deeply internalize accurate ideas regarding NOS.

> Darwin and Wallace were exchanging ideas with each other, supporting some ideas while rejecting others. This shows that scientists work together and gather information from many other sources other than themselves. (AL, W4)

> To be a good scientist, one must be sociable. Scientists must compare ideas to gain new hypotheses and see different sides of various subjects. Scientists must broaden their horizons on the world and one of the many ways to do that is to get different people's views of it. (BK, W4)

Response notes that people don't have to be geniuses or that the scientists are not that special. They seem to focus on the "genius" rather than "lone". (n = 3)

> Science doesn't need to be conducted by geniuses all the time. It can be conducted by anyone. All you need is a passion for something, like Darwin for studying the evolution as a possiblility in life. Science textbooks are misleading in how they show who first presented ideas. Scientific ideas are everchanging and even the average person can discover something or be scientific just like a genius could. (JH, W4)

> That science can be done by anyone who has a notion to do it and that you don’t have to be a genus to do it. (ZD, W4)

Lone genius model or the textbooks are accurate (n = 2)

> This historical narrative shows that the basis of science has been discovered by a few lone scientists. (AT, W4)

Prominent individuals or ideas are more important or insightful, so given rightful place at lead. (n =4)

> It shows that science uses prominent individuals to account for whatever was proven or being studied at the time. (SN, W4)

> … Little discoveries are made that build up to the one “big” discovery, and that scientist is credited for the whole thing. (CD, W4)

Proven truth (n =1)

> Darwin and Wallace were not even the first people to come up with their theories, but the first ones to prove it, and only Darwin is awarded with the accomplishment of discovering evolution. (CP, W4)

Short story is fictional (n =1)

> This historical fiction shows that science isn’t always done alone, like many people believe…. (RM, W4)

General Confusion (n = 5)

> Scientists are competitive. Wallace and Darwin once agreed, but then one idea struck a change and Darwin rejected Wallace. Regardless of the disagreement, they were both striving for the same goal. Science textbooks emphasize on an individual’s achievements and ideas the affect our community today. (EH, W4)

Student struggles across short story questions

Problematic responses across questions addressing similar NOS ideas

Some NOS ideas were addressed by multiple short story questions. The themes of students' problematic responses were compared across these questions to investigate to what extent similar problematic ideas were conveyed by students when addressing similar NOS ideas.

Social Nature of Science

Both question 2 of "Naturalists and Chronologists" and question 4 of "Alfred Russel Wallace" addressed the social nature of science. When comparing problematic responses from these two questions, no overlap was noticed. For question 2 of "Naturalists and Chronologists" students most commonly misunderstood the word social. In question 4 of "Alfred Russel Wallace" students most commonly did not address the collaborative nature of scientific investigations.

Creative Nature of Science

Question 3 of "A Very Deep Question" and question 3 of "The Work of Gregor Mendel" asked how both the way scientists test ideas and the ideas scientists generate demonstrate that science is a creative endeavor. While problematic responses varied, some overlap was observed. When answering both questions many students either focused on how ideas in science are creative or how scientific methods are creative. In "The Work of Gregor Mendel", 27 students focused only on creativity in the ideas scientists generate and 14 students focused only on how the design of investigations is creative. In "A Very Deep Question", 21 students focused only on creativity in the ideas scientists generate while 36 students focused solely on how the methods scientists use are creative. Which aspect of science more students focused on switched between the questions indicating that neither the creativity associated with the methods or the ideas scientist generate is inherently more difficult to understand. Rather, the selective focus by students indicates the need to break the questions in to parts. For example, break the question into part A and part B and ask about how the methods of science are creative in part A and how the ideas scientists come up with are creative in part B.

Interaction of Science and Religion

Question 4 of “Naturalists and Chronologists” asked students why “science versus religion is not an accurate description of efforts to understand the age of the Earth?” Question 4 of “Charles Darwin” asked students how permitting supernatural explanations in science might interfere with science. Both of these questions relate directly to the interaction between science and religion. In both questions, some students viewed science and religion as opposing one another – reinforcing the idea that science and religion must be mutually exclusive. Other students claimed that science and religion should integrate when answering both questions. These students advocate using religious ideas in science or vice versa. In “Charles Darwin”, six students believed science and religion are mutually exclusive while five students believed science and religion should mix. In “Naturalists and Chronologists”, 16 students viewed science and religion as mutually exclusive, while 13 believed science and religion should integrate.

Interpretive Nature of Data Analysis

Three questions explicitly addressed the role of interpretation in data analysis: question 3 of “Naturalists and Chronologists”, question 2 of “Alfred Russel Wallace, and question 2 of “The Work of Gregor Mendel”. Respectively, these questions asked how the story illustrates that data doesn’t show or tell scientists what to think, made an explicit statement that “data does not tell scientists what to think”, and asked students how the story illustrates that data analysis is not objective.

Responses to both “Naturalists and Chronologists” and “Alfred Russel Wallace” generated problematic responses related to science’s ability to arrive at proven truth. Eleven students and five students, respectively, demonstrated this misconception. In all three questions, some portion of students implied or explicitly claimed that data *does* tell scientists what to think. In “Naturalists and Chronologists” sixty students made this claim while in “Alfred Russel Wallace” and “The Work of Gregor Mendel” 26 and four students made this claim respectively. The lower number of students conveying this misconception in the Mendel story is likely due to the question’s attention to objectivity rather than strictly data interpretation. Considering that so many students continue to hold onto the misconception that data does tell scientists what to think, more forceful confrontation of this misconception may be necessary.

Problematic responses across all short story questions

To understand the extent that problematic NOS ideas pervade students’ responses to the short story questions, problematic views that were observed in multiple questions were placed in the matrix below (Table 27). The matrix shows what problematic ideas were observed in multiple short story questions, which short story questions the problematic ideas were observed and how many responses contained each problematic response for each question. Question one from “A Very Deep Question” (DQ1) was not placed in the matrix because the question is a simple calculation so problematic responses were largely calculation errors. Interpreting what pervasive problematic ideas exist regarding the NOS is made easier using this matrix.

Table 27: Matrix reporting problematic responses across short story questions.

Problematic Responses	NC1	NC2	NC3	NC4	DQ2	DQ3	DQ4	M1	M2	M3	M4	D1	D2	D3	D4	W1	W2	W3	W4
Science vs Religion	**9**	**6**		**16**							**19**		**5**	**12**	**34**				
Integrate Sci & Religion		**5**		**13**			**1**					**7**			**5**				
Proven Truth			**11**	**12**							**7**		**9**	**10**	**25**	**10**	**5**	**3**	**1**
Science not need evidence or overstate subjectivity			**6**			**1**			**15**										
Data tells			**60**										**1**				**26**	**3**	
Theory/Law				**5**										**4**		**1**	**1**	**4**	
Science is objective				**3**					**28**									**6**	
Misunderstand some aspect of question		**20**	**34**		**5**	**6**	**7**		**32**	**11**		**6**	**21**			**5**	**13**	**5**	**8**
Only address one part of question					**52**	**81**		**58**		**43**									**25**
Scientific Method					**2**								**1**	**22**			**2**		
Discovery								**5**					**2**			**1**			
Short story not same as normal or current science										**2**			**9**						**1**
Technology needed to improve science	**5**										**2**					**3**		**4**	
Lone Genius											**7**					**1**			**6**
Experimental & Observational Science														**20**		**1**			
Science is social only to gain support		**13**																	**6**

Not surprisingly the most common problematic response across questions is some form of misunderstanding of the question. Thirteen of the nineteen questions had at least some students misunderstand the question. While many of the numbers are small, and some misinterpretation of questions will always exist, the prevalence of student misunderstandings highlights the importance of clarity when asking about complex topics regarding NOS.

Ten different questions had students bring up notions of science arriving at proven truth. This misconception was not addressed directly by any of the short stories, yet continually showed up in student responses. If students think science arrives at proven truth, they likely do not fully understand the subjective or tentative natures of science. This misconception also might inhibit students' ability to deeply understand the way in which knowledge is generated. Thinking science arrives at truth removes the contextual, creative and social natures in which science knowledge is generated.

Misconceptions related to science and religion show up in the responses to nine different questions in the short stories despite the issue only being explicitly addressed in two of the questions. Some students want to combine science and religion while others seem to view science and religion as mutually exclusive. That is, either science or religion is "right" or science and religion are battling each other for prominence. More desirable views would be that science and religion serve different purposes, are different ways of knowing, and are governed by different rules regarding what counts as knowledge and how that knowledge is generated. Students' problematic views related to science and religion are likely highly emotional and resistant to change as evidenced by the problematic views showing up in multiple questions, despite the professor's attention to methodological naturalism during class discussions.

One last problematic response observed across questions is students only answering one part of some questions. While only answering part of question is not as common across questions, the numbers for each question in which the problem is observed are quite high, ranging from 25 to 81 on single questions. Many of the short story questions are written to reflect the multifaceted nature of many NOS ideas. Unfortunately, many students are attending to only one aspect of these questions and not fully exploring the NOS ideas. While the students' responses do not necessarily constitute misconception, attending to only how science is tentative may cause students to miss the ways in which science ideas are highly resistant to change.

CHAPTER 5. SUMMARY AND DISCUSSION

Summary of Findings

Instructor

The instructor of the course studied, Glenn, would not fit popular views of professors at large universities. While much of Glenn's class sessions were lecture-based, he seems aware that students' deeply held beliefs about science might not be changed simply because they can respond accurately on test questions. To promote deep mental engagement Glenn encouraged students to ask questions, addressed common misconceptions, encouraged students to talk in small groups, and asked students to write reflectively. While covering content was clearly of great concern, Glenn was highly concerned with students' learning of the content.

Although Glenn believed he devoted little time to NOS instruction, classroom observations make clear his attention to NOS. Glenn used language consistent with accurate NOS views and regularly addressed fundamental ideas like the tentative nature of science, the purpose of theory, and the importance of evidence. Glenn's inclusion of historical figures in his lectures demonstrates his desire for students to be familiar with the people behind the ideas about which they are learning.

Glenn's efforts to include NOS ideas beyond the use of the short stories seems to stem from his belief that NOS understanding will improve student learning of content and decrease their resistance to biological evolution. Interestingly, Glenn's beliefs about the benefit of NOS instruction coincide with rationales present in science education literature. For many years, science educators have noted how NOS understanding can improve content understanding (Matthews, 1994; Lin, 1998; Millar and Osborne, 1998; Galili and Hazan, 2000; Heilbron, 2002) and reduce student resistance to biological evolution (Johnson and Peeples, 1987; Sinatra and Southerland, 2003).

Glenn viewed the short stories as a way to more forcefully address NOS in his course. Because of his high interest in student learning of NOS ideas, Glenn believed only assigning the stories would not likely result in deep engagement by students. To encourage students to mentally engage with the stories, Glenn made clear that test questions would come from the stories, assigned points to the short story assignments, and asked students to discuss the short stories in class.

While Glenn was clearly interested in students coming to understand NOS ideas, his interest was generated by his more fundamental concern with students learning biology content. Heilbron (2002) predicts this concern of science content instructors and notes the need to ensure that historical materials not focus solely on history. Glenn's views provide empirical support for Heilbron's claims. Importantly, high quality history of science curricular materials ought include high levels of science content (Clough, 2006; Kolsto, 2008).

Related to Glenn's content focus is his unwillingness to spend time on a "nature of science unit". Glenn likes the short stories because of their ability to be included throughout the semester as related content is addressed. Glenn's view provides additional rationale for suggestions that history of science curricular materials be modular. That is, each story ought stand on its own so that each story can be interchanged and used where appropriate (Duschl, 1988, 1990; Hodson, 1988; Bybee, 2002; Heilbron, 2002; Stinner, et al., 2003).

While Glenn saw benefit in using the short stories, he recognized his inability to create the stories on his own. Glenn's admission coincided with Chamany et al.'s (2008) note that few science educators have the formal education in history of science needed to create historical materials. Heilbron's (2002) suggestion to include scientists, science educators, philosophers and historians of science together highlights the multidisciplinary nature of history of science materials. Glenn seems to recognize the power of bringing these diverse areas of expertise together as well as his own inability to provide this expertise on his own.

Students

While Glenn recognizes the value of the short stories, students may have different perceptions. Importantly, students' view of the stories will affect how and to what extent they engage with the stories. That is, students' attitudes toward and perceived value of the stories will affect their engagement and therefore, their learning (Pintrich et al., 1993; Southerland et al., 2006). Fortunately, most students had positive views toward the stories and recognized that the stories helped them learn about how science works.

The students' interest in the short stories is evidenced by their responses to the in-class questionnaire. While the average reported level of interest in the stories was very close to neutral, most students wanted to have some short stories as part of the course while only 7.7 percent of students wished to not have any stories in class. Furthermore, on average, students reported an increased interest in science careers and recognized the value of the short stories for learning about how science works.

Student claims that the stories increased their interest in science careers provides empirical support of rationales for the history of science (HOS) found in the science education literature. Since the early 1900s HOS has been purported to increase student interest in science (Leite, 2002). Specifically, the HOS may illuminate the philosophical, contextual, and human sides of science. These humanistic aspects of science are claimed to be motivating for students not inherently interested in science (Metz, 2003; Tobias, 1990). However, few studies have explored the effect of HOS on student interest. This study provides evidence that even students already interested in science are likely to claim their interest increased.

Student claims that the stories helped them learn about how science works supports both theoretical and empirical literature regarding HOS to teach NOS. Many science educators have noted the utility of HOS to teach NOS (Bauer, 1992; Clough, 2006; Irwin, 2000; Kolsto, 2008; Matthews, 1994; Monk and Osborne, 1997). Other science educators have provided empirical support that HOS inclusion aids in NOS learning (Klopfer and Cooley, 1963; Solomon et al, 1992; Roach, 1993; Irwin, 2000; Lonsbury and Ellis, 2002; Dass, 2005;). This study lends credence to previous findings, but adds the dimension that students are aware of how HOS helps them understand how science works. When students recognize that the short stories help them gain new knowledge their perception of value in the short stories will likely increase. As noted previously, if perceived value increases, student engagement with the stories will likely increase.

Students' perception of value and interest in the stories will affect their engagement with stories; however, conceptual change is also affected by prior ideas and the intelligibility/plausibility of new ideas (Posner et al, 1982). That is, students' ability to make sense of the short stories will be determined by their prior ideas and their ability to understand the stories. Unfortunately, the most common problem identified in students' responses to short story questions was some form of misunderstanding the question or only attending to some parts of multipart questions. This finding highlights the need to use language students will understand when addressing NOS ideas. However, educators must use caution when trying to make NOS ideas intelligible. The contextual and multifaceted nature of NOS ideas means simply identifying a set of tenets may lead to incomplete or inaccurate understanding (Clough, 2007).

Making NOS ideas and reflective questions intelligible is important. However, the intelligibility of ideas and the manner in which students interpret the stories depends on students' prior thinking. Tao (2003) found that students used historical materials to reinforce their naïve ideas about how science works. In contrast to Tao's findings, this study found most students were able to accurately make sense of the NOS ideas being illustrated by the stories. This discrepancy is likely due to the bullet points and questions embedded within each story to draw students' attention to NOS ideas.

While most students were able to make the desired sense of the stories, some misconceptions persisted. Across many questions, many students, demonstrated a deterministic view of science despite the issue not being explicitly addressed in the stories. Other researchers have noted the prevalence of the proven truth misconception (Abd-El-Khalick and Lederman, 2000; Irwin, 1997), but only noted how common and resistant to change the misconception is. In this study and others making use of similar short stories (Vandelinden, 2007), the proven truth misconception seems to moderate or inhibit students' sense making of other NOS ideas including: methodological naturalism, interpretation of data, theory-laden knowledge, and the tentative nature of science.

Another common problematic response possibly related to student views of science as Truth concerned the relationship between science and religion. Only two questions explicitly addressed this issue, but problematic views were observed in nine different questions. The stories and course instructor promoted methodological naturalism in which scientists do not make use of supernatural events or beings to explain natural phenomena. Importantly, methodological naturalism makes no claim as to the ontological status of the supernatural and does not require scientists to hold materialistic beliefs. The stories tried to demonstrate both the utility of ignoring supernatural ideas when doing science and that scientists can do science and maintain faith in the supernatural.

Students exhibited two types of problematic responses related to science and religion. Some students believed science and religion ought be integrated. That is, science ought make use of supernatural ideas, or supernatural ideas ought make use of scientific methods. If science adopted this view, the utility of ideas would diminish. If religion adopted this view, the notions of faith and mystery disappear. These students' views likely stem from desires to keep faith-based knowledge on par with scientific knowledge. This view implies science is an inherently better way of knowing rather than seeing science as a particularly useful way to investigate *certain kinds of questions*.

Other students saw science and religion in a state of constant battle. These students also viewed science as a better way of knowing, but were not concerned with maintaining other knowledge systems. This view often failed to recognize the limits of science and likely stem from popular discourse about the wonders of scientific progress. The implicit messages sent by popular culture concerning science is that science is based on observable facts and as such is more valuable than other knowledge systems.

Student views of science as proven truth and their struggle to internalize methodological naturalism might be explained by prior research regarding NOS conceptual ecologies. While Abd-El-Khalick and Akerson (2004) claim religious beliefs to be a major factor influencing student learning of NOS, the view of Southerland, et al. (2006) may be of greater use to explain student struggles with proven truth as well as science and religion. Rather than focus on religious beliefs, Southerland et al. (2006) focused on how individuals viewed their own beliefs or their view of knowledge more generally. Specifically, Southerland et al. noted how students' level of dogmatism affects their NOS views. That is, to what extent people appealed to authority or how comfortable they were with ambiguity better accounted for struggles to learn NOS than simply whether learners held religious beliefs. This dogmatism is related to what Perry (1970) referred to as dualism in which students hold either/or views of knowledge. Rather than considering the contextualized nature of knowledge in which some ways of thinking might be better suited for different situations, these dogmatic or dualistic students believed there are "right" and "wrong" answers with little middle ground.

Using the ideas of Southerland et al. (2006), the struggle to deeply internalize methodological naturalism might be explained. If students hold dogmatic beliefs toward religion, they are likely to try and combine the science ideas they learn into their religious beliefs rather than see science and religion as distinct ways of knowing. Students who hold dogmatic views of religion likely cannot maintain two distinct knowledge systems for different purposes. Instead, these students use their religious knowledge system to make sense of the science ideas they are learning. This process might result in hybrid accounts of evolution and creationism or, more generally, that science and religion ought support one another. While these students are not dismissing the science ideas *a priori*, their high level of dogmatism related to their religious beliefs likely hinders their ability to maintain two separate kinds of knowledge suitable for different purposes.

Similarly, those students who hold dogmatic beliefs about science will claim religion has no legs to stand on and wrongly believe science is capable of answering all questions. These students see science as a march toward proven truth and religion as an obstacle to overcome. These students' dogmatic views of science seem to prevent their willingness to admit limitations of science. While these students understand some key differences between science and religion, they take the dominance of science on faith rather than deeply understanding why science is so good at answering particular kinds of questions and why science is ill equipped to answer other kinds of questions.

Dogmatic views in which students are not comfortable with ambiguity likely hinder students from deeply understanding many NOS ideas. The deeply contextual nature of science and the tension between extreme views (Clough, 2007) requires students to be comfortable with ambiguity. For example, students who are very dogmatic are less likely to deeply engage with multifaceted questions such as, "In what ways is scientific knowledge tentative and in what ways is it durable?" Instead, students with high levels of dogmatism would prefer that science be *either* tentative or durable.

Dogmatic views and other learning dispositions are constructed throughout students' lives. Modifying students dogmatic views toward more comfort with ambiguity can be done (Kruse et al., 2010), but takes much sustained effort on the part of teachers to undo years of dogmatic messages. Yet, if students are to come to deep understanding of the nuances of NOS ideas, addressing students learning dispositions may be necessary.

Recommendations and Implications

Glenn placed significant emphasis on the short stories in his course. This emphasis seems to be rooted in his view that understanding NOS will improve students' acceptance and understanding of fundamental science concepts. Teachers who do not hold similar views are not likely to place so much emphasis on the stories or may not be convinced to include the short stories at all. For this reason, efforts must be made to make science content teachers aware of students' naïve views regarding NOS and how historical short stories can be used to address these naïve views as well as increase student interest in science. These efforts might take the form of professional development workshops, published work in related professional journals, conference presentations or even online resources. Importantly, such efforts should not only address why use of historical short stories is valuable, but how the stories ought be implemented to achieve greatest gains in student understanding of NOS.

Helping instructors understand the benefits of historical short stories may increase implementation, but the stories themselves can still be improved upon. While some recommendations for specific questions were made in chapter four, more general recommendations will be made here. First, because of the complex nature of NOS ideas, many of the questions asked students to address more than one facet of a NOS idea. For example, two questions asked students to address how both the methods and the interpretation of data demonstrate that science is creative. In most all such multifaceted questions, many students attended to only one aspect or another and did not address the full question – meaning they likely did not reflect on the multiple dimensions of the NOS idea. To remedy this problem, questions that address multiple aspects ought be broken down. Instead of asking students to address how both the methods and the interpretation of data demonstrate science is creative, the question might read, "Some people believe science is not creative. A) Use examples from this story to illustrate how the methods scientists use require creativity. B) Use examples from this story to illustrate how data interpretation requires creativity." By separating out these aspects, students are more likely to address both parts of the question.

While several students claimed the short story questions were confusing, the numbers of students who misunderstood each question was quite minimal with most questions having fewer than ten students misunderstand. When numbers were higher than ten, the confusion is usually linked to a single word. For example, many students misunderstood the word "objective". Instead of asking students to discuss why scientists cannot be objective, students might better respond to asking why scientists are biased. As curricular materials continue to be developed, developers must use care to ensure questions and NOS ideas are intelligible to students.

Beyond ensuring that short stories and the embedded questions are as clear as possible, findings from this study can be used to suggest additional resource materials for classroom implementation. Some students wanted to discuss the short stories during lectures. While Glenn provided students the opportunity to discuss in small groups, he did not address the stories in his lectures. Perhaps providing instructors access to simple slides that highlight the NOS ideas promoted by each story might encourage instructors to discuss the stories in lectures. However, providing summary slides might encourage instructors to simply use the slides instead of assigning the stories. Therefore, the slides ought be reflective in nature – asking students to consider how the stories did or did not fit with their views of science or what new ideas the students learned about how scientific knowledge is developed.

Summary slides and in-class reflective questions are important considerations, but do not address how students' prior thinking will affect how they make sense of the stories. As noted earlier, some fundamental misconceptions about NOS seem to hinder students' interpretation of the stories and embedded questions. Perhaps common misconceptions ought be directly addressed before reading the historical short stories. As Abd-El-Khalick and Lederman (2000) state:

> one possible way to ameliorate the aforementioned "obstacles" is to provide learners with a conceptual framework consistent with current views of NOS prior to their enrollment in HOS courses. And since learners tend to interpret and make sense of new experiences from within their extant schemas, such a framework might help students, including student teachers, to interpret the historical narrative from within an alternative mindset, one that is more consistent with current views of NOS. This framework coupled with coursework in HOS could serve to reinforce, elaborate, and deepen student teachers' understandings of various aspects of NOS and to enrich these understandings with examples, metaphors, and stories. Indeed, data analyses revealed a pattern consistent with the suggestion that students who enter HOS courses with a framework consistent with current NOS views are more likely to leave such courses with more adequate and enriched views. (p. 1088)

While Abd-El-Khalick and Lederman note that having previous coursework in NOS might provide the framework necessary to accurately interpret HOS materials, requiring all students to take a nature or philosophy of science course is impractical. Furthermore, making such coursework a prerequisite to content courses may be ideal, but unlikely given institutional constraints. The curricular materials in this study are not concerned with coursework, but are modular so instructors can make use of the stories within content courses. However, helping students have a more accurate framework before reading the short stories is worth consideration since some misconceptions seem to inhibit student understanding of NOS in the short stories. Furthermore, students might be unable to fully attend to the NOS ideas within the stories as they are simultaneously trying to make sense of science content.

When having students read McComas' (1996) "Ten Myths of Science", Abd-El-Khalick and Akerson (2004) noted that students expressed shock about the myths and were surprised they held so many "erroneous" views. By reading this piece, students were clearly becoming dissatisfied with their prior thinking as Posner et al. (1982) notes as necessary for conceptual change. Perhaps having students read a "primer" that addresses some fundamental NOS ideas before engaging with the short stories will better prepare students to make sense of the historical short stories. Importantly, this primer ought be reflective in nature and will necessarily be less contextualized than the stories themselves. The less contextualized nature of the primer will help students focus their cognitive effort on the NOS ideas rather than be distracted by the history or high-level science content (Clough, 2006).

Metz et al. (2007) make several recommendations for creating historical curricular materials that can further inform recommendations for the stories studied here. Metz et al. (2007, p. 320-321) note that implementation of HOS ought to:

1. Activate prior knowledge through activities that capture student interest and connect students' background with the story details. This can be done within or independently of the story.
2. Use an interrupted story approach to enable students to make inferences and predictions
3. Solicit individual and/or group reactions while asking open-ended questions.
4. Employ compare and contrast strategies that relate student ideas to the historical ones.
5. Provide for related demonstrations and experiments, projects and research, and cross-curricular integration.
6. Use writing activities such as a log or journal, for reflections and question generation.
7. Use guided reading strategies such as issue-based analysis or paired reading.

Some of these suggestions are targeted toward teaching strategies and some have already been considered in designing the short stories in this study. However, the notion of activating students' prior knowledge might lend additional support for including a "primer" reading or even adding some questions to the beginning of each story to activate student thinking about certain topics. That is, a primer reading or introductory primer sections within each story ought explicitly note common misconceptions regarding NOS ideas so that students might become dissatisfied with naïve ideas.

Future Work

The recommendations provided above provide ample directions for future research regarding the use of historical short stories in science education. First, the effect of a "primer" reading might be investigated to see to what extent decontextualized confrontation of common misconceptions might improve students' ability to make sense of the short stories. As a related study, a single primer reading could be compared with mini primers placed at the beginning of each story. Since each story addresses particular NOS ideas, an introductory paragraph or two could be added to each story to introduce the NOS ideas and common misconceptions. Furthermore, having each story contain its own primer better fits with suggestions to make HOS materials modular.

Common misconceptions observed in student writing such as "science arrives at proven truth" and that "science is inherently more valuable than other ways of knowing" might be effectively addressed in a primer reading. However, as discussed earlier, these views might hint at deeper problematic views students have about knowledge and the nature of learning. Most pertinent to this study, students' level of dogmatism might impact their willingness and ability to engage with the contextualized nuances inherent in deeply understanding NOS. To shed light on the interaction between learning disposition and NOS learning, more research is needed to explore 1) correlations between various learning dispositions and robust NOS understanding, 2) how NOS instruction might alter students learning dispositions, and 3) how explicit instruction targeting learning disposition might impact students' understanding of NOS. Students' deeply held beliefs about learning and knowledge likely impact their beliefs about how scientists learn and generate knowledge, but to what extent and in what ways ought be explored.

Another area of research that ought be explored is student attitudes toward science. While this study lends some empirical support to the idea that HOS improves student interest in science, a pretest/posttest model might provide additional insight to how students' attitudes are being affected. Additionally, this study was comprised mostly of students majoring in science leading one to wonder how the interest of non-science majors be affected by the short stories. Multiple avenues for possible research in this area exist. Researchers might track students from HOS infused content courses to investigate in what ways HOS inclusion might impact career choices. Additionally, researchers might investigate students' attitude toward science learning, level of importance placed on science learning, or level of apprehension associated with science learning.

Contrary to Tao's (2003) findings, most students accurately interpreted the stories in this study. Therefore, creating similarly designed stories for secondary students ought be explored. Many students likely decide very early in their academic careers not to pursue science careers. However, many of these students believe science to be a lonely, dull process.

Introducing HOS to younger students might encourage them to see value in continuing to study science.

Another area to be explored relates to gaining deeper understanding of how students interpret the stories. Kolsto (2008) notes that students might not understand how lessons about NOS from HOS apply to contemporary science. He suggests that students compare historical episodes to contemporary episodes to make similarities and differences explicit. Only a few students in this study explicitly claimed that the science in the stories did not reflect how science is done today. However, this depth of student thinking was not easily investigated through short story question responses. Investigating how students believe the short story science compares to contemporary science might also illuminate to what extent the students believe/internalize the NOS ideas being promoted by the stories.

Perhaps most important in any educational setting is the role of the teacher. This study found that Glenn placed great importance on student learning of NOS. Research is required to investigate how to help teachers at all levels understand the value of NOS learning. Beyond investigating how to help teachers understand the importance of NOS, studies ought investigate to what extent this understanding translates to teachers explicitly addressing NOS in their classrooms.

Conclusion

Science reform documents continually call for inclusion of NOS in science education (NRC, 1996; AAAS, 1993, 1989; NSTA, 2000). Yet, post-secondary science instruction oftentimes continues to focus on content alone. The curricular materials developed for this study ought satisfy the high content demands of post-secondary instructors while making

NOS instruction explicit in a reflective (Abd-El-Khalick & Lederman, 2000a) and highly contextualized (Clough, 2006) manner using short stories and questions. By illuminating student and instructor attitudes toward such curricular materials and student struggles to interpret the stories, this study provides important insight for development and improvement of future classroom materials designed to foster NOS inclusion in the post-secondary classroom.

By designing HOS curricular materials that draw students' attention to NOS ideas, most students interpret the stories as intended and are able to meaningfully reflect on NOS ideas modeled in the stories. The students claim to be learning about how science works from the stories and gaining interest in science by hearing about the people behind the science. While some students still demonstrate problematic interpretations of the stories, many of these relate to incomplete rather than inaccurate reflection.

The content-laden nature of the stories helps instructors see value in the stories and the modular design reduces the intimidation of including NOS into science instruction. Importantly, instructors' views of content learning and how NOS affects content learning play a large role in how the short stories are implemented. Therefore, educating instructors on the benefits and implementation of the short stories will be of utmost importance for expanding the use of these historical short story curricular materials.

The high implementation by the instructor in this study and corresponding student success and engagement with the stories demonstrates the importance of teacher implementation. As with all reform efforts, curricular materials alone are not enough. The teacher plays an important role in how curricular materials are implemented and how students are able to make sense of curricular materials.

REFERENCES

Abd-El-Khalick, F. (1999). Teaching Science with History, *The Science Teacher,* 66(9), p 18-22.

Abd-El-Khalick, F. (2003). Socioscientific issues in pre-college science classroom. In: Zeidler D.L. (ed). *The role of moral reasoning on socioscientific issues in science education*. Kluwer Academic Publishers, Dordrecht.

Abd-El-Khalick, F., & Akerson, V. L. (2004). Learning as conceptual change: Factors mediating the development of preservice elementary teachers' views of nature of science. Science Education, 88(5), 785 – 810.

Abd-El-Khalick, F. & Lederman, N.G (2000a). Improving Science Teachers' Conceptions of Nature of Science: A Critical Review of the Literature, *International Journal of Science Education,* 22(7), 665-701.

Abd-El-Khalick, F. & Lederman, N.G (2000b). The Influence of History of Science Courses on Students' Views of Nature of Science. *Journal of Research in Science Teaching*, 37(10), 1057-1095

Abd-El-Khalick, F., Bell, R.L., & Lederman, N.G. (1998). The Nature of Science and Instruction Practice: Making the Unnatural Natural. *Science Education* 82, 417-436.

Abd-El-Khalick, F., Waters, M., Le, A. (2008). Representations of Nature of Science in High School Chemistry Textbooks over the Past Four Decades. *Journal of Research in Science Teaching,* 45(7), 835-855.

Aikenhead, G. & Ryan, AG. (1991). Students' views on the epistemology of science. Ottawa:

Social Science and Humanities Research Council of Canada.

Aikenhead, G.S. & Ryan, A.G. (1992). The Development of a New Instrument: Views of Science-Technology-Society (VOSTS). *Science Education* 76, 477-491.

Akerson, V., & Abd-El-Khalick, F. (2003). Teaching Elements of Nature of Science: A yearlong Case Study of a Fourth-Grade Teacher. *Journal of Research in Science Teaching*. 40, 1025-1049.

Alioto, A.M. (1993). *A history of Western science*, 2nd ed. Prentice-Hall.

Allchin, D. (2000). How not to teach history of science. *Journal of College Science Teaching.* 30, 33-37. Online at: www.pantaneto.co.uk/issue7/allchin.htm (March 8, 2008).

Allchin, D. et al. (1999), 'History of Science-With Labs', *Science and Education* **8**, 619–632.

American Association for the Advancement of Science (AAAS) (1989), *Project 2061: Science for All Americans*, AAAS, Washington, DC.

American Association for the Advancement of Science (1993). Benchmarks for Science Literacy: Project 2061. New York: Oxford University Press. http://www.project2061.org/publications/bsl/online/index.php

Ausubel, D., Novak, J., and Hanesian, H. (1978). *Educational Psycology: A Cognitive View*, 2nd Ed., New York: Holt, Rinehart, and Winston.

Bauer, H.H. (1992). Scientific literacy and the myth of scientific method. Chicago: University of Illinois Press.

Benson, G.D. (1984). *Teachers' and Students Understandings of Biology,* Doctoral dissertation, University of Alberta, ERIC Document Reproduction Service No. ED280683.

Bianchini, J.A. & Colburn, A. (2000). Teaching the Nature of Science Through Inquiry to Prospective elementary teachers: A Tale of Two Researchers. *Journal of Research in*

Science Teaching. 37, 177-209.

Brickhouse, N. (1990). Teachers' beliefs about the nature of science and their relation to classroom practice. Journal of Teacher Education, 41, 53–62.

Brush, S. (1974). Should the history of science be rated X? Science, 183, 1164–1172.

Bybee, R.W. (1997). *Achieving Scientific Literacy: From purposes to practices*. Heinemann, Portsmouth, N.H.

Bybee, R.W., Powell, J.C., Ellis, J.D., Giese, J.R., Parisi, L. & Singleton, L. (1991), Integrating the History and Nature of Science and Technology in Science and Social Studies Curriculum, *Science Education* 75(1), 143–155.

Bybee, R. (2002). We Should Teach about Biological Evolution. *Bioscience* 52, 616-619.

Campanario, J.M. (2002). The parallelism between scientists' and students' resistance to new scientific ideas. *International Journal of Science Education*, 24(10), 1095-1110.

Carey, R.L., & Strauss, N.G. (1970). An analysis of experienced science teachers' understanding of the nature of science. *School Science and Mathematics*, 70(5), 366-376.

Carey, S., Evans, R., Honda, M., Jay, E., & Unger, C. (1989). An experiment is when you try it and see if it works: A study of grade 7 students' understanding of the construction of scientific knowledge. International Journal of Science Education, 11, 514–529.

Chamany, K., Allen, D., & Tanner, K. (2008). Making Biology Learning Relevant to Students: Integrating People, History, and Context into College Biology Teaching.

Clough, M.P. (2006). Learners' Responses to the Demands of Conceptual Change: Considerations for Effective Nature of Science Instruction. *Science & Education*, 15(5), 463-494.

Clough, M.P. (1997). Strategies and Activities for Initiating and Maintaining Pressure on Students' Naïve Views Concerning the Nature of Science, *Interchange*, 28(2 & 3), 191-

204.

Clough, M.P. (1998). Integrating the Nature of Science with Student Teaching: Rationale and Strategies. In McComas (ed.) *The Nature of Science in Science Education*. Kluwer Academic Publishers, Dordrecht, The Netherlands, p. 119-208.

Clough, M.P. & Olson, J.K. (2001). *Structure of a course promoting contextualized and decontextualized nature of science instruction*. Paper presented at the 6th International History, Philosopy and Science Teaching Conference with the History of Science Society, Denver, CO.

Clough, M.P. & Olson, J.K. (2004). The Nature of Science: Always Part of the Science Story, *The Science Teacher*, 71(9), 28-31.

Clough, M. P., Olson, J. K., Stanley, M., Colbert, J. & Cervato, C. (2006). Project title: *Humanizing science to improve post-secondary science education: Pursuing the second tier*. Proposal (Number 0618446) submitted to the National Science Foundation Course Curriculum and Laboratory Improvement (CCLI) Phase II (Expansion) Program. Submitted for and funded at $293,718.

Cobern, W.W. (1991). Worldview Theory and Science Education Research, Monograph No. 3 from The National Association for Research in Science Teaching Annual Conference, Manhattan, Kansas.

Cobern, W. W. (1996). Worldview theory and conceptual change in science education. Science Education, 80(5), 579 – 610.

Conant, J.B. (1947). On understanding science: An historical approach. New Haven: Yale University Press.

Conant, J.B. (1957), *Harvard Case Histories in Experimental Science*, Harvard University Press, Cambridge.

Conant, J.B. (1961). *Science and common sense*. Yale University Press: New Haven, CT.

Davson-Galle, P. (2008). Why Compulsory Science Education Should *Not* Include Philosophy of Science. *Science & Education*. 17, 677-716.

Dawkins, K.R. & Vitale, M.R. (1999). *Using historical cases to change teachers' understandings and practices related to the nature of science.* Paper presented at the National Association for Research in Science Teaching Annual Conference, March 1999. Boston, MA, USA

DeBoer, G. (1991). *A history of ideas in science education: Implications for practice*. New York: Teachers College Press.

Dibbs, D.R. (1982). *An Investigation into the Nature and Consequences of Teachers' Implicit Philosophies og Science*, University of Aston, Bermingham, UK, Unpublished doctoral dissertation.

Dodick, J. & Orion, N. (2003). Geology as an Historical Science: Its Perception within Science and the Education System. *Science & Education*. 12, 197-211.

Driver, R. Leach, J., Millar, R., Scott, P. (1996). Young peoples' images of science. Open University Press, Buckingham.

Duschl, R. (1985). Science education and philosophy of science: Twenty five years of mutually exclusive development. School Science and Mathematics, 87, 541–555.

Duschl, R.A. (1988). Abandoning the scientistic legacy of science education. *Science Education*, 72(1), 51-62.

Duschl, R.A. (1990). *Restructuring science education: The importance of theories and their development*. Teachers College Press, Columbia University, New York.

Eichman, P. (1996). Using History to Teach Biology, *The American Biology Teacher* 58(4), 200–204.

Eick, C.J. (2000). Inquiry, Nature of Science, and Evolution: The Need for a More Complex Pedagogical Content Knowledge in Science Teaching. *Electronic Journal of Science Education.* 4(3), 1-16.

Emerson, R.M., Fretz, R.I., and Shaw, L.L. (1995). *Writing Ethnographic Fieldnotes*, The University of Chicago Press, Chicago and London.

Galili, I. & Hazan, A. (2000). 'The Influence of an Historically Oriented Course on Students' Con- tent Knowledge in Optics Evaluated by Means of Facets-Schemes Analysis', *Physics Education Research: A Supplement to the American Journal of Physics* **68**(7), S3–S15.

Gallagher, J.J. (1991). Prospective and practicing secondary school science teachers' knowledge and beliefs about the philosophy of science. Science Education, 75, 121–134.

Garner, R. (1990). When Children and Adults Do Not Use Learning Strategies: Toward a Theory of Settings. *Review of Educational Research* 60(4), 517-529.

Glaser, B.G. & Strauss, A.L. (1967). *The discovery of grounded theory: Strategies for qualitative research*. Hawhorne, NY: Aldine.

Gould, S.J. (1999). *Rocks of Ages: Science and Religion in the Fullness of Life.* Ballantine Books, New York.

Hagen, J., Allchin, D. & Singer, F.: 1996, *Doing Biology*, HarperCollins, New York, NY

Hardy, G. H. 1908. Mendelian proportions in a mixed population, *Science*, N. S. Vol. XVIII:49-50. (letter to the editor)

Haywood, H. (1927). Fundamental laws of chemistry. School Science Review, 9, 92.

Heilbron, J.L.: 2002, History in Science Education, with Cautionary Tales About the Agreement of Measurement and Theory, *Science & Education* 11(4), 321–331.

Hodson, D. (1986). Philosophy of science and science education. Journal of Philosophy of Education, 20, 215–225.

Hodson, D. (1988). Toward a philosophically more valid science curriculum. *Science Education*, 72(1), 19-40.

Hodson, D. (2009) *Teaching and Learning about Science: Language, Theories, Methods, History, Traditions and Values.* Sense Publishers: Rotterdam / Boston / Taipei.

Horton, R. (1971). “African Traditional Thought and Western Science.” In M. F. D. Young (ed.), *Knowledge and Control*, Collier-Macmillan, London, pp. 208-266.

Hurd, P. D. (1958). Science Literacy: Its Meaning for American Schools,” *Educational Leadership* 16, 13-16

Huybrechts, J. M. (2000). Integrating the history of science into a middle school science curriculum. *Dissertation Abstracts International, 61*(01A), 127.

Irwin, A. R. (1996). A survey of the historical aspects of science in school textbooks. *School Science Review*, 78, 282.

Irwin, A. R. (1997). Theories of burning: A case study using a historical perspective. School Science Review, 78, 31–38.

Irwin, A.R. (2000). Historical Case Studies: teaching the nature of science in context. *Science Education* 84(1), 5-26.

Johnson, R.L. & Peeples, E.E. (1987). The Role of Scientific Understanding in College: Student Acceptance of Evolution. *The American Biology Teacher*. 49, 93-98.

Kimball, M.E. (1967). Understanding the nature of science: A comparison of scientists and science teachers. *Journal of Research in Science Teaching*, 5(1), 110-120.

Klopfer, L.E. (1969). The teaching of science and the history of science. *Journal of Research in Science Teaching* 6, 87-97.

Klopfer, L.E. & Cooley, W.W.: 1963, The History of Science Cases for High Schools in the Development of Student Understanding of Science and Scientists, *Journal of Research in Science Teaching* 1(1), 33–47.

Kolsto, S.D. (2001). Scientific Literacy for Citizenship: Tools for dealing with the science dimension of controversial socio-scientific issues. *Science Education* 85(3), 291-310.

Kolsto, S.D. (2008). Science education for democratic citizenship through the use of the history of science. *Science & Education* 17, 977-997.

Kruse, J.W. (2008). Integrating the Nature of Science Throughout the Entire School Year. Iowa Science Teachers Journal, 35(2), 15-20.

Kruse, J.W., Wilcox, J.L., Herman, B. (2010). Modifying Student Views of Cognition: Explicit instruction concerning the nature of thinking and assessing student views. Paper Presented at the Annual Meeting of the Association for Science Teacher Education, Sacramento, CA, January.

Kuhn, T.S. (1962). *The Structure of Scientific Revolutions* 3rd ed. University of Chicago

Press, Chicago, IL.

Kuhn, D., Amsel, E., & O'Loughlin, M. (1988). The development of scientific thinking skills. Orlando, FL: Academic Press.

Kyle, W. C. (1970). Assessing students' understanding of science. Journal of Research in Science Teaching, 34, 851–852.

Lattuca, L., Voigt, L., Fath, Q. (2004). Does interdisciplinarity promote learning? Theoretical support and researchable questions. *Review of Higher Education*. 28, 23-48.

Leach, J., Hind, A. & Ryder, J. (2003), Designing and Evaluating Short Teaching Interventions About the Epistemology of Science in High School Classrooms, *Science Education* 87(6), 831–848.

LeCompte, M., & Priessle, J. (1993). Ethnography and qualitative design in educational research. San Diego, CA: Academic Press.

Lederman, N.G. (1992). Students' and Teachers' Conceptions of the Nature of Science: A Review of the Research. *Journal of Research in Science Teaching,* 29(4), 331-359.

Lederman, N.G. (1986b). Relating Teaching Behavior and Classroom Climate to Changes in Students' Conceptions of the Nature of Science, *Science Education*, 70(1), 3-19.

Lederman, N.G. & Abd-El-Khalick, F. (1998). Avoiding De-natured Science: Activities that Promote Understandings of The Nature of Science, in McComas (ed. *The Nature of Science in Science Education,* Kluwer Academic Publishers, Dordrecht, 221-234.

Lederman, N.G., Abd-El-Khalick, F., Bell, R.L. & Schwartz, R.S. (2002). Views of Nature of Science Questionnaire: Toward Valid and Meaningful Assessment of Learners' Conceptions of Nature of Science. *Journal of Research in Science Teaching*. 39(6). 497-521.

Lederman, N.G. & Zeidler, D.L. (1987). Science teachers' conceptions of the nature of science: Do they really influence teacher behavior? Science Education, 71, 721–734.

Lin, H. (1998). The effectiveness of teaching chemistry through the history of science. Journal of Chemical Education, 75, 1326–1330.

Lin, H.S. & Chen, C.C. (2002), Promoting Preservice Chemistry Teachers' Understanding About the Nature of Science Through History, *Journal of Research in Science Teaching* 39(9), 773–792.

Lincoln, Y. & Guba, E. (1985). *Naturalistic Inquiry*, Sage Publications, Beverly Hills.

Longbottom, J.E. & Butler, P.H. (1999). Why teach science? Setting rational goals for science education. Science Education, 83, 473–492.

Lonsbury, J.G. and Ellis, J.D. (2002). Science History as a Means to Teach Nature of Science Concepts: Using the Development of Understanding Related to Mechanisms of Inheritance. *Electronic Journal of Science Education*, 7(2).

Mackay, L.D. (1971). Development of understanding about the nature of science. Journal of Research in Science Teaching, 8, 57–66.

Mamlok-Naamon, R., Ben-Zvi, R., Hofstein, A., Menis, J., Erduran, S. (2005). Learning Science through a Historical Approach: Does it affect the attitudes of non-science oriented students toward science? *International Journal of Science and Mathematics Education*, 3, 485-507.

Marques, L., & Thompson, D. (1997b). Portuguese students' understanding at ages 10-11 and 14-15 of the origin and nature of the Earth and the development of life. *Research in Science and Technological Education, 15*(1), 29-51.

Martin, B. E. and Brouwer, W. (1991) The sharing of personal science and the narrative element in science education. Science Education, 75, 707–722.

Martin-Hansen, L.M. (2008). First-Year College Students' Conflict with Religion and Science. *Science & Education*. 17, 317-357.

Matthews, M.R. (1989). A Role for History and Philosophy in Science Teaching, *Interchange,* 20(2), 3-15

Matthews, M.R. (1994). *Science Teaching: The Role of History and Philosophy of Science,* Routledge, New York.

Matthews, M. R. (1998) In defense of modest goals when teaching about the nature of science. *Journal of Research in Science Teaching,* 35, 167–174.

Maxwell, J.A. (2005). *Qualitative Research Design: An Interactive Approach* (2nd Ed.). Sage Publications, Thousand Oaks.

McComas, W. (1996). Ten myths of science: Reexamining what we think we know about the nature of science. *School Science and Mathematics,* 91(1), 10 – 16.

McComas, W. (1998). The Principal Elements of the Nature of Science: Dispelling the Myths, in McComas (ed. *The Nature of Science in Science Education*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 53-70.)

McComas, W. F. (1998) The Nature of Science in Science Education: Rationale and Strategies (Dordrecht: Kluwer).

McComas, W.F. (2003). A Textbook Case of the Nature of Science: Laws and Theories in the Science of Biology. *International Journal of Science and Mathematics Education*, 1, 141-155.

McComas, W.F. (2008). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education*, 17, 249-263.

McComas, W., Clough, M., & Almazroa, H. (1998). The role and character of the nature of science in W. F. McComas (Ed.) *The Nature of Science in Science Education: Rationales and Strategies* (pp. 3–39) Boston: Kluwer Academic Publishers

McComas, W. F., & Olson, J. K. (1998). The nature of science in international science education standards documents. In M. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 41-52). Klewer Academic Publishers: The Netherlands.

Mendel, Gregor. (1866). Versuche über Plflanzenhybriden. *Verhand- lungen des naturforschenden Vereines in Brünn, Bd. IV für das Jahr 1865*, Abhandlungen, 3–47.

Metz, D.: 2003, Understanding the Nature of Science through the Historical Development of Conceptual Models, A paper presented at the Annual Meeting of the National Association for Research in Science Education Conference, Philadelphia, PA, USA. March 23–26, 2003.

Metz, D., Klassen, S., McMillan, B., Clough, M., Olson, J. (2007). Building a Foundation for the use of Historical Narratives. *Science & Education*, 16, 313-334.

Meyling, H. (1997). How to Change Students' Conceptions of the Epistemology of Science, *Science & Education* 6(4): 397–416.

Millar, R. & Osborne, J. (1998). Beyond 2000: Science education for the future. King's College London, London.

Millar, R. & Wynne, B. (1988). Public understanding of science: from contents to processes. International Journal of Science Education 10(4), 388-398.

Milne, C. (1998) Philosophically correct science stories? Examining the implications of heroic science stories for school science. Journal of Research in Science Teaching, 35, 175–187.

Monk, M. & Osborne, J. (1997). Placing the History and Philosophy of Science on the Curriculum: A Model for the Development of Pedagogy, *Science Education* 81(4), 405–424.

Munby, H. (1976). Some Implications of Language in Science Education, *Science Education,* 60(1), 115-124.

NARST (2009). Mission Statement. http://www.narst.org/about/mission.cfm Retrieved January 29, 2009

National Research Council (2005). *Facilitating Interdisciplinary Research,* Washington, DC: National Academy of Sciences. www.nap.edu/catalog/11153.html (March 8, 2008).

National Research Council (1998). *Teaching About Evolution and the Nature of Science*, National Academy Press, Washington D.C..

National Research Council (1996). *National Science Education Standards, National Academy Press*, Washington, D.C.

NSTA Position statement on NOS: http://www.nsta.org/about/positions/natureofscience.aspx (accessed 3/19/10)

Numbers, R.L. (1998). *Darwinism Comes to America*, Harvard University Press, Cambridge, Massachusetts.

OECD (2001). Knowledge and skills for life first results from PISA (2000). Organisation for Economic Cooperation and Development.

Palmquist, B.C. & Finley, F.N. (1997). Pre-service teachers' views of the nature of science during a postbaccalaureate science teaching program. Journal of Research in Science Teaching, 34, 595–615.

Perry, W. G. (1970). *Forms of intellectual and ethical development in the college years: A scheme*. New York: Holt, Rinehart & Winston.

Piaget, J. (1926). *The Child's Conception of the World.* Routledge.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research*, 63, 167 – 199.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66, 211 – 227.

Roach, L. E. (1993). Use of the history of science in a nonscience majors course: Does it affect students'understanding of the nature of science? *Dissertations Abstracts International*, *55*(03A), 0525.

Robinson, J.T. (1965). Science teaching and the nature of science. *Journal of Research in Science Teaching*, 3(1), 37-50.

Robinson, J.T. (1969). Science teaching and the nature of science: Implications for teacher education. *Journal of Research in Science Teaching*, 6(1), 99-104.

Rubba, P., Horner, J., & Smith, J.M. (1981). A study of two misconceptions about the nature of science among junior high school students. *School Science and Mathematics*, 81, 221–226.

Rudge, D.W. (2000). Does Being Wrong Make Kettlewell Wrong for Science Teaching? *Journal of Biological Education* 35(1), 5–11.

Rudolph, J.L. & Stewart, J. (1998). Evolution and the Nature of Science: On the Historical Discord and its Implications for Education, *Journal of Research in Science Teaching* 35(10), 1069–1089.

Russell, T.L. (1981). What History of Science, How Much, and Why? *Science Education* 65(1), 51–64.

Rutherford, J.F. (1964). The role of inquiry in science teaching. Journal of Research in Science Teaching, 2(2), 80±84.

Rutherford, F.J., Holton, G. & Watson, F.G. (1970). *The Project Physics Course*, Holt, Rinehart and Winston, New York, NY.

Ryan, A. & Aikenhead, G.S. (1992). Students' Preconceptions about the Epistemology of Science. *Science & Education.* 76, 559-580.

Ryder, J. (2001). Identifying science understanding for functional scientific literacy. *Studies in Science Education* 36, 1-44.

Scharmann, L. C. (1990). Enhancing an understanding of the premises of evolutionary theory: The influence of a diversified instructional strategy. *School Science and Mathematics*, 90, 91 – 100.

Scharmann, L.C., Harris, W.M. (1992). Teaching Evolution: Understanding and Applying the Nature of Science. *Journal of Research in Science Teaching*. 29(4), 375-388.

Schwab, J. J. (1962). The concept of a structure of a discipline. *The Educational Record, 43*(3), 197-205.

Schwartz, R.S., Lederman, N.G., & Crawford, B. (2000). Making Connections Between the Nature of Science and Scientific Inquiry: A Science Research Internship for Preservice Teachers. *Paper Presented at the Annual Meeting of the Association for the Education of Teachers of Science*, Akron, Ohio.

Shamos, M. (1995). *The Myth of Scientific Literacy*, Rutgers University Press, New Brunswick.

Sinatra, G. M., & Pintrich, P. R. (2003). *Intentional conceptual change*. Mahwah, NJ: Lawrence Erlbaum Associates.

Smith, M. U., Lederman, N. G., Bell, R. L., McComas, W. F. & Clough, M. P. (1997). How great is the disagreement about the nature of science? A response to Alters. *Journal of Research in Science Teaching, 34*(10), 1101-1103.

Solomon, J., Duveen, J. & Scot, L. (1992), Teaching About the Nature of Science Through History: Action Research in the Classroom, *Journal of Research in Science Teaching* 29(4), 409–421.

Solomon, J. (1994). Pupils' images of scientific epistemology. International Journal of Science Education,16, 361–373.

Southerland, S.A., Johnston, A., Sowell, S. (2006). Describing Teachers' Conceptual Ecologies for the Nature of Science. *Science Education,* 90, 874-906.

Staver, J.R. (1999). When Public Understanding of Science Thwarts Standards-based Science Education. *Electronic Journal of Science Education.* 3, 1-3.

Stinner, A., McMillan, B.A., Metz, D., Jilek, J.M. & Klassen, S. (2003), The Renewal of Case Studies in Science Education, *Science & Education* 12(7), 617–643.

Strauss, A. and Corbin, J. (1990). *Basics of qualitative research: Ground theory procedures and techniques*. Newbury Park, CA: Sage.

Strauss, A. and Corbin, J. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory* (2nd ed.). Thousand Oaks, CA: Sage.

Strike, K. A., & Posner, G. J. (1992). A revisionist theory of conceptual change. In R. A. Duschl & R. J. Hamil- ton (Eds.), Philosophy of science, cognitive psychology, and educational theory and practice (pp. 147–176). New York: State University of New York.

Sutton, W. S. (1902). On the morphology of the chromosome group in *Brachystola magna*. *Biological Bulletin*, 4:24-39.

Tao, P.K. (2003). Eliciting and Developing Junior Secondary Students' Understanding of the Nature of Science Through a Peer Collaboration Instruction in Science Stories, *International Journal of Science Education*, 25(2), 147-171.

Thompsen, P.V. (1998). The historical-philosophical dimension in physics teaching: Danish experiences. Science & Education 7, 493-503.

Tobias, S. (1990). *They're not dumb, they're different: Stalking the second tier*. Research Corporation, Tucson.

Tobin, K. (1995). *Issues of commensurability in the use of qualitative and quanti- tative measures*. Paper presented at the Annual Meeting of the National association for Research in Science Teaching, San Francisco, CA.

Toulmin, S. (1972). Human understanding: The collective use and evolution of concepts. Oxford, UK: Clarendon Press.

Trend, R. D. (2001). Deep time framework: A preliminary study of U. K. primary teachers' conceptions of geological time and perceptions of geoscience. *Journal of Research in Science Teaching, 38*(2), 191-221.

Tsai, C. C. (2002). Nested epistemologies: Science teachers' beliefs of teaching, learning and science. *International Journal of Science Education*, 24(8), 771 – 783.

Vandenlinden, D.W. (2007). Teaching the content and context of science: The effect of using historical narratives to teach the nature of science and science content in an undergraduate introductory geology course. Unpublished Doctoral Dissertation. Iowa State University.

Vygotsky, L. (1978). Mind in Society: The Deveopment of Higher Psychological Processes, Harvard University Press, Cambridge.

Wandersee, J. H. (1985). Can the history of science help science educators anticipate students' misconceptions? *Journal of Research in Science Teaching, 23*(7), 581-597.

Wandersee, J.H. (1992), The Historicality of Cognition: Implications for Science Education Research, *Journal of Research in Science Teaching* 29(4), 423–434.

Wandersee, J.H., Mintzes, J.J., & Novak, J.D. (1994). Research on alternative conceptions in science. In D.L. Gabel (Ed.), Handbook of research in science teaching and learning (pp. 177± 210). New York: Macmillan.

Welch, W.W. & Walberg, H.J. (1972). A national experiment in curriculum evaluation. *American Educational Research Journal*, 9, 373–383.

Winchester, I. (1989). Editorial – History, science, and science teaching. *Interchange, 20*(2), i-vi.

Wood, R.L. (1972). University education students' understanding of the nature and processes of science. *School Science and Mathematics*, 72(1), 73-79.

Yager, R.E. (ed.) (1996). *Science/Technology/Society As Reform in Science Education*. State University of New York, Albany.

Yager, R.E. & Wick, J.W. (1966). Three emphases in teaching biology: A statistical comparison of results. Journal of Research in Science Teaching, 4, 16–20.

Zeidler, D.L. & Lederman, N.G. (1989). The Effects of Teachers' Language on Students' Conceptions of the Nature of Science, *Journal of Research in Science Teaching*, 26(9), 771-783.

Ziman, J. (1980). Teaching and learning about science and society. Cambridge University Press, London.

APPENDICES

Appendix A: Student Questionnaires

First Anonymous Questionnaire

This semester you read several short stories regarding scientists and how science ideas came to be accepted. Your honest feedback regarding these experiences would be very much appreciated.

1. How interesting did you find the short stories as a whole?

1	2	3	4	5
Very Interesting		Neutral		Very Uninteresting

2. Please rank order from most interesting (1 indicating MOST interesting) to least interesting the short stories *you actually read* (If you didn't read a short story, simply leave the line empty).

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

___ A Very Deep Question: Just How Old is the Earth?

___ Creativity and Discovery: The Work of Gregor Mendel

___ Charles Darwin: A Gentle Revolutionary

___ Adversity and Perseverance: Alfred Russel Wallace

3. To what extent did the short stories teach you something new about how science works?

1	2	3	4	5
Very Much		Somewhat		Not at all

4. To what extent did the short stories change some of your views regarding how science works?

1	2	3	4	5
Very Much		Somewhat		Not at all

5. If assigned short stories replaced other homework, how many of these kinds of short stories would you like as part of your class?

None ___ 1-2___ 3-4 ___ 5+___

6. Additional comments you have would be very much appreciated. Thanks!

Second Anonymous Questionnaire:

Last week, you answered some questions related to the short story assignments given in this course. I forgot to ask you one important question, so I'm including it here.

1. To what extent did the short stories impact your interest in science as a career?

1	2	3	4	5
Decreased My Interest		No Effect on My Interest		Greatly Increased My Interest

Additional Comments:

Appendix B: Homework Assignments (Short Stories)

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

Advances in science are too often wrongly portrayed as the work of one person or a few individuals battling in the name of modern science against the darkness of ignorance and narrow-minded religion. How scientific understanding changes, as illustrated in early attempts to understand the earth's age, debunks 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.

In the Western world, 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. The disinterest in pursuing serious study of the earth's age was illustrated by the lack of activity in this area among theologians or those we today would call "scientists".

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 texts. 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 scrutinized texts 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 found in texts that included, but was not limited to, Biblical scripture. This approach entailed 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 secular 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 regarding the veracity of old and new information. They decided that this conflicting new evidence was unreliable and dismissed it, trusting their own written records instead.

Overall, chronology is a good example illustrating how inquiry of the natural world must be considered within the timeframe it occurred and the prevailing culture. In the late 1600s, chronology drew respect 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. That the chronologists did not force the earth to be young is important for understanding the context of early work regarding the age of the earth. The dominant culture already told chronologists that the earth was young. They simply found a method to defend their culture's viewpoint.

A second approach to understanding the earth's age, which came to be known as 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. Because of the significance this emerging new way of thinking would have for science and all of society, this period of time (circa 1550 to 1730) is often called the Scientific Revolution. Astronomers like Copernicus argued that the sun should be 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 coincide 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.

This complex and changing cultural backdrop is the context that the first 'true' geologists (using today's standards) worked within. While 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. Calling this approach learning from "the Book of Nature," 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 former and emerging 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 in Derbyshire 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 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. Embedded in these layers, Steno and others noticed, were preserved shapes of animal bones that nobody had ever seen before—fossils. This discovery would drive a whole new generation of naturalists to study the earth's age to explain how the fossils got there.

1. Those who are investigating the natural world at this time have either the personal financial resources or the financial support from others to conduct their work. The word "scholar" comes from the Latin word "scholee" which means "leisure time". Today we hardly think of conducting scholarly work as "leisure". Why do you suppose that in the past, leisure time was associated with doing science and other forms of scholarship?

Determining the age of the earth was also necessarily tied to developing an explanation that would account for how physical processes work to shape the earth over time. Two approaches existed for developing a 'theory' of the earth. One was to use Biblical events to explain a short timescale, and the other was to use natural events to predict a long 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 proponents 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 and James Hutton illustrates these two approaches, but they are only two of the many individuals in both camps.

Jean-André de Luc was born in Geneva, Switzerland, and would later move to England and travel most of Europe. He was the first to use the word 'geology.' He was adept with tools and made the portable barometer used by Saussure in the Alps. 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 called this the "apple of discord between [scientific scholars]." How could aquatic life be fossilized 7,000 feet above sea level in a landlocked region? Around 1780, the best explanation, he thought, was that at one point, the earth had been entirely flooded. Very gradually, the water levels lessened and at the same time, the current continents on which naturalists now walked 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 very recent catastrophic flood shaped the world's landmass.

De Luc was just one of many scientists who tried to link scientific laws to biblical history. Almost 100 years earlier, Thomas Burnet had written *The Sacred Theory of the Earth* using Scriptures as the starting point and trying to weave Newton's laws into his theory of the earth's evolution. As Burnet's friend and colleague, Isaac Newton had assisted with and endorsed Burnet's book.

- **Note that De Luc and other scientists are straddling two worlds – one trying to understand the natural world in terms of naturalism, the other trying to understand the natural world in terms of biblical literalism.**

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. He presented arguments for and against the Biblical account of Genesis, remarking that his new 'geological' method illuminated the full meaning of Scripture without contradicting it. However, he shied away from explaining the origin of the earth. Noting the oldest rocks, or the "Primary" rocks, had no fossils, he turned to the "Secondary" rocks of more recent origin. He interpreted this to mean that at one time animals and vegetation unlike those seen in modern times populated the earth. In the late 1700s, though, 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.

About the same time, across the English Channel in Britain, James Hutton also traveled the countryside looking at exposed strata. 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 like Erasmus Darwin, hunting minerals to be used for industry. In other cases they were like de Luc, trying to explain the earth. In some recent histories, Hutton is portrayed as the noble scientist who fought the tyrannical grasp of religion. This is far from the truth.

Hutton was most well known for his 1795 book, *Theory of the Earth*, which argued for a near eternal 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 that conducted nature and caused the seasons and other natural phenomena. He was also a deist, a new religious 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. The Newtonian laws, then, commanded over a land with was set up for human life, or as Hutton said, "We are thus bountifully provided with the necessities of life; we are supplied with things conducive to the growth and preservation of our animal nature, and with fit subjects to employ and nourish our intellectual powers."

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 formidable grasp of chemistry to bear on the geological problems that Hutton was considering.

2. Consider how scientist's many associations likely influence and nurture 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. After a trip in 1786 to southwestern Scotland to Galloway, he wrote, "...here we found the granite interjected among the strata, in descending among them like a mineral vein, and terminating in a thread where it could penetrate no farther...[this] will convince the most skeptical with regard to this doctrine of the transfusion of granite."

The most popular story of Hutton is his trip in 1788 to Siccar Point on the east coast of Scotland. As he looked up at the cliff face, he saw an 'unconformity' in the rocks. At the bottom of the cliff was gray micaceous greywacke. However, instead of lying horizontal, as they were accustomed to seeing in quarry walls, the beds were standing straight up. Above this layer was a nondescript jumble of large fragments of the greywacke, in a layer perhaps two feet high. 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, he explained, 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. The jumble of fragmented greywacke that overlay the top of the buckled rocks was formed in the early stages of submersion, when waves crashed onto the shore. 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 so did every other theory of the earth. Hutton's main contribution to the history of geology at Siccar Point was to propose that very small changes happened over a very long time, which would become the backbone of the uniformitarian argument. Much later, Hutton's associate John Playfair would remark of their trip to the Scottish coast:

> We felt ourselves necessarily carried back to the time when the [sedimentary rock] on which we stood was yet at the bottom of the sea, and when the sandstone before us was only beginning to be deposited in the shape of sand or mud, from the waters of a superincumbent ocean. An epoch still more remote presented itself, when even the most ancient of the rocks instead of standing upright in vertical beds, lay in horizontal planes at the bottom of the sea, and was not yet disturbed by that immeasurable force which has burst asunder the solid pavement of the globe. Revolutions still more remote appeared in the distance of this extraordinary perspective. The mind seemed to grow giddy by looking so far into the abyss of time.

3. 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 faired 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.

4. How does this story illustrate that science versus religion is not an accurate description of efforts to understand the age of the earth?

A Very Deep Question:
Just How Old is the Earth?

Early efforts to understand the earth's age cannot be fairly categorized as a battle between science and religion. Rather, those early efforts reflected two different empirical 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 camps.

The naturalists argued that the earth was old, but how old remained a mystery. Many naturalists, including James Hutton, 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* 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 wider 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 focus did not last long. Politicians sought geological evidence to help locate valuable coal, and 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, 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. Throughout human history, these remnants had been used in religious and cultural ceremonies and collected like memorabilia, 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. As rocks wore away, or 'denuded,' from rain, wind and floods, particulate matter (ranging from large grains to silt) and dissolved ions would be sent to settle in lower lying areas such as valleys, rivers, and oceans. Some geologists believed they could measure this flow of sediment and calculate how long it would take to make some of the enormous rock formations. For instance, if the thickness of a modern sedimentary deposit is measured, and the rate that sediment is added to it over a period of a year is known, then the length of time that the sedimentary deposit has been forming can be easily calculated.

1. **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, calculate the approximate age of the earth he came to.**

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 – 300 million years.

- **While this age range is enormous, geologists are all in agreement that the earth is very old.**

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. A schooled physicist, Kelvin had no formal training in geology. He made his name in the 1850s as a technical advisor on the transatlantic telegraph cable, and he made several contributions to our scientific understanding of heat. His work in this area contributed to the foundations of the second law of thermodynamics, known as 'entropy.' To him, entropy was the measure of heat lost when two bodies of different temperatures interacted and came to equilibrium of temperature. 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 reallocated to the air, the glass, the table, or something else. He thought this reallocation 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 and sun as well. Thus, since their respective beginnings, both have been losing heat. He first turned his approach on the sun. Because the sun gave off enormous heat over a long time, it must be fueled by something. Many scientists thought the sun's heat was a product of chemical reactions, but nobody understood how chemicals could react to produce such enormous energy. Kelvin suggested that meteors crashing into the sun powered the reactions, analogous to meteors that were known to strike the earth. He thought that the sun's enormous gravity pulled in these unseen meteors. That interaction, he speculated, would provide enough reallocated energy to keep the sun burning for a long time.

In 1850, however, scientists had no evidence that anything similar had been going on with the earth, so 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 and compared it 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 uniformitariansim 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. In 'On the Secular Cooling of the Earth,' 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, which in turn he believed was the working of a providential intelligence. However, the universe for Kelvin 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' adherence to these two assertions. He and other geologists were using different data, and their calculations based on it gave a much older earth. Joly applied the technique of sediment analysis to the salinity, or salt content, of the oceans. He assumed the oceans began as entirely fresh water, and that through erosion of rocks had slowly acquired its current salinity. This argument hinged on the realization that sodium appears in the ocean paired with chlorine, magnesium, and potassium. He had to measure the respective amounts of each salt present in the ocean and then factor the chemical weight of sodium. He concluded that there was 14.151x1012 tons of salt in the ocean, and then divided this by what was accepted at that time as a good estimate of the annual flow of sodium into the ocean. The result of this calculation was that 90 million years would have to pass to reach the ocean's current salinity level. Announcing this result in 1899, he and many other geologists had reached a similar conclusion that the earth was approximately 100 million years old.

At the turn of the century, then, two quantitative, 'scientific' 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 accumulation 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.

2. Note that how scientific research is conducted (the *processes* of science) is intertwined with prevailing ideas about natural phenomena. This, in turn, affects new thinking about the natural world. Use information from this short story to explain how scientific knowledge and scientific process are intertwined.

3. Many students today choose not to pursue science careers, thinking that science is a dull and unimaginative process. Using this historical episode, 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 at the turn of the 20th century into newly observed phenomena. In 1896, Henri Becquerel serendipitously noticed that wrapped photographic plates in a drawer with a mineral called "pitchblende" become exposed. He interpreted this to mean that the mineral was emitting something that caused the photographic plate exposure. After subjecting the mineral to extreme heat, acids, and bases, the pitchblende sometimes chemically reacted, but the emanation exposing photographic plates continued. This was interpreted as meaning that the emanation was not the result of a chemical reaction, but rather was coming from deep within atoms in the pitchblende. Moreover, the emanation 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 announced they had isolated two new elements—radium and polonium—and called the energy they gave off "radioactivity." A few years later, Ernest Rutherford determined that X-rays and radioactivity were actually two different events. Whereas X-rays were high energy electromagnetic radiation (the same kind of energy that made up visible light), radioactivity was the process by which elements *changed* into other elements. Put simply, unstable *parent* elements gave off protons and neutrons and form a *daughter* element. At the time, Rutherford's claim that one element could change into another sounded like old-fashioned and now rejected alchemy. Nonetheless, research progressed quickly and just after the turn of the century, researchers had determined that three kinds of radiation existed. Weak and easily absorbed radiation that could be deflected by a magnetic field was called *alpha* radiation. Somewhat penetrating radiation that was deflected by a magnetic field in the opposite direction of alpha radiation was called *beta* radiation. And highly penetrating radiation that was not deflected by a magnetic field was called gamma radiation.

This newly observed phenomenon, radiation, would soon play the key role in the fifty-year struggle to determine the earth's age. While the processes responsible for radioactivity would not be understood for another 20 years, in 1903, Pierre Curie and his student announced that as radium gave off energy, it also gave off heat; enough 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 transcended scientific disciplines.**

Kelvin refused to accept that radiation actually gave off energy as had been reported—for him, all energy was the result of gravitational interactions. Kelvin remained firm in his view that the earth was 24 million years old, and this produced some awkward situations. At one conference, Rutherford 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 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. But 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 while any one kind of element had the same number of protons, it could contain different numbers of neutrons. These different forms of the same element are called **isotopes**. Carbon, for example, has three isotopes. Most all carbon on earth is in the form of carbon-12, which has six protons and six neutrons. However, minute amounts of carbon-13 and carbon-14 exist, with seven and eight neutrons respectively. 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 nuclear properties can vary drastically. In the case of Boltwood, he tried to measure the decay rate from uranium to lead. Measured in a 'half-life,' or 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. Once understood, however, 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, studying a particular kind of mark left by radioactive decay in rocks. Interestingly, while 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 calculations using radioactive decay. Meanwhile Arthur Holmes, perhaps the first geologist to fully grasp the implications of modern physics, was willing to try all the new methods to get the two fields working with each other. A lifelong geologist who had traveled the world working for mining and oil companies, Holmes would 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.

4. 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?

Beginning in the 1850s, over a century's worth of work was needed to convince most scientists by the 1950s that the earth was very old. Another century 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 staggering and difficult to grasp age of the earth. The modern estimate of the earth's age, 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), is about 4.5 billion years. Science textbooks often cite that number, but 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 cohere. In doing so, they distort how science works, and make science careers appear far less than the creative and interesting profession than it is.

Creativity and Discovery: The Work of Gregor Mendel

In the summer of 1878, Abbot Gregor Mendel was visited in his monastery by the horticulturalist C.W. Eichling, representing a French seed company. The 22-year old Eichling was touring Central Europe, and had been urged to visit Mendel's collection of pea plants at his monastery in the town of Brno in what is now called the Czech Republic. At the age of 56, Mendel had been nearly five years removed from his scientific work with pea plants, having been so preoccupied with the daily operations of a large monastery that he could only spend rare free hours in his garden.

On Eichling's visit, Mendel showed him the grounds and 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 — consisting of wild-grown plants mixed with the local sugar-pod types. Eichling wondered how this unassuming 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 it 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 account, and was told that Mendel was "one of the best clerics," but "not a soul believed his experiments were anything more than the maundering of a charming putterer." About 20 years later, this "charming putterer" would be hailed for developing two ideas that we now accept as fundamental laws of inheritance.1

Born Johann Mendel in 1822 in the village of Hync□ice (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 boarding school in the German speaking town of Opava. 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. Earning top grades, he gained a great deal of self-discipline throughout his youth, but such pressure burdened him with broken nerves that would haunt him for the rest of his life. Unable to secure a job as a full-time teacher after graduation, he returned home a beaten man and spent a year on his parents' farm. In 1841 he was accepted to the University of Olomouc, in a Czech speaking town. Attending University was a tough decision for Mendel—in addition to hardly speaking a word of Czech, his father had been injured and the farm was in real danger of collapsing. Mendel opted to continue his education.

At Olomouc, Mendel fervently pursued a degree that included work in mathematics, physics, philosophy and ethics. He made good relationships with his professors and again earned top marks. After his two year degree, though, 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. When she married while he was away at the university, her new husband gained the farm. In the contract handing over control of the farm to Mendel's new brother-in-law, a clause stipulated that Johann would receive a handsome annual sum of money in return for entering the priesthood. Luckily for Johann, his physics professor at Olomouc had been a member of an Augustinian Monastery. With his grades and his teacher's reference, in 1843 Johann was accepted at the Augustinian Monastery in Brno without so much as meeting the elders. There he would be christened "Gregor," and as long as he performed his clerical duties, he was free to study whatever he wished. While faithful, Mendel obviously did not take vows purely because he felt driven to serve God.

- **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 "scholee" 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, and a librarian willing to procure any needed volumes. Mendel used these resources extensively, hoping to procure a certificate to become a full-time teacher.

Mendel's teaching career, however, never took off. While praised for his classroom teaching, he couldn't pass the very tough certification exams. Taking the exams over four times, he failed for a variety of reasons, mostly because he limited his studies to what was on hand at the monastery. Another time, Mendel's nerves got him so riled up he couldn't finish his test and just walked out. 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 Brno monastery later learned that Mendel hadn't passed the certification exams, he made a merciful move. The Abbot decided to send Mendel to the University of Vienna to sharpen his education.

Vienna proved incredibly important for Mendel's future. His experimental physics class was taught by Professor Christian Doppler, for whom the Doppler Effect is named. Doppler used a textbook he had written himself, which included emphasis on probability. This unanticipated encounter with ideas regarding probability likely influenced Mendel's interpretation of his later experiments with pea plants. Furthermore, as a minister, Mendel's education included a broad category of coursework including botany, zoology, and anthropology. He finished his degree in 1854, returning to the monastery and immediately commencing his work on peas.

At the time Mendel began his scientific work, discussions regarding heredity had already been very active for a century. Well known figures in science like Erasmus Darwin (Charles' grandfather), the Comte de Buffon (who developed convincing ideas regarding the earth's age) and Carl Linnaeus (who developed a classification system whose basic framework is still used today) had speculated on the subject. Erasmus Darwin, for example, put forth the idea that if a man thought about himself during sex, the offspring would be male; if he thought about his wife, then the offspring would be female.

Early investigations into heredity were done with animals. Plants were not used in hybridization experiments until the 1700s. In *Origins of Mendelism,* Olby maintains this was likely due to the difficulty natural scientists had in accepting that plants sexually reproduced. In observing the great number of pollen grains dusting the few seed chambers of a plant, J.G. Siegesbeck, Professor of Botany at St. Petersburg, was compelled to say, "What man will ever believe that God Almighty should have introduced such confusion, or rather such shameful whoredom, for the propagation of the reign of plants. Who will instruct young students in such a voluptuous system without scandal?"

Carl Linnaeus (1707-1788) not only believed it, he made the plant's sexual organs the basis for his system of plant classification. After some observation of various plants, Linnaeus concluded that any plant showing a combination of characteristics from those of two known species must be hybrids. Linnaeus proposed a "two-layer theory of heredity," in which the outer layer, containing the leaves and the rind of the stem, was inherited from the father, and the inner layer, containing the central part of the flower and the pith of the stem, was inherited from the mother. 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.

When Mendel began his investigations into heredity in 1856, the publication of Charles Darwin's *Origin of Species* was still three years in the future. The transmutation (or 'evolution') of species was an old idea that was periodically discussed, but it was not prevalent in the scientific community. Linnaeus, a devout Christian, was willing to accept that God's creatures could procreate 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. As such, his original list of classified species was filled with hybrid plants that today would not be considered species because those hybrids could not have viable offspring. So at the time Mendel began his work, scientists were thinking about heredity and were considering the idea that new species might result from procreation. However, precisely how characteristics were transferred from parents to offspring remained a complete mystery.

What stimulated Mendel and others to begin investigating the mechanism of heredity 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. He even wrote Linnaeus asking him for seeds of hybrids. Koelreuter made two important observations. The first was that not all hybrids could produce offspring, and 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 interesting explanation: in nature, species remain fixed and like parents give birth to like offspring, but when humans interfere is when the ‘unnatural’ crosses appear.

While Koelreuter’s explanation is no longer accepted, his work was important for questioning one of the major ideas regarding heredity, called “preformation.” Preformation stated that an exact miniature replica of the parent existed inside sperm cells or ovum cells. Therefore, exact blueprints were passed on in each generation, with slight changes depending on the influence of either the male sperm or female egg – not both. 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 the miniature replicas of parents in the sex cells, the preformation idea lived on because it explained why so many species had more or less identical offspring. Taking his extensive examples, Koelreuter measured key points on his hybrid plants, and 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 of plant physiology at Vienna, was yet another influence on Mendel’s thinking. Unger rejected the idea that species were stable and, in contrast to Koelreuter, proposed that variations arise in natural populations.

So at the time Mendel graduated from the University of Vienna, his thinking regarding heredity would be 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. After graduation in 1854, Mendel again filled a substitute teaching position in Brno, teaching over a hundred students a day. He took the teaching certification test again. His nerves broke and he stormed out of the examination room. Again he failed.

In the summer of 1856, in between clerical duties and teaching (at Brno they chose to ignore the teaching certification exam failure), Mendel began his research on pea plants of the genus *Pisum*. He favored these plants for their purity and more easily observed characteristics. Mendel’s experiments followed from a speculative idea that he had already formulated. His crucial conjecture that no one had previously considered “was simply the prediction of the number of different forms that would result from the random fertilization of two kinds of ‘egg cells’ by two kinds of pollen grains.”2 In other words, Mendel postulated the existence of what he called “factors” for each characteristic, and that these factors responsible for different variations of a trait would not occur together in the same sex cell. Mendel does not know what these factors are, but his idea has observable consequences as illustrated in figure 1.

Figure 1. Ratio of progeny expected from the random cross of two kinds of egg cells and two kinds of pollen grains.

	T	t
T	TT	Tt
t	Tt	tt

If equal numbers of two kinds of egg cells existed (one for long stem length, the other for short stem length) were randomly fertilized by two kinds of pollen grains (one for long stem length, the other for short stem length), and if long stem length was dominant to short stem length, then the resulting ratio of progeny would be 3 long:1 short. These predictions are what Mendel set out to test.

1. Explain how Mendel's thinking shows both a gradual progression from prior ideas regarding heredity and also a break from those prior ideas.

Mendel used varieties of the genus *Pisum* that he had tested for purity of type. That is, through self-fertilization crosses, he determined that particular plants were "true-breeding" (only contained one factor) for certain characteristics. This was a crucial step, for, as Mendel wrote, "The value and utility of any experiment are determined by the fitness of the material to the purpose for which it is used...". He then began making strategic crosses between plants. But rather than simply observing what resulted (as his predecessors had done), he *counted* the number of each kind of progeny resulting from his crosses.

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 1⁄2 feet high), he crossed them together. The offspring that resulted from the crossbreeding (called the F_1 generation) all had long stems. 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 F_1 generation, was caused by a *recessive* factor.

The resulting tall hybrid plants were then self-fertilized, thus creating the next or F2 generation. When the F2 progeny 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 this F2 progeny, Mendel interpreted the numbers as exhibiting a certain constancy, averaging three talls to one short, or a 3:1 ratio. Table 1 below contains Mendel's published numbers of tall and short F2 progeny as well as the results of the same type of crosses with other characteristics that Mendel conducted in pea plants.

Table 1 Mendel's F_2 experimental results[3]

Characteristic	F₂ Progeny Results				Ratio
Seed shape	Round	5,474	Angular	1,850	2.959:1
Cotyledon color	Yellow	6,022	Green	2,001	3.010:1
Seed coat color	Colored	705	White	224	3.147:1
Pod shape	Inflated	882	Constricted	299	2.950:1
Pod color	Green	428	Yellow	152	2.816:1
Flower position	Axial	651	Terminal	207	3.145:1
Stem length	Tall	787	Short	277	2.841:1
Total	Dominant	14,949	Recessive	5,010	2.984:1

Note that the numbers do not reflect a precise 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 above were selected by Mendel for presentation, and were likely chosen because they best illustrate his proposed ideas regarding heredity. Varying levels of ambiguity is part of all scientific work, and those who do research must make judgments to make sense of that ambiguity. Mendel's crucial interaction with and interpretation of his data is apparent in: 1) his having to observe and judge which categories the outcomes of his crosses belonged, 2) his choice of which data to present publicly, and 3) the way he identifies and reacts to anomalous data. Moreover, one biographer of Mendel, Viteslav Orel, 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.4

- **Mendel wasn't fudging his data. Scientists must make sense of data, and this entails interpretive judgments, because 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, and this reduces, but does not eliminate subjectivity in science.**

2. How does Mendel's work illustrate that observation and data analysis is not objective (i.e. scientists "see" through the lens of their theoretical commitments)?

Mendel next allowed these F2 plants to fertilize themselves. All progeny resulting from the self- fertilization of the F2 recessive parents exhibited, as expect, the recessive trait. The self-fertilization of the F2 parents exhibiting the dominant trait yielded a more complex result. Mendel proposed that two-thirds of the F2 individuals expressing the dominant trait should be hybrids and the remaining one-third should be true-breeding, giving a ratio of 2:1.

He tested this by allowing the dominant F2 plants to self-fertilize, and then observing the expressed traits of the F3 generation. Table 2 presents Mendel's experimental results in regards to the expected 2:1 ratio.

Table 2. Ratio of hybrid to pure-breeding dominant individuals in F_2 generation[5]

Characteristic	F_2 Individuals				Ratio
Seed shape	Heterozygous	372	True-breeding	193	1.927:1
Cotyledon color	Heterozygous	353	True-breeding	166	2.127:1
Total for seed traits	Heterozygous	725	True-breeding	359	2.019:1
Seed coat color	Heterozygous	64	True-breeding	36	1.778:1
Pod shape	Heterozygous	71	True-breeding	29	2.448:1
Pod color	Heterozygous	60	True-breeding	40	1.500:1
Flower position	Heterozygous	67	True-breeding	33	2.080:1
Stem length	Heterozygous	72	True-breeding	28	2.571:1
Pod color (repeat)	Heterozygous	65	True-breeding	35	1.857:1
Total for plant traits	Heterozygous	399	True-breeding	201	1.985:1

These results again illustrate that research findings must be interpreted. For instance, 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."6 Data is always interpreted in light of other data, prevailing ideas, hunches, and other factors.

Mendel's extensive empirical research into plant hybridization provided evidence supporting his idea that factors for particular characteristics 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 (what we today refer to as the law of independent assortment). Interestingly, Mendel applied his idea of segregation *only* to hybrids. This is evident in his representing factors in hybrids with a two-letter designation (e.g. Tt), but his representing true-breeding plants with only one letter (e.g. T or t instead of TT or tt). But his work illustrated how the development of hybrids could be accounted for by the segregated transfer of factors. Of course, Mendel had no idea what these factors were, or how they were passed from parents to offspring. But his empirical work did not support the preformationist idea that the entire organism was transferred to an offspring).

3. 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 biographer Orel asserts that the three important contributions made to science by the *Pisum* experiments were these: 1) The application of mathematics in research into heredity; 2) The elucidation of the basic mechanism of fertilization in connection with heredity; and 3) The application of probability to the production of germ cells in the fertilization process, and in the transmission of parental traits to offspring.7 However, Mendel's research did not immediately revolutionize thinking regarding heredity, and only a few scientists really took Mendel's research to heart.

4. Consider that Mendel's ideas involved "factors" for particular traits, and the application of mathematics and probability to biological systems. Why might scientists in Mendel's time have found each of these ideas difficult to accept?

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. He spent the last years of his life under increased stress, taking up cigar smoking to calm his nerves. For the better part of a decade he fought a new ecclesiastical tax with would have taken 10% of the monastery's funds. 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."8

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 entities 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. After much research, however, 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.

1 Story taken from Robert Olby, *Origins of Mendelism* [2nd Ed] (Chicago: University of Chicago Press, 1985), 90; and Viteslav Orel, *Gregor Mendel: The First Geneticist*, trans. Stephen Finn (Oxford: Oxford University Press, 1996), 259.
2 Olby, 101.
3 Fairbanks, D.J. & Rytting, B. (2001). Mendelian Controversies: A Botanical and Historical Review. *American Journal of Botany*, 88(5), 737- 752., p. 739.
4 Orel, 102.
5 Fairbanks, D.J. & Rytting, B., p. 739
6 Fairbanks, D.J. & Rytting, B., p. 740.
7 Orel, 178.
8 Olby, 106.

Charles Darwin: A Gentle Revolutionary

Most everyone recognizes the name of Charles Darwin. To some he is an icon of rational thinking, to others a devil. His near legendary status has made him seem larger than life. Few people accurately understand the events in his life, his motives, and his contributions to our understanding of biology. Many modern readers wrongly consider Darwin to be the sole developer of evolutionary theory and debunker of religious creationism. In reality, Darwin's work was just one of many forms of evolutionary thinking at the time, and it even included aspects of creationism. Some conservative Christian groups have voiced that evolution cannot be reconciled with their Church's doctrine. Those holding this stance overlook the fact that religious groups of all faiths have long wondered how the diversity of life on our planet arose. The real Darwin was a complex man, very different than common perceptions of him.

Born in 1809, Charles Darwin had a family history of interest and work in science. His grandfather, Erasmus Darwin, had been a successful physician and naturalist, writing his own ideas on evolution in the book *Zoonomia*. His father, Robert Darwin, had also been a successful physician. Charles remembered his father most fondly, as his mother died when he was only eight years old. Following in his father's footsteps, Charles planned on also being a physician. In 1825 he enrolled at Edinburgh University to obtain his degree as a medical doctor. However, much like students today, he found the lectures boring, and he recoiled in disgust from his anatomy classes, unable to stomach opened cadavers. He wrote:

> The instruction at Edinburgh was altogether by lectures, and these were intolerably dull, with the exception of those on chemistry by Hope; but to my mind there are no advantages and many disadvantages in lectures compared with reading. Dr. Duncan's lectures on Materia Medica at 8 o'clock on a winter's morning are something fearful to remember. Dr. -- made his lectures on human anatomy as dull as he was himself, and the subject disgusted me.

Much later when he had become a professional naturalist and dissector of animals, he wished his anatomy professor had forced him to practice dissection more, because of the utility it held for his future work.

A career as a physician was not for Charles, and he and his father decided that he should pursue the life of a clergyman. In 1827 Charles moved to Cambridge University where those aspiring to be clergymen took the same challenging classes as those studying to be scientists. Over a hundred years before, Isaac Newton had pursued a life in theology at Cambridge, only to turn away when he deemed the Anglican Church to be full of heresy. Darwin had sent himself down the same path to be a clergyman, but would turn to a different career for a much different reason than dissatisfaction with religious doctrine.

The many theological works Darwin read at Cambridge included Paley's *Natural Theology* and *Evidence of Christianity*. Paley argued that the supreme complexity of life was evidence that all beings had been specifically designed by a Creator. At this time, Darwin accepted the divine creation of species, and found Paley's arguments agreeable. While at Cambridge, Darwin met the luminary scientists William Whewell and John Herschel. Both contributed to Darwin's attitude and efforts toward investigating nature. From Herschel came the balance of observation and experiment; from Whewell came the idea that successful scientific theories draw from many fields of research. Thus, along with being well versed in theology, Darwin became a keen observer and critical investigator in the fields that we now call geology and zoology. 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:

> 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 acrid fluid, which burnt my tongue so that I was forced to spit the beetle out, which was lost, as was the third one.

Perhaps most important during his time in Cambridge, he 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 advocated a then popular position in geology called '**catastrophism**,' which argued that landscapes such as mountains, canyons and lakes were formed swiftly through epic hurricanes, earthquakes or floods. Sedgwick advocated this idea to Darwin on the trip to Wales. Darwin had his reservations, but nonetheless developed a passion for studying the natural world. His aspirations to be a clergyman disappeared.

Upon returning from his trip to Wales, 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 and conduct scientific experiments along the way. Fearing the daily drudgery of interacting with sailors below his social status, the captain had been looking for a scholarly gentleman to lighten the days with intelligent conversation. Darwin accepted the offer, and the ship set sail on December 27, 1831. Early on, Darwin failed at his job of being a conversation piece—while discussing theology or slave trade, both he and FitzRoy often became enraged and unable to communicate. They made peace as the voyage continued, and maintained a friendship as the ship steered along the coast of South America.

Darwin did not set out on this adventure with the intent of undermining the view that all species were divinely created. The situation is better understood as that of 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, evidence overwhelmingly supported the idea that the Earth was very old, but just how old was heavily debated. While ideas regarding the evolution of species had been proposed and discussed prior to this time, Darwin did not appear to find them so compelling that he would set out on this voyage to determine how species originated. Thus, nothing noteworthy appears to have precipitated Darwin's change in thinking while at sea.

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 (including Erasmus Darwin), 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, although his mechanism of use and disuse for how species adapt has since been discredited. 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 thought these sorts of changes were passed to offspring.

Later, in 1844, Robert Chambers also put forth a popular evolutionary idea. In his book, *Vestiges of Natural Creation*, Chambers combined astronomy, geology, theology, biology, and a lucid writing style to advocate that life forms progressed 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 contemporary 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 advocating ideas regarding the evolution of species.**

Darwin would have read all of these works—one could not be a naturalist in his day without being familiar with Lamarck and the *Vestiges of Natural Creation* (the latter he would have read in 1844, seven years after his return on the *Beagle*). However, on this expedition, which Darwin famously memorialized in his book *Voyage of the Beagle*, he 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. This book essentially countered catastrophism. Lyell 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 system, called "**uniformitarianism**:"

> Along the whole coast of Brazil, for a length of at least 2000 miles, and certainly for a considerable space inland, wherever solid rock occurs, it belongs to a granitic formation. The circumstance of this enormous area being constituted of materials which most geologists believe to have been crystallized when heated under pressure, gives rise to many curious reflections. Was this effect produced beneath the depths of a profound ocean? Or did a covering of strata formerly extend over it, which has since been removed? Can we believe that any power, acting for a time short of infinity, could have denuded the granite over so many thousand square leagues?

Darwin was saying that he 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 vast landscape had been slowly built up over time. He made many more of these geological observations, and they were very important because he began to apply this 'gradualism' to his second important group of observations he made on the trip: living organisms. Lyell, on the other hand, associated his uniformitarianism principle with a steady state viewpoint of the earth and denied a progressive evolution of species.

As the *Beagle* skirted the South American coast and pulled in at the major ports of call, Darwin collected and categorized insects, crustaceans, flowers, and made observations of the larger mammals. Once collected, he packed them up and left them at port for the next ship bound for 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 landed birds (short fliers like finches) were entirely unique to the islands. Other birds, like seagulls, could fly back and forth 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 just slightly different than the mainland birds. In his own words:

> The naturalist, looking at the inhabitants of these volcanic islands in the Pacific, distant several hundred miles from the continent, yet feels that he is standing on American land. Why should this be so? Why should the species which are supposed to have been created in the Galapagos Archipelago, and nowhere else, bear so plain a stamp of affinity to those created in America?

Then he pushed the question one step further. Why would two distant locales with similar environments, such as Africa and South America, have completely different flora and fauna? Again in Darwin's words:

> On the other hand, there is a considerable degree of resemblance in the volcanic nature of the soil, in climate, height, and size of the islands, between the Galapagos and Cape de Verde Archipelagos: but what an entire and absolute difference in their inhabitants! The inhabitants of the Cape de Verde Islands are related to those of Africa, like those of the Galapagos to America. I believe this grand fact can receive no sort of explanation on the ordinary view of independent creation; whereas on the view here maintained, it is obvious that the Galapagos Islands would be likely to receive colonists, whether by occasional means of transport or by formerly continuous land, from America; and the Cape de Verde Islands from Africa; and that such colonists would be liable to modification; — the principle of inheritance still betraying their original birthplace.

In other words, Darwin began questioning that each species had been uniquely created for its particular environments. 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, often called **transmutation**, became a staple of Darwin's evolutionary theory.

1. **Summarize the evidence and reasoning Darwin uses to support the view that species change to become adapted to their environment rather than having been uniquely created for that environment.**

Upon returning to Cambridge in 1837 from his trip on the *Beagle*, Darwin began the lengthy process of reviewing all his specimens. In these first years back in England, he married and had children, published his *Voyage of the Beagle*, and caught up on research presented while he was at sea. A significant influence on Darwin's thinking was an essay he read and incorporated into his notes in 1838. Roughly 40 years earlier, the clergyman Thomas Malthus had published an *Essay on the Principle of Population*, stating that because mankind tended to enjoy procreation, its population would, if uninhibited, increase exponentially. Because resources are limited, a struggle for existence would ensue. Malthus believed this to be a simple fact of God's law, and those without food had a moral obligation to stop having children. 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. When Malthus had written the "struggle for existence", he was referring to wars between Asiatic tribes. Darwin dissociated this idea from Malthus' moral purpose, and applied it 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. Here then I had at last got a theory by which to work...

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, and spent nearly twenty more years analyzing his collections, conducting further studies, and discussing ideas with others to garner what he hoped would be overwhelming evidence for his ideas.

In 1844, the same year as the appearance of Chamber’s *Vestiges*, 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. This splitting, or **speciation**, 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. Whereas 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,” or in other words, why so many varied species existed.

2. Scientists are human beings and part of society. Like all humans, their work is influenced by the culture in which they exist. a) What cultural factors are influencing scientists’ thinking that adaptation must follow some sort of plan? b) How does Darwin’s struggles and anxiety indicate he is wrestling with those same cultural influences?

Darwin’s ongoing work was expansive and included, but was not limited to, studying pigeon breeding, the geographical distribution of organisms, and barnacles. Darwin knew that 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 for desired traits, but it 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 or undirected variation from which breeders select their traits must also exist in nature. This *natural* selection is analogous to artificial selection, but the former is far more pervasive and creative because it acts continually on every feature in every generation.

As for barnacles, Darwin had collected a wide variety of these little crustaceans, known for clinging to ship hulls. In part, the barnacle research began because Darwin was criticized for discussing species when he was an expert in none. Furthermore, Darwin felt that studying variation in the hapless crustaceans could help him understand why *all* species undergo change. Prevailing 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. 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 keen. Key to the process were the ecological pressures acting on populations. Thus natural selection was not the sole factor causing divergence.

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’. 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 determined 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 environmental changes 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 was such a rare occurrence in the first place.

For Darwin, another challenge loomed on the horizon—convincing scientists that his ideas had merit. Fearing the voracious readers of the Victorian age would ruin his life by labeling him a ‘materialist’ or an ‘atheist,’ he had thus far withheld publishing his ideas. However, he had long been forging friendships with scientists dissatisfied over the older evolutionary theories. Alfred Russel Wallace was one of these colleagues. Unlike Darwin, Wallace’s world travels were, at least in part, motivated by his view that the idea of evolution was compelling. In June 1858 while working in the Malay Archipelago, 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. Courageously, he first informed Charles Lyell and another mutual friend, Joseph Hooker, of Wallace’s letter. Darwin was so concerned about honesty that he asked Lyell, “As I had not intended to publish any sketch, can I do so honorably because Wallace has sent me an outline of his doctrine? I would far rather burn my whole book, than that he or any other man should think that I had behaved in a paltry spirit.” 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*, which Darwin once referred to as “one long argument from the beginning to the end," he drew upon extensive taxonomical and geological 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.**

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. Huxley didn't accept gradualism, and thought speciation could occur rapidly. Other scientists advocated a kind of guided evolution. Even Darwin remained tied to the past as illustrated by his admitting a role for Lamarkian adaptation. 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 "one long argument" turned into a scientific debate that continued for decades. The idea of evolutionary "progress", and the rejection of natural selection continued until the synthesis with genetics early in the twentieth century put those arguments to rest in the scientific community.

- **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.**

Charles Darwin was a complex man who put a lifetime of work into his theory of evolution. Very much a man of his time, he infused his understanding of morality, order, theology, economics, geology, and zoology into his theory. Once published, it did not triumphantly storm the world; in fact, it wouldn't be considered a true landmark of science until geneticists infused natural selection into their work on heredity in the 1930s. In 1879 he published *The Descent of Man*, which emphasized the importance of adapted features in attracting sexual mates, and the application of the theory of evolution to mankind.
Contrary to popular opinion, Darwin never claimed that man descended from apes. Rather, he argued that man and apes descended from a common ancestor, diverging gradually and eventually resulting in the separate species we see today. His work, again, was highly controversial both within and outside the scientific community. During the past 100 years, overwhelming evidence has supported Darwin's most fundamental ideas regarding 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, driven not by his theory of evolution, but by his witnessing the painful and early deaths of his daughters. His view that evolution lacked purpose and his reservations about religion undoubtedly caused him emotional and physical stress that plagued him throughout his later life. To this day, some religious groups continue to see Darwin as an embodiment of the devil. This is far from the truth. Believing that ultimately some power must be in charge, Darwin died an agnostic. Recognizing his significant contributions to science, the powers of time, including the Church, made sure that he was buried in London at Westminster Abbey. In a service attended by England's dignitaries, Charles Darwin was buried next to another icon in science, Sir Isaac Newton.

Many religious groups came to terms with evolution by the 1900s. One of Darwin's colleagues argued that explaining adaptation through natural selection fit with theists' belief that natural law is an expression of God's will. Some Calvinists used evolutionary thinking to argue that humans were not a product of inevitable progress and had fallen from grace. Today many religious groups have put forth position statements in support of biological evolution. However, some of the more conservative Christian and Muslim religious groups continue to deny evolution. Choosing to ignore that evolution has always been an idea bigger than one man, these conservative groups unfortunately target Darwin as a heretic.

- **Reactions toward biological evolution have varied greatly. Many religious, science, and science education groups have written position statements supporting biological evolution as a sound scientific idea (http://www.natcenscied.org/article.asp?category=2 and http://www.uwosh.edu/colleges/cols/religion_science_collaboration.htm). This illustrates that public education controversies regarding the teaching of biological evolution are not simply a battle between religion and science.**

3. Nobel prize winning scientist Percy Bridgeman once stated that science is "doing one's damndest with one's mind, no holds barred." He was expressing that doing science research demands creativity and that scientists will use most any method that will help them understand the natural world. 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 defy investigation by means of a controlled experiment. a) How might you account for the prevalence of these two significant misconceptions regarding how science research is done? b) How might the public's adherence to these misconceptions cause them to reject biological evolution?

4. Science's approach to explaining events in the universe without reference to the supernatural is called "methodological naturalism". Individual scientists often have a deep personal faith in a supernatural being, but when doing science, researchers must provide natural rather than supernatural explanations for phenomena. This approach has undeniably been successful and has provided useful scientific explanations for phenomena that in the past were attributed solely to supernatural intervention. How would permitting supernatural explanations in science interfere with the quest to develop explanations humans can understand and use?

Adversity and Perseverance: Alfred Russel Wallace

Science textbooks are often criticized for distorting how science is actually done. The scant attention to the life and work of scientists is one of many ways that science textbooks convey mistaken notions about what being a scientist and doing science is like. When textbooks sometimes note an individual scientist's contribution to our current understanding of the natural world, they usually focus only on the most notable historical figure and ignore the contribution of others. This wrongly conveys that science is a solitary undertaking, and that advancements in our understanding of the natural world are due to single individuals. This misconception is evident in the way biology textbooks often address the important work of Charles Darwin, and ignore or quickly pass over the work of Alfred Russel Wallace.

Alfred Russel Wallace was born in Wales on January 8, 1823, his middle-name accidentally misspelled on the register and never changed. Born into an Anglican family, his parents mishandled their inheritances from well-to-do uncles and as a result sent their boys off to work. Alfred ended his formal schooling at the age of thirteen, going off to live with his older brother as a carpenter's apprentice. The job never took, and in 1837 he moved in with another brother to work as a land surveyor. This proved to be a fortunate decision, for the Industrial Revolution had been surging in Britain. Demand for new railroad tracks put a high demand on surveyors, and Wallace was able to earn a stable living. Along the way he developed an interest in geology, collecting and mapping rocks as he went along. Wallace also developed an interest in plants, and he read as much as he could on these two subjects.

In 1844, a widely popular book, *Vestiges of the Natural History of Creation*, changed the direction of Wallace's life. Written by Robert Chambers, *Vestiges* combined the most recent scientific studies with theology. People of all walks read the book, from the queen down to the shopmaiden. Chambers' argument was that species 'progressed' up an evolutionary ladder according to God's rules. Every adaptation that passed along generations led to some final goal. Reviews, comments, and conversations regarding *Vestiges* permeated Victorian society for a time. Convinced that species did evolve, Wallace determined his life goal would be to figure out *how* species went along this progression. Thus, Wallace's world travels, unlike Darwin's aboard the Beagle, were significantly motivated by, what Wallace thought, were compelling arguments for the evolution of species.

- **The idea that species may be related to one another and that they might evolve was introduced well before Darwin and Wallace's time. In 1844, *Vestiges* was just one of several ideas that had been put forward regarding the evolution of species.**

Wallace determined that he would be a naturalist, an explorer who penetrated deep into foreign jungles and rivers to collect and preserve biological specimens. However, he had neither the money nor the training to be a naturalist. After reading Darwin's *Voyage of the Beagle*, Wallace determined his best shot would be a trip to Brazil, navigating up the Amazon to where no European had been before. There, he thought, would be unmatched biodiversity in a relatively cheap land governed by colonial rule. He and his friend, Henry Bates, hired an agent to represent their collections. Every specimen would draw four pence, of which the agent took one pence. Thus, to make a middle-class wage, they needed to collect, preserve, and ship over 3,000 specimens a year, and that did not include the costs of financing the trip.

They sought out respected adventurers for lessons in taxidermy and preservation. They learned shipping methods from the India Museum in London. They learned preservation from their agent, Samuel Stevens. Preservation was paramount to the adventurer's list of skills, otherwise all their hard work would arrive in England putrid and decayed, useless for study. Some specimens had to be bathed in alcohol, but some organisms simply distorted in the harsh substance. They carried many other tools as well, as the historian Ross Slotten writes:

> The basic equipment of the collector included knives, scissors, scalpels, pliers, a large assortment of pins of various sizes, needles, a hammer, a small hatchet, cotton, paper, a folding net, a hoop net, a water net, forceps, a digger, glass phials, large and small packing cases, and a great number of pillboxes, all of which could be purchased from Stevens' shop on Bloomsbury Street near the British Museum.

On top of this, the most important supply was arsenic soap. Negligibly toxic to the collector, the arsenic soap was key to removing the ants, spiders, fleas, and other insects that could ravage animal skins. Then came the preparation of the sample. A description, again provided by Slotten:

> All adherent fat was scraped away: if any remained, the skin was strewn with powdered tan, made from willow or oak bark, or another potent astringent that dissolved fat without penetrating other tissues, before the application of the arsenic soap. The ears, lips, and feet of the larger mammals were doused with turpentine to accelerate the drying and destroy potentially destructive insects. When completely dry, the skin was rolled up, hair innermost, beginning with the head. To prevent damage from abrasion, dried grass or moss was inserted during the rolling process. The skin had to be unrolled periodically and checked for moisture. If possible, it was further exposed to the sun and sprinkled once again with turpentine. If insects were detected, strong tobacco, or better, aromatic spices were added.

Thus prepared, Wallace and Bates headed to the Amazon. The expedition could only be described as near catastrophe. Arriving in the town of Pará in May 1848, the conditions were not what they expected, and animals were scarce around town. When they did stumble across an animal, Wallace was such a poor aim with his shotgun that he either missed completely or utterly decimated his victim. The two pushed inland, tensions rising and tempers flaring. Within the first year, Bates and Wallace had an argument and parted ways. Alone in the Amazon, Wallace pressed down the Rio Negro. He contracted malaria, periodically enduring hallucinogenic fevers that forced him to land for days. More than once his crew left, upset at the dangers and lack of food. Wallace persisted, learning the Portuguese and local languages and making friends. At one point he connected with his younger brother Edward, another son sent off by his parents to make money. Within a year Edward contracted yellow fever and died.

By July 1852, Wallace had collected and shipped off a great amount of specimens, and decided to return home for a break. He boarded the ship *Helen* along with his journals and many of his live and preserved specimens for the month-long journey. Tragically, the *Helen* caught fire in the middle of the Atlantic, and sunk with all of Wallace's journals. Adrift for ten days, he and other survivors were picked up by the *Jordeson*, a vessel already low on food. The crew hunted rats as they pulled into the English Channel, where they were hit by a storm and nearly sunk. In October 1852, Wallace returned home, and vowed to never again leave British soil. He recorded his feelings in *A Narrative of Travels on the Amazon and Rio Negro*:

> It was now, when the danger appeared past, that I began to feel fully the greatness of my loss. With what pleasure had I looked upon every rare and curious insect I had added to my collection! And now everything was gone and I had not one specimen to illustrate the unknown lands I had trod, or call back the recollection of the wild scenes I had beheld.

Wallace held his promise for only a year. After publishing his experiences in the abovementioned book and producing a few scientific articles, Wallace determined that he again needed to sail. What prompted him this time was a very specific flaw he noticed in his and other naturalists work—hardly any species had been categorized by their geographical boundaries. For instance, many explorers would note that some bird would inhabit the banks of the Amazon River, but Wallace recalled that many birds would inhabit only one bank. One example Wallace remembered from the Amazon was the hyacinthine macaw, reported to be a strong flier. The macaw, however, inhabited a very small range. Why would a strong flier not be widespread? Wallace's answer was that food supplies changed over distance, so the macaw purposefully limited itself to a very specific range.

Determined to do another expedition to gather species and catalogue their geographical boundaries, Wallace decided to sail for Malaysia in 1854. Largely controlled by the British and allied Dutch, Wallace could again go where very few explorers had ever set foot. His excitement for departure had to be pushed back, however. Britain had just entered into the Crimean War with Russia, disrupting ship routes. After waiting for months, Wallace hopped aboard a boat set for Cairo, making the pre-canal trek across the desert with Muslim traders before setting off again to Singapore. In 1855, Wallace took up base in Borneo where he spent fifteen months collecting extensive specimens and studying orangutans.
Wallace noted that orangutans kept to a given territory. This was simply one example of a widely observed phenomenon that related species appear in close geographical proximity to one another. Moreover,

Wallace was aware that fossils of what appeared to be closely related organisms appear in the same geological layer. To account for these observations, he put forward the idea that "Every species comes into existence coincident in time and space with a preexisting closely allied species." Spending the rainy season indoors caring for an infant orangutan he rescued from a swamp, he put forward this idea in a paper titled, "On the Law Which Has Regulated the Introduction of New Species." The Sarawak Law, as it came to be known, was the equivalent of Darwin's principle of divergence.

- **In science, the word "law" refers to a statement of a relationship. The word "principle" sometimes, but not always, means the same thing. Many people wrongly think that scientific theories will, with sufficient evidence, become scientific laws. However, rather than conveying the certainty of an idea, the terms "law" and "theory" refer to what particular science ideas do. Scientific laws convey relationships between phenomena. Scientific theories make sense of laws by providing an explanation for those relationships. Both laws and theories are developed to account for natural phenomena. When first conceived, all scientific knowledge (including laws and theories) has a speculative character.**

This statement caused a stir when it reached England in September 1855. Some of the more open- minded creationists, like Charles Lyell was at the time, maintained that if any extinction and evolution happened, God would make one species die off and then replace it with a new and different species. Wallace, however, said that the old and new species existed at the same time, which was a very unsettling idea for some naturalists—it clearly implied modification of organisms from one species into another perhaps without supernatural intervention. As justification, Wallace pointed out that the broadest categories of organisms, like felines for example, were widespread over the earth, while the smaller categories of species had specific locations, such as the Bengal Tiger or African Lion. In these specific locations, fossils of extinct species were found near similar existing species, showing some sort of relation between the two. Wallace commented that this could only be the result of evolution—so much variation could not logically be the result of endless continued creations. Many scientists rejected Wallace's Sarawak Law arguing that it was too much speculation with too little evidence. Wallace had predicted this very problem in his paper, saying,

> If we consider that we have only fragments of this vast system, the stem and main branches being represented by extinct species of which we have no knowledge, while a vast mass of limbs and boughs and minute twigs and scattered leaves is what we have to place in order, and determine the true position originally occupied with regard to the others, the whole difficulty of the true Natural System of classification becomes apparent to us.

In June 1856 Wallace visited Bali, where he got so caught up in collecting that he missed his intended ship to the Celebes. Stranded for a month, Wallace toured the local straits between the islands of Bali and Lombak. The fifteen-mile crossing was no problem, the islands being in constant sight of each other. What stood out to Wallace, however, was that these two nearby islands had completely different animal species—Bali having the flora and fauna (e.g. placental mammals) native to Asia, and Lombak having that of Australia (e.g. marsupial mammals). In *The Malay Archipelago,* Wallace wrote, "I believe the western part to be a separated portion of continental Asia, the eastern the fragmentary prolongation of a former Pacific continent." Wallace argued that the islands of Bali and Lombock were the most demonstrative of the two divisions of the archipelago, "differing as essentially in their animal life as Europe does from America." This is when Wallace drew his famous "line" (i.e. referred to as the "Wallace line") for the first time. Wallace, his mind always on geographical boundaries, had stumbled upon what he maintained was clear evidence that natural factors dominated evolution. If controlled by a divine hand, then what reason would a creator have for making different sets of animals for such similar islands? Wallace did catch the next ship to the Celebes and then eventually moving to the islands of Ternate and Gilolo, where he would formulate his own version of the theory of natural selection.

Spending about a month on the two islands, Wallace was again stricken by malarial fever. In his autobiography, he recalls being bedridden, staring at the ceiling, thinking about all of his work.

> The problem then was not only how and why do species change, but how and why do they change into new and well-defined species, distinguished from each other in so many ways; why and how do they become so exactly adapted to distinct modes of life; and why do all the intermediate grades die out (as geology shows they have died out) and leave only clearly defined and well-marked species, genera, and higher groups of animals?

As with all creative processes, how and why previously disparate ideas suddenly coalesce for scientists is unclear. While lying there considering his work with animals, Wallace's thinking turned to humans. Perhaps subtly at first, but then more forcefully, he recalled the work of Thomas Malthus (the same book that was key in Darwin's thinking). The late eighteenth century clergyman Malthus had written his *Essay on the Principle of Population* some fifty years earlier, where he pointed out that much of mankind had been involved in a "struggle for existence," in which populations warred and dealt with famine and disease. Particularly, Malthus had the primitive Asiatic tribes in mind when he spoke of 'struggle,' and Wallace had been traveling the very area in question investigating the same things. Suddenly, he came to an idea that explained how and why species change in ways that are adapted to their environment, and why intermediate grades go extinct. Wallace recounts then writing the entire theory within two days.

Calling his paper "On the Tendency of Varieties to Depart Indefinitely from the Original type; Instability of Varieties Supposed to Prove the Permanent Distinctness of Species," he argued that two factors controlled evolution: first, his Sarawak Law of divergence, and second, that the winners of the struggle for existence would lead to new species. This explained several factors—those most likely to die would be the weakest. The modifications would be most apparent during periods of stress—climate change, war, famine, etc. Convinced he now understood the natural mechanism of evolution, Wallace sent his paper to his trusted colleague Darwin for his and other scientists' assessment.

Darwin opened Wallace's letter in his country house in June 1858. Reading Wallace's words, Darwin felt very uncomfortable with how similar his colleague's ideas were to his own. By this time, Darwin had spent over twenty years coming to understand and provide evidence for the mechanisms of natural selection and divergence. He had written two unpublished preliminary manuscript essays in 1842 and 1844, but until this point he had never felt rushed to present his work. Now with Wallace closing in, Darwin acted. To his merit, Darwin could have never told anybody of Wallace's work, but he did inform Charles Lyell and another mutual friend Joseph Hooker. In fact, Darwin was so concerned about honesty that he asked Lyell, "As I had not intended to publish any sketch, can I do so honorably because Wallace has sent me an outline of his doctrine? I would far rather burn my whole book, than that he or any other man should think that I had behaved in a paltry spirit." After convening a group of scientists, Lyell and Hooker compared Darwin and Wallace's notes, giving Darwin his rightful priority in the matter. When word reached Wallace, he showed no anguish, just gratitude that he had arrived at a similar conclusion as his well-respected acquaintance Darwin. On July 1, 1858, Hooker and Lyell, presented Wallace's manuscript, together with excerpts from Darwin's manuscripts and letters, to the Linnaean Society of London. That August, the *Journal of the Proceedings of the Linnean Society of London* published a paper by Darwin alongside Wallace's. One year later, Darwin published his abstract, *Origin of Species*. Thus, it was made clear that Darwin had originally formulated his theory twenty years earlier, preserving the primacy of his findings. This sequence of events has resulted in widespread recognition of Charles Darwin, but unfortunately very little recognition of Wallace's contributions.

Darwin was, by all accounts, polite and generous to his young colleague, and the two men corresponded for many years. In 1870, Darwin wrote to Wallace, "I hope it is a satisfaction to you to reflect—and very few things in my life have been more satisfactory to me—that we have never felt any jealousy towards each other, though in one sense rivals." For his part, Wallace treated Darwin with the greatest respect. In an 1868 letter to Darwin, Wallace wrote, "As to the theory of Natural Selection itself, I shall always maintain it to be actually yours and yours only." He went on to acknowledge that Darwin had worked the theory out years in advance in "details I had never thought of" and seemed convinced that his paper would have been seen as nothing more than "ingenious speculation," while Darwin's *Origin of Species* revolutionized the study of Natural History.

1. Both Darwin and Wallace developed the same theory to account for their interpretations of the data they had observed. How can you account for Wallace's view that his putting forth the theory of evolution would have been seen as simply an "ingenious speculation" rather than the revolutionary effect of Darwin's *Origin of Species*?

2. Data does not tell scientists what to think! However, what does the above illustrate about the importance of data in science?

As amicable as the relationship between Darwin and Wallace was, they differed fundamentally in the way that they viewed the power of natural selection. Wallace and Darwin's thinking was not identical. Like the species they studied, their ideas greatly diverged. Wallace returned in 1862, tired and ready to publish numerous articles. By then, Darwin's life had been engulfed in defending and promoting the *Origin of Species* and preparing his next work, *The Descent of Man*. In *Descent*, Darwin wanted to show how natural selection and sexual selection applied to human evolution. Wallace, however, disagreed entirely.

Darwin argued that while natural selection was the primary force at work, other processes also came into play. He had the important insight that organisms possessed many features that were not adaptations and not directly related to survival. While Darwin maintained that an organ built under the influence of selection for a specific role may be able to perform many other unselected functions, Wallace thought the opposite. Wallace wrote, “None of the definite facts of organic selection, no special organ, no characteristic form or marking, no peculiarities of instinct or of habit, no relations between species or between groups of species, can exist but which must now be, or once have been, useful to the individuals or races which possess them.” Wallace argued that if we could not see the utility of a given organ or characteristic, it must be due to our own ignorance of its intended purpose or origin.

Darwin and Wallace also disagreed on the role of sexual selection in evolution. Darwin proposed sexual selection as a mechanism that could account for the presence of features that might be irrelevant, or even harmful, in the struggle for existence, but that played an important role in successful mating. For example, the bright red plumage of the male Cardinal could be dangerous to his existence, since it might stand out in the presence of a predator. However, that same bright red plumage could be attractive to the female Cardinal, thus, increasing the likelihood of a successful mating and therefore, the propagation of the species. Darwin theorized two types of sexual selection: competition between males for access to females, and female choice of mate. Wallace disliked the idea of sexual selection for three reasons: first, it compromised the idea of natural selection as the struggle for life itself, rather than merely the struggle for copulation (though the idea of male combat was sufficiently close to his conception of a battle for existence as to be acceptable); second, the concept of sexual selection placed too much emphasis on the role of ‘choice’, particularly female choice, in the struggle for existence; third, and most importantly, it allowed the development of important features that were irrelevant, if not downright harmful, to the functioning of an organism that, in Wallace’s view, was a superbly-designed machine.

• **Note that while Darwin and Wallace disagree on the details regarding how biological evolution occurs, they both accept the overarching idea that species do evolve. Today, while many disagreements between Darwin and Wallace have been settled on Darwin’s side, other details continue to be debated (e.g. Gradual evolution vs. Punctuated Equilibrium) without affecting the overwhelming evidence in favor of biological evolution.**

Wallace’s unshakeable confidence in the exclusive action of natural selection caused Darwin to have second thoughts about his theory of sexual selection. In an 1870 letter to Wallace, Darwin wrote:

I grieve to differ with you, and it actually terrifies me and makes me constantly distrust

> myself. I fear we shall never quite understand each other... You will be pleased to hear that I am undergoing severe distress about protection and sexual selection; this morning I oscillated with joy towards you; this evening I have swung back to [my] old position, out of which I fear I shall never get.

The biggest split between Darwin and Wallace, however, came with the question of human origins—in particular, they disagreed on human intellect. Darwin suggested that human intellect evolved according to the demands of the environment in which a group of humans found themselves. The intellect of the "savage," that is, the uncivilized tribesman living in the wilds of Africa, for example, had not evolved as far as the intellect of the sophisticated white European living in civilized society. It was commonly thought at this time that the brain of the savage was small and poorly organized. Wallace, on the other hand, maintained that all human groups had naturally equal abilities to develop their intellect. Instead, he suggested that the difference in sophistication resulted not from a lack of intellectual capacity, but rather from a failure to use existing capacities. As an example, Wallace pointed to the native peoples who had been trained to play complex instruments and music in Britain's colonial military bands.

> **3. Today, the scientific community has rejected Darwin's view regarding the relative intelligence of races. So while his overarching theory and many of its details are still accepted, other notions have been modified or rejected. How does this illustrate that the scientific community is more willing to revise their thinking regarding biological evolution than many critics assert?**

That is not to say that Wallace did not consider European culture to be superior, as most of his contemporaries did. Indeed, he shared many of the same ethnocentric opinions of that time. But Wallace maintained that natural selection could not be at work in human intellect because it does not operate *before* it is needed. For example, he asked how higher math could be an environmental adaptation. Efforts had shown that the 'primitive' mind could learn higher math, an adaptation obviously irrelevant for hunter-gatherer societies. Why would primitive man have a more highly developed brain than he either needed or used? If it is developed in anticipation of a future need, there must be some other phenomenon at work. Wallace suggested that this other phenomenon must be some higher being at work, "...a superior intelligence [that] has guided the development of man in a definite direction, and for a special purpose." Having begun with agnostic views, Wallace had now become a proponent of natural theology. That the human brain possessed these unexplained powers—such as higher math, morality, spirituality, etc— meant that human evolution must have been inspired by a divine presence at one point. This combination of spirituality and evolution was well-accepted by many of his contemporaries.

Darwin was shocked and appalled by this abrupt change in direction by Wallace, who had fully supported the idea of natural selection up to the point of human intellect, but not beyond. In 1869, Darwin wrote to Wallace, "I hope you have not murdered too completely your own and my child." But, Wallace didn't see that he had "murdered his child," because it was his view of natural selection that led him to reject it as the mechanism for human intellect, not an unwillingness to extend natural selection to human beings. Certainly, Darwin did not agree with Wallace's conclusions on human intellect, writing in a letter to Wallace, "If you had not told me, I should have thought that had been added by someone else. As you expected, I differ grievously from you, and I am very sorry for it." From that point on, Wallace ruefully referred to his theory of human intellect as "my special heresy."

Much of the information available to Darwin and Wallace was also known among other naturalists. However, Darwin and Wallace possessed the intellectual background, life experiences, and insights to invent an idea that would satisfactorily account for these and other data. Neither Darwin nor Wallace was the first to propose that species are related, but they were able to provide a plausible mechanism for that relationship. Furthermore, Darwin had collected massive amounts of data that the theory and mechanism successfully accounted for.

4. While science is often portrayed as being done by lone geniuses, what does this historical narrative illustrate about the social nature of science? How do science textbook's emphasis on individual scientists distort how science really works?

Today, however, the theory of evolution that is remembered is Darwin's. In the late 1800s, any talk of evolution demanded mention of his books. When conservative religious groups attacked evolution, it was Darwin's theory they deemed 'atheist.' When modern genetics combined with evolutionary theory, it was called the "Darwinian Synthesis." While both Darwin and Wallace's theories of evolution through natural selection are considered incomplete by modern standards, Darwin is almost always remembered as the theory's sole founder. Wallace, however, reached almost the same conclusion in a much different manner. He was the iconic Victorian explorer—always moving, learning, ready for adventure. His contribution of biological specimens was unmatched in his day. His story almost lost, the example of Alfred Russel Wallace shows how different paths can lead to the same conclusion, and even that conclusion can be utilized in different ways.