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Historical Short Stories and the Nature of Science in a High School Biology Class

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**Historical short stories and the nature of science
in a high school biology classroom**

by

Jennifer Ann Reid Smith

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Education

Program of Study Committee:
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Iowa State University
Ames, Iowa
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ABSTRACT

To overcome students' misconceptions regarding the nature of science, it is essential that teachers utilize instructional activities that accurately and explicitly portray the nature of science within the context of the science content being taught. This study examines the impact of implementing two historical short stories in a high school biology course during units on genetics and biological evolution. The stories describe the lives and work of Mendel and Darwin and how their scientific ideas were developed. Questions embedded in the stories explicitly draw students' attention to key nature of science concepts. Students in the treatment group demonstrated significantly higher understanding of several key nature of science concepts than students in the control group. Additionally, most students reported preferring the short stories to textbook readings.

CHAPTER 1: INTRODUCTION

Rationale for this Study

In *The National Science Education Standards*, the NRC (1996) claims developing an understanding of the nature of science (NOS) should be a goal for every K-12 science program. In a representative democracy where citizens contribute to legal policy and science funding decision-making through elected officials, forming a scientifically literate citizenry capable of making informed judgments is essential. McComas, Clough, and Almazroa (1998) argue, "At the foundation of many illogical decisions and unreasonable positions regarding issues involving science are misunderstandings of the character of science." Accurately portraying the NOS in school science is essential for improving social decision-making, and enhancing students' interest in science, science classes, and the learning of science content (McComas et al., 1998). Thus, developing an accurate understanding of the NOS is essential for building students' science literacy (AAAS, 1989; Matthews, 1994; McComas & Olson, 1998) and reducing the flight of talented students out of science education (Eccles, 2005; Schaefer, 1990; Seymour & Hewitt, 1997; Tobias, 1990).

While science students and the general public have many strongly-held misconceptions about the nature of science (Clough, 2000; Elfin, Glennman, & Reisch, 1999; McComas, 1998; Lederman, 2007; Ryan & Aikenhead, 1992), prior research has shown that accurately teaching the NOS in an explicit and reflective manner improves students' understanding the NOS (Abd-El-Khalik, Bell, &

Lederman, 1998; Abd-El-Khalik & Lederman, 2000; Clough, 2006). An explicit and reflective approach utilizes deliberately designed lessons to address specific NOS concepts and pedagogical practices that help students make connections between their activities and these specific NOS concepts (Abd-El-Khalik & Lederman, 2000; Clough, 2006).

In addition to the explicit and reflective approach, Clough (2006) argues that effective NOS instruction must be tightly linked to actual science content. He writes, “explicit and reflective highly contextualized NOS instruction plays a crucial role in NOS instruction by overtly drawing students’ attention to important NOS issues entangled in science content and its development... highly contextualizing the NOS means integrating historical and contemporary science examples that are tied to the fundamental ideas taught in particular science subjects” (p. 474). Because materials created for teachers to incorporate history and philosophy of science (HPS) into the curriculum failed to recognize the perceived needs of classroom teachers, those materials have rarely been successfully implemented (Monk & Osborn, 1997). Teachers often do not recognize NOS instruction as necessary (Abd-El-Khalick et al., 1998; Lederman, 1998), and feel time spent on explicit NOS and HPS instruction is time taken away from teaching science content. For this reason, teachers resist using HPS activities if they are seen as add-on material. Encouraging science teachers to use NOS curriculum materials would likely be more successful if those materials were integrated into science content so that understanding both the NOS and important science content were achieved (Clough, 2006; Monk & Osborn, 1997).

As part of a NSF grant-funded project (Clough, Olson, Stanley, Colbert, & Cervato, 2006) thirty historically accurate short stories were created for use in post-secondary introductory science courses. The intent of the project was to produce curriculum materials that teach both science content and the NOS and that instructors could introduce into their science courses where they felt it appropriate. The stories produced were designed to draw students' attention to the NOS concepts entangled in the development of fundamental science ideas taught in post-secondary science courses. This was accomplished by developing short historical and contemporary stories focused on the development of fundamental science ideas which include embedded comments and questions that explicitly draw students' attention to key NOS concepts and common NOS misconceptions. This approach is expected to increase students' understanding of the NOS while not detracting from, and perhaps improving, science content understanding. However, those materials were designed for use at the post-secondary level. So, the question arose regarding whether this same approach could be useful at the secondary level.

Although effective NOS instruction increases students' science literacy, understanding of key science content, and interest in science, many secondary teachers do not utilize available NOS instructional materials. Effective NOS instructional materials must take little time and be highly integrated into the content curriculum if secondary teachers are to implement them (Monk & Osborn, 1997). Historical short stories focused on the development of scientific ideas that are already included in the curriculum may be an ideal format for use at the secondary level. For this reason, two of the short stories from the project were modified to a

more appropriate level for secondary students. The two stories were then implemented in an introductory high school biology course.

Research Questions, Study Design, and Study Limitations

In this study, two historical short stories with embedded comments and questions explicitly addressing the NOS were used in a 10th grade biology course. The intent of this study was two-fold: to determine the impact of these stories, if any, on students' understanding of the NOS, and assess students' perceptions of the stories. The study was designed to answer the following research questions:

1. What difference in students' accurate understanding of fundamental NOS ideas, if any, exists between students who use two NOS historical short stories and students who use two control readings in a high school biology class?
2. What do students who complete the two historical short stories express regarding:
 - a. their interest in reading the short stories compared to reading their science textbook?
 - b. their interest in reading about scientists and how science ideas are developed?
 - c. the impact of the readings on their interest in pursuing a science career?

For the first research question, the hypothesis tested was: biology students that receive instruction with the two historical short stories will have higher scores on an instrument measuring understanding of fundamental NOS concepts than will

students not utilizing the historical short stories. The null hypothesis was that no difference will exist in the scores on an instrument measuring understanding of fundamental NOS concepts between student utilizing the historical short stories during instruction and students not utilizing the stories.

The participants in this study were students in an introductory high school biology course, with ages ranging from fourteen to eighteen years old. The study took place in four classes split into two treatment and two control classes by the toss of a coin. The four classes were taught by the same teacher and received the same instruction except in relation to the stories used during the genetics and biological evolution units. During these units of study, both groups utilized two readings about the lives and work of Mendel and Darwin as in-class activities. Each story involved two to three days of in-class work including students reading in small groups of three to five students, small group discussion of questions integrated into the readings, and instructor-led class discussion of the readings and questions.

The treatment group utilized two historically accurate short stories containing integrated questions and bolded statements addressing the NOS while also learning about the work of Mendel and Darwin. The integrated questions and bolded statements in the short stories were explicitly focused on fundamental NOS concepts. The control group utilized two different readings containing integrated questions about the life and work of Mendel and Darwin. However, the questions integrated into the control reading focused on science content and did not explicitly address fundamental NOS ideas.

All students' understanding of the NOS was assessed prior to the beginning of the genetics unit and again following the unit on biological evolution. Students' NOS understanding was evaluated with the Views on Science Questionnaire 1 (VSQ1) and Views on Science Questionnaire 2 (VSQ2). The VSQ1 contains eight questions selected from the *Views on Science and Education Questionnaire* (VOSE) (Chen, 2006b). The VSQ2 contains three additional questions using the VOSE format. Appropriate quantitative statistical tests were conducted to analyze and compare pre and post scores for the control and treatment groups on the VSQ1 and VSQ2 separately. The statistical results from this test were utilized to answer the research question and support or reject the study's hypothesis.

In addition to the VSQ1 and VSQ2, treatment students completed an interest survey following the completion of the post test. The results of this survey were analyzed to investigate students' interest in the historical short stories, preference for short stories versus textbook readings, and the effect of the readings on students' interest in pursuing science careers.

Several assumptions and limitations exist in this study. That no significant difference existed between students in the treatment and control groups was assumed, but may not be the case. The student population in the school where the study took place was very homogeneous and the results of this study may not apply to more diverse settings. This study was performed over a relatively short time period and included only two historical short stories — a relatively short intervention. Moreover, the stories focused on a limited number of the NOS ideas included on the

questionnaires. Thus, results and conclusions drawn must be interpreted with caution.

CHAPTER 2: LITERATURE REVIEW

The Nature of Science and Why NOS Instruction is Crucial

“ The phrase ‘nature of science’ (NOS) is often used in referring to issues such as what science is, how it works, the epistemological and ontological foundations of science, how scientists operate as a social group and how society itself both influences and reacts to scientific endeavors” (Clough, 2006, p. 463). Although science can be defined in different ways, many common characteristics of science agreed upon by philosophers of science exist which can be taught to students (Clough, 2000; Eflin et al., 1999; McComas, 1998; McComas, 2008).

Abd-El-Khalick et al. (1998) state:

The disagreements that continue to exist among philosophers, historians, and science educators are far too abstract for K-12 students to understand and far too esoteric to be of immediate consequence to their daily lives... There is, however, an acceptable level of generality regarding the NOS that is accessible to K-12 students and also relevant to their daily lives. At this level of generality we can see clear connections between students'/citizens' knowledge about science and decisions made regarding scientific claims. Also, at this level of generality, virtually no disagreements exist among historians, philosophers, and science educators (p. 418).

McComas (2008) describes a number of NOS “ideas appropriate to inform K-12 curriculum development, instruction and teacher education” (p. 251). The following are abbreviated descriptions of NOS ideas appropriate for K-12 instruction from McComas (2008, p. 251):

- A. Science produces, demands, and relies on empirical evidence.
- B. There is no one step-wise scientific method by which all science is done. Experiments are not the only route to knowledge.

- C. Scientific knowledge is tentative, durable and self-correcting.
- D. Laws and theories are related but distinct kinds of scientific knowledge.
- E. Science has a creative component.
- F. Science has a subjective element. In other words, ideas and observations in science are “theory-laden”.
- G. There are historical, cultural and social influences on the practice and direction of science.
- H. Science and technology impact each other, but they are not the same.
- I. Science and its methods cannot answer all questions.

Modern organizations and reform documents consider the incorporation of NOS in school science to be crucial (AAAS, 1989; AAAS, 1993; National Research Council, 1996; National Science Teachers Association, 1995). Scientific literacy is a central goal of science education reform, and an accurate understanding of the NOS is an essential prerequisite for scientific literacy (Matthews, 1994; McComas et al., 1998; Shamos, 1995). NOS instruction is essential in preparing students to become active members of society. Without an accurate understanding of the NOS, our students are ill prepared to be contributing citizens in our democratic society able to make informed scientific decisions and judgments (Driver, Leach, Miller, & Scott, 1996; McComas et al., 1998). Additionally, an accurate understanding of NOS enables citizens to make sense of science and manage the technological objects and processes which are

prevalent in our society (Driver et al., 1996; McComas et al., 1998). McComas et al. (1998) state:

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

In addition to preparing students for citizenship, study of the NOS supports successful learning of science content. An accurate understanding of NOS promotes student understanding about how scientific ideas develop and why they change. As a result, NOS instruction reduces resistance to integral science ideas, such as evolution. Students' accurate understanding of the NOS also increases their interest in science; consequently, students' resistance to learning is reduced (Driver et al., 1996; McComas et al., 1998; Meyling, 1997). Additionally, NOS instruction may humanize science, thereby increasing students' interest in science content and science careers and improving students' attitudes towards science (Tobias, 1990).

Prior research has shown that students, teachers, and the general public have many misconceptions regarding NOS and how science operates (Abd-El-Khalick & Lederman, 2000; Clough, 2000; Eflin et al., 1999; McComas, 1998; Ryan and Aikenhead, 1992). Such misconceptions impair the success of all the science education goals described above that are promoted by an accurate

understanding of the NOS. Misconceptions about what science is, how science works, and characteristics of science damage scientific literacy and cause many individuals to opt out of science to pursue careers perceived as more human and creative than science (Eccles, 2005; Tobias, 1990). The abundant misconceptions about NOS in our society make effective NOS instruction crucial for building a scientifically literate citizenry and promoting student interest in science careers.

Effective NOS Instruction

Students have many misconceptions regarding NOS that are highly resistant to change. For this reason, teaching NOS concepts, as with content concepts, is a matter of conceptual change (Clough, 2006). A variety of experiences may contribute to forming students' NOS misconceptions. Such prior experiences may include: media portrayals of science and scientists, textbooks and teachers that represent the end products of science without addressing how scientific knowledge is developed, classroom experiences with cookbook laboratory activities, teacher and societal language and misuse of words with special scientific meaning, and traditional classroom assessments (Clough, 2006). If NOS instruction is to be effective, teachers must be aware of the misconceptions students likely possess.

Teacher behaviors, activities, and language influence students' accurate understanding of NOS (McComas et al., 1998; Ryan and Aikenhead, 1992).

Students' views of the NOS are influenced by the way they are taught science, even if their teacher does not attempt to do so explicitly (Dibbs, 1982); hence it is important that science teachers accurately and explicitly portray the NOS throughout the school year. However, many teachers consistently use classroom behaviors, activities, and language that misrepresent NOS (McComas et al., 1998; Ryan & Aikenhead, 1992). Effectively teaching the nature of science and changing students' misconceptions requires that science teachers are not only aware of students' misconceptions but also use behaviors and language consistent with accurate portrayal of the nature of science throughout the year.

NOS instruction may be implicit or explicit and may also have a reflective character. Implicit instruction assumes NOS concepts will be accurately learned as a by-product of engagement in science-based activities. In contrast, explicit teaching of the NOS requires teachers to plan for the instruction of particular NOS concepts and draw students' attention to these concepts. For NOS instruction to be reflective, teachers must use pedagogical approaches that help students make connections between the classroom activities and the targeted NOS concepts (Clough, 2006). When trying to change students' conceptions of the NOS, research has shown implicit NOS instruction to be less effective than explicit instruction; NOS instruction that has both an explicit and reflective character is most effective (Abd-El-Khalick & Lederman, 2000; Abd-El-Khalick et al., 1998; Akerson, Abd-El-Khalick, & Lederman, 2000; Clough, 2006; Khishfe & Abd-El-Khalick, 2002).

Explicit and reflective instruction may include both contextualized and decontextualized activities. Contextualized and decontextualized instructional activities play different, but important, roles in NOS instruction (Clough, 2006). Decontextualized NOS activities are used to explicitly introduce and draw students' attention to important NOS ideas without being integrated into the context of specific science content (Clough, 2006). Examples of decontextualized NOS activities include, among others, black-box activities, discrepant events, puzzle solving activities, and pictorial gestalt switches (Clough, 1997; Clough, 2006; Lederman & Abd-El-Khalick, 1998). Use of such decontextualized NOS activities provide important opportunities to encourage students to internalize NOS concepts without simultaneously struggling with complex science concepts (Clough, 2006; Lederman & Abd-El-Khalick, 1998).

Several limitations apply to the use of decontextualized NOS activities. First, such activities may not match students' perceptions of authentic science. This may lead students to create two alternative conceptions of NOS; one for these types of NOS activities and one for authentic science (Clough, 2006). In such a situation, no conceptual change will have occurred. Second, teachers often perceive decontextualized NOS activities as additions to their curriculum that take away time from science content instruction, thus making them less likely to be utilized (Clough, 2006; Abd-El-Khalick et al., 1998). Finally, although decontextualized activities are important for drawing students' attention to specific NOS issues and making analogies to authentic science, alone they are

insufficient for students to develop an accurate and deep understanding of NOS (Clough, 2006).

As opposed to decontextualized activities, contextualized NOS activities explicitly draw students' attention to NOS issues embedded within science content and the development of scientific knowledge. "Inescapably, highly contextualizing the NOS means integrating historical and contemporary science examples that are tied to the fundamental ideas taught in particular science subjects" (Clough, 2006 p. 474). Highly contextualized NOS lessons are necessary for: demonstrating the human side of science and the development of science content ideas, demonstrating challenges scientists face while constructing new ideas, and illustrating important epistemological and ontological lessons integral to the content and understanding NOS (Clough, 2006). By drawing students' attention to such considerations, the use of highly contextualized NOS activities may lead to better understanding of both content and NOS ideas.

Students' perspectives of the NOS and the ability to apply their understanding to other situations are partially dependent on the science content and context framing NOS discussion (Abd-El-Khalick, 2001; Brickhouse, Dagher, Letts, & Shipman, 2000; Driver et al., 1996; Ryder, Leach, & Driver 1999). Thus, highly contextualized activities are necessary for students to develop a deep understanding of NOS ideas that are transferable to new situations (Clough, 2006). If highly contextualized NOS activities are only occasionally used, students will likely only apply NOS concepts to very specific examples. To

prevent students from narrowly applying NOS concepts, highly contextualized NOS activities must be continuously integrated throughout a science course in multiple contexts (Clough, 2006).

Students are more likely to undergo conceptual change regarding their misconceptions of the NOS when several conditions are applied to NOS instruction. First, NOS instruction should scaffold back and forth between decontextualized and contextualized activities (Clough, 2006). Such instruction provides students opportunities to learn and reinforce NOS concepts without struggling to learn complex science content simultaneously, and also provides opportunities to relate specific NOS concepts to the development of scientific ideas taught throughout the course. Additionally, NOS concepts must not be reduced to a list of tenets to be memorized. Clough (2007) argues:

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

When NOS concepts are reduced to tenets, the goal of students may become accurate recitation of the tenets rather than understanding, explaining, or applying the key concepts. For students to deeply understand the NOS, and thus undergo conceptual change, they must explore the contextual nature of the NOS. This cannot be accomplished by memorizing tenets. Rather, Clough (2007) promotes turning NOS tenets into questions for students and teachers to deeply investigate. Examples include: “In what sense is scientific knowledge tentative? In what sense is it durable?” and “ To what extent are scientists and scientific

knowledge subjective? To what extent can they be objective?" (Clough, 2007, p.3). By utilizing contextualized examples from the history of science to investigate NOS concepts with their teachers, students are more likely to deeply understand the NOS and undergo conceptual change.

The Role of History of Science (HOS) in NOS Instruction

Integrating the instruction of HOS into content instruction can be effectively used as highly contextual NOS instruction, and has long been advocated in science education (AAAS, 1990; Bybee et al., 1991; Cough, 2006; Conant, 1957; Eichman, 1996; Hagen, Allchin, & Singer, 1996; Klopfer & Cooley, 1963; Russell, 1981; Stinner, McMillan, Metz, Jilek, & Klassen, 2003). Research indicates that historically contextualized instruction may have a variety of positive impacts on science instruction. Student understanding of both the NOS (Brush, 1989; Irwin, 2000; Solomon, Scott, & Duveen, 1996) and science content (Galili & Hazen, 2000) are increased and enriched (Clough, 2006; Klassen, 2006; Jung, 1994). Additionally, science teaching is enlivened (Castro & DeCarvalho, 1995) and student attitudes towards science improve with the inclusion of historical instruction (Allchin, Anthony, & Bristol, 1999). However, not all studies show that incorporation of HOS leads to increases in students' NOS understanding. The most effective studies utilized an explicit approach to teaching the NOS (Abd-El-Khalick & Lederman, 2000).

According to Clough (2006), multiple approaches for incorporating HOS have been advocated in the research. Such approaches include:

1. utilizing historical case studies (Conant, 1957; Klopfer, 1964; Matthews, 1994).
2. adding significant historical components in the curriculum (Cassidy, Holton, & Rutherford, 2002; Lin & Chen, 2002; Rutherford, Holton, & Watson, 1970).
3. addressing misleading textbook accounts of science content (Rudge, 2000).
4. integration of historical short stories into the content (Clough, 1997; Hagan et al., 1996; Leach, Hind, & Ryder, 2003; Solomon et al., 1992; Tao, 2003).
5. utilization of short historical vignettes reflecting the lives of scientists (Monk & Osborne, 1997; Wandersee, 1992).

Martin and Brouwer (1991) argue that science narrative stories are particularly useful for humanizing science instruction:

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

Although a long history of materials created for teachers to incorporate history and philosophy of science (HPS) into the curriculum exists, these materials have not always been successfully implemented in the classroom

(Monk & Osborn, 1997). Several factors influence whether HPS materials will be successfully implemented. Teachers often do not recognize NOS instruction as necessary (Abd-El-Khalick et al, 1998; Lederman, 1998), and feel time spent on explicit NOS and HPS instruction is time taken away from teaching science content. Teachers do not use HPS activities if they are perceived as add-on material. Materials must be integrated into the content curriculum and take little time if teachers are to implement them (Monk & Osborn, 1997). Therefore, longer approaches for integrating HPS into the science classroom, such as extensive case studies and significant historical components in the curriculum, are often not used.

Tao (2003) identified another potential problem when implementing historical narratives as a method of teaching the NOS. Tao (2003) found that students often do not interpret and make sense of stories as intended by the instructor. Science stories may influence students' views of the NOS in several ways. The stories may confirm and reinforce students' already adequate views of the NOS, change students' views of the NOS, or confirm and reinforce students' inadequate views of the NOS. Many students in Tao's (2003) study "interpret the science stories in idiosyncratic ways other than that intended by the instruction" (p. 168). Without guidance from the teacher, students selectively focus their attention to portions of the stories that match their prior views of the NOS. Hence the stories serve to confirm students' misconceptions of the NOS more often than changing them to more accepted views (Tao, 2003). For narrative stories to be successfully used as an instructional method for teaching

an accurate understanding of the NOS, the stories and teachers must make the intended NOS instruction explicit. Instructors must not assume students will correctly interpret NOS concepts implicit within scientific narratives.

Summary

Nature of science instruction is necessary for forming a scientifically literate citizenry, improve student understanding of science content, and improve students' attitudes towards science. However, not all methods of NOS instruction are effectively implemented or effective for changing students' inadequate views of the NOS. Effective NOS instruction must be explicit and reflective in character, utilized throughout the course, and scaffold between both decontextualized and contextualized activities. Integration of history of science is necessary for contextualizing NOS instruction into the science content. HOS also provides students opportunity to learn about the social and humanistic side of science, which has been shown to increase student interest in science content and careers.

For widespread use of NOS instruction by secondary science teachers, it is essential that activities are perceived as being highly integrated with the content and not requiring extensive time be taken from content instruction. Short historical narratives focused on specific scientists or the development of specific scientific ideas may provide a type of medium secondary teachers would use to teach NOS in their science classes. Such narratives are, by nature, highly

contextualized with science content already viewed as important by teachers. If the narratives are kept short, teachers may not object to the use of class time needed to utilize these activities. Instruction utilizing these narratives may have an explicit/reflective character if comments and questions are embedded within the narrative to explicitly draw students' attention to important NOS ideas.

Clough et al. (2006) have developed short historical narratives with embedded questions and comments explicitly drawing students' attention to key NOS concepts for use in post-secondary science classes. However, it still needs to be seen if the utilization of such narratives in secondary science classes will positively impact secondary students' accurate understanding of the NOS.

CHAPTER 3: RESEARCH METHODOLOGY

Study Context

The study took place in a tenth-grade introductory biology course taught at a high school located in a small suburban city in the Midwest region of the United States. The student population of this school was very homogeneous; more than 95 percent of the population was of Caucasian decent and less than ten percent received free or reduced lunch. The school operated with eight 43-minute class periods daily and an additional thirty minute advisement period prior to lunch. Classes utilized in this study met five days a week during a forty-three minute period.

The introductory biology course is required for high school graduation, and the age of students in the course ranged from fourteen to eighteen. For most students, the class was preceded by a ninth grade physical science course. However, several students were accelerated following eighth grade, transitioning directly into introductory biology as freshmen. The classes also included several juniors and seniors repeating the course.

The school offered ten sections of the course, and this study utilized four sections taught by the researcher. By the flip of a coin, two of the four classes were designated the treatment group and the other two classes were designated the control group. The treatment groups consisted of a morning class with 23 students and an afternoon class with 18 students. The control groups consisted of a morning class with 26 students and an afternoon class with 12 students.

Study Participants

The study was described to potential participants the week following completion of the post-test. An informed consent form, found in Appendix A, was also provided to students at this time. Students were informed that their voluntary participation in the study simply permitted their pre and post questionnaire results and survey responses to be anonymously utilized for data analysis in the study. Grades had previously been recorded for completion of the reading questions and questionnaires as in-class activities. Students were informed all names would be removed from the questionnaires prior to analysis and all data analysis would occur following the completion of the school year; choosing to participate or not in the study would have no impact on their course grades. Students and their parents were provided contact information for the researchers involved in the study and encouraged to ask questions about the study or participation. Students were provided up to three weeks to return the consent form with both student and parent or guardian signatures.

A total of 79 students were originally enrolled in the four sections of the course utilized during the study. Seven students either dropped the class or left the school. One student in both the control and treatment groups failed to complete either the pre or post test; this data was removed from the study. Of the 70 students eligible to participate, three students in the control group and four students in the treatment group failed to return signed consent forms. The sample size was 63 out of a possible 70 students.

The Instructor

At the time of the study, the participating classroom teacher was completing her sixth year as a high school biology and chemistry teacher. The teacher earned a B.S. degree in biology with a chemistry minor and had previously completed all course work required for earning a M.S. degree in education. Graduate level course work included courses on the nature of science, advanced science pedagogy, and the application of learning theories to science education. The NOS course focused not only on developing an accurate understanding of the NOS, but also on the application and impact of NOS on science education and appropriate pedagogy for utilizing NOS activities in the classroom. Through work in the NOS course the teacher became passionate about using and researching effective integration of NOS into the classroom.

Treatment

Instruction during the spring 2009 semester was led by the researcher who was employed full-time by the school district and a student teacher under the researcher's guidance. The semester included units of study in DNA structure and function, genetics, biological evolution, and ecology each lasting approximately four weeks. All four class periods received the same instruction except in relation to the readings pertaining to this study used during the genetics and biological evolution units. During these units of study, both the treatment and control groups completed two readings about the lives and work of Mendel and Darwin as in-class activities.

These two topics were selected for use in the project because they fit into the second semester curriculum for the course, which included units on genetics and biological evolution. In all four classes, the teacher-researcher directed instruction of the reading activities and class discussions.

To reduce the impact of other treatment variables, the instructor limited NOS instruction throughout the school year compared to prior years. Prior to completion of the post NOS assessment, NOS instruction during the spring semester was restricted to utilization and discussion of the Mendel and Darwin readings and embedded questions. Instruction early in the fall semester included limited NOS instruction. This instruction was primarily focused on understanding what differentiates science from other ways of knowing about the world, what constitutes a scientific explanation, why scientific explanations must be naturalistic rather than invoking supernatural forces, limits of scientific knowledge, and the subjectivity of interpretation when drawing conclusions from evidence. However, roughly one third of the students changed instructors between semesters. Thus, students participating in this project did not have consistent prior NOS instruction.

The instructor attempted to reduce any bias introduced to the study due to the teacher-researcher's involvement in the instruction and collection of data in several ways. First, the instructor randomly assigned class periods to treatment or control groups by the flip of a coin. The assignment process was observed by a student teacher who had no investment in the outcome of this study. Second, NOS instruction was limited in all class periods to discussion of the readings and embedded questions. Thus, the chance of providing additional NOS instruction to

the treatment group was reduced. Third, instruction in all class periods was the same except in respect to the particular readings utilized for this study. Additionally, except for utilization of the study readings, class instruction during these two units was primarily led by the student teacher. Therefore, any other implicit NOS instruction would be the same for both groups as the student teacher had no personal investment in the results of this study.

Instructional Materials

While the topics of the two readings in both the treatment and control groups were the same, the structure of the readings was not. The Mendel and Darwin readings used in the treatment group were modified stories from an NSF project directed at post-secondary introductory science courses (Clough, et. al., 2006). These stories (available at <http://www.storybehindthescience.org>) teach science content and overtly draw students' attention to accurate features of nature of science (Clough, 2009). However, because these project stories were written for students at the post-secondary level, modifications (e.g. reducing the length of the stories, simplifying language, and adding additional questions) were made so that the stories were appropriate for secondary school science students. The modified stories appear in Appendices B and C.

The control group completed two different readings about the life and work of Mendel and Darwin. These readings, found in Appendices D and E, are comprised of selected excerpts from online exhibits at The Field Museum and the American Museum of Natural History. The Field Museums' online exhibit, Gregor Mendel:

Planting the Seeds of Genetics (www.fieldmuseum.org/mendel), was the source of excerpts for the control group's reading about the life and work of Mendel. Excerpts from The American Museum of Natural History's online exhibit, Darwin (www.amnh.org/exhibitions/darwin/), were utilized in creating the control group's reading about the life and work of Charles Darwin. As with the treatment group, the control group's readings contained integrated questions written by the teacher-researcher. However, the control group's questions focused on science content and did not explicitly address fundamental NOS ideas.

The control readings discuss the work of scientists from a historical perspective. As such, the readings cannot avoid implicitly addressing the NOS. The control readings implicitly portray a number of NOS concepts accurately. Both the Mendel and Darwin readings portray the development and acceptance of new scientific ideas over extended periods of time and scientific ideas changing over time. Both control readings also provide examples of scientists who are religious, demonstrating that science and religion do not have to be at odds. The two control readings also implicitly reinforce several common misconceptions about the NOS. As with most textbooks and readings developed for the general public, the control readings misrepresent the role of scientists' creativity and interpretation when analyzing data. For example, the Mendel reading states, "In later generations the recessive traits reappeared – and in a mathematically predictable pattern. For example, later generations of plants had one green pea for every three yellow peas. The same ratio appeared for all several pairs of traits.", and "As in his initial experiments, the traits appeared in predictable ratios. This told Mendel that the

elements governing traits were not linked, but passed separately to the offspring.”

These quoted statements do nothing to draw students' attention to the creativity and interpretation required during data analysis. Additionally, these statements imply Mendel's data contained exact 3:1 ratios of dominant to recessive phenotypes rather than demonstrating how Mendel had to interpret his data which never contained exact 3:1 ratios. The use of statements such as, “This told Mendel that the elements governing traits were not linked” in the Mendel reading, and “Thus, a single fossil could tell the story of a slowly changing landscape” in the Darwin reading, portray data as “telling” scientists what to think. The role of interpretation and drawing inferences during the process of reaching conclusions is not portrayed in either control reading.

In contrast, the treatment stories very explicitly draw the readers' attention toward a variety of NOS concepts and more accurately portray the role of data, creativity, and interpretation in science. Bolded statements and questions within the treatment stories overtly draw attention to the following NOS concepts: scientific ideas build on the work of previous scientists; science and religion do not have to be at odds; scientific ideas are tentative and may change over time; scientists are influenced by the culture in which they exist; new scientific ideas often take long periods of time to develop and to be accepted by the scientific community; there is no single scientific method and not all scientific ideas are developed using controlled experiments; science does not permit the use of supernatural explanations; data must be interpreted, thus, data analysis is subjective; science is a creative endeavor. The misconception implicitly portrayed in the control readings, that scientific data

“tells” scientists what to believe, is very explicitly countered in the Mendel treatment story. Exerts from Mendel’s actual data are utilized to demonstrate that Mendel had to use creativity and infer the existence of specific whole number ratios. The bolded statements and questions are incorporated into the story to explicitly draw the reader’s attention to the subjectivity and creativity required during the process of data interpretation. For example, the following statement, “Mendel wasn’t fudging his data. Scientists must make sense of data, and this requires making judgments when interpreting data, because data doesn’t tell scientists what to think” and the question, “How does Mendel’s work illustrate that observation and data analysis is not objective, but is subjective and influenced by their expectations and their perceptions of the world?” specifically draw students’ attention to this complex NOS concept.

Pedagogical Implementation Practices

Instruction of each story involved in-class work over two to three 43 minute class periods. Prior to reading the stories, the teacher-researcher orally provided background information and projected images of the scientists and some of the places each scientist worked. The introductory information and images used were the same in each of the four classes. Use of the images and discussion was intended to assist students in creating mental images while they read and provide a contextual setting to the readings.

Following the class introduction, students were divided into small groups of three to five students. To assist students with lower reading abilities, each small

group read the story aloud and students worked together to discuss and answer the integrated questions. To maintain students' attention to the readings and questions, the teacher-researcher and student teacher circulated through the room, redirected students' attention to the assignment when off task, and clarified questions students had about the reading. The last ten to fifteen minutes of each class period were spent in instructor-led whole-class discussion of the reading questions every group had answered. This instructional pattern was followed for two days while students completed each reading. A portion or all of a third class period was spent completing whole class discussion of the readings and questions. Any students missing one or more days of instruction were required to meet with the teacher-researcher outside of class time to discuss the reading and their answers to the questions.

Earlier in the school year, the teacher had developed an open, safe, and respectful environment for students to share and discuss their ideas. By the time of the study, students were typically comfortable sharing their ideas in small groups and with the class, discussing and debating the merits of ideas presented in class, and treating everyone's ideas with respect. The teacher typically asked open-ended and extended response questions during the class discussions of both the control and treatment Mendel and Darwin readings. To promote sharing of ideas from all students, the teacher utilized encouraging and expectant nonverbal behaviors and intonations. Student responses were not judged by the teacher. Instead, the teacher accepted all student ideas offered. In order to draw out and clarify students'

understanding, the class was often asked to elaborate on an idea, provide evidence for an idea from the reading, or tie their ideas to other aspects of the reading.

Assessment Instruments

A number of high quality instruments are available for measuring students' understanding of the NOS. Two of the most popular include the Views on Science-Technology-Society (VOSTS) (Aikenhead & Ryan, 1992), and the Views of the Nature of Science Questionnaire (VNOS) (Lederman et al., 2002). However, both the VOSTS and the VNOS have limitations to their usefulness. The VOSTS is an empirically-based instrument in which students read a statement about a science-technology-society topic and then choose the student position that best fits their point of view from a multiple choice list. The student positions in the VOSTS were developed from analyzing the written responses of 11th and 12th grade Canadian students about the relationships between science, technology, and society. The strength of the VOSTS lies in the use of empirically derived student positions rather than researcher developed positions (Aikenhead & Ryan, 1992). However, because the responses were empirically based on student positions, for some items no fully accurate response exists. In addition, Chen (2006a) claims several other shortcomings with the VOSTS instrument:

- a. students may have a viewpoint that combines several of the student positions available in the multiple choice responses.
- b. "it contains oversimplified, overgeneralized statements" (p. 804).

- c. because of ambiguous statements that may be chosen for different reasons, it “sometimes creates different interpretations between researchers and subjects” (p. 804).
- d. some responses had overlapping meanings, and thus were redundant.

The VNOS, composed of ten open-ended questions, takes a more qualitative approach to determining students' views on the nature of science. The VNOS is limited in its usefulness due to the time required to complete the questionnaire and its written format. “It is challenging to participants to fully articulate their views in 40-60 minutes, and it is difficult for researchers to gain the intended information from every participant” (Chen, 2006a).

For these reasons, in this study the Views on Science and Education Questionnaire (VOSE; Chen, 2006a) was utilized to determine students' views on several NOS issues. The VOSE was developed in response to the limitations of the VNOS and VOSTS. Chen (2006a) states, “all efforts have been made to develop a pencil and paper assessment tool... aimed at increasing validity and minimizing interpretation biases” (p. 805). The VOSE is a valid and reliable instrument based on select VOSTS items considered particularly relevant to secondary science education. Seven aspects of NOS addressed by the VOSE include: tentativeness of scientific knowledge; nature of observation; scientific methods; hypotheses, laws, and theories; imagination; validation of scientific knowledge; and objectivity and subjectivity in science. The VOSE includes fifteen questions: ten questions addressing the seven NOS aspects listed above and an additional five questions examining teachers' attitudes toward teaching NOS concepts. A variety of responses

appear under each of the fifteen questions , and participants respond to each using a five-point Likert-scale that ranges from strongly disagree to strongly agree (See Figure 1).

VOSE items remove the over-generalized and redundant statements appearing on the VOSTS instrument, and it clarifies ambiguous statements from the VOSTS items. Additionally, the VOSE may detect a subject's conflicting viewpoints about a NOS concept by utilizing contextualized questions (Chen, 2006a). Although the VOSE items were field tested with university students, they were based on VOSTS items empirically derived from the writings of high school students. As such, the VOSE items are arguably suitable for use with high school students.

2. Scientific investigations are influenced by socio-cultural values (e.g. society's current trends, values).					
A. Yes, socio-cultural values influence the direction and topics of scientific investigations.	SD	D	U	A	SA
B. Yes, because scientists participating in scientific investigations are influenced by socio-cultural values.	SD	D	U	A	SA
C. No, scientists with good training will remain value-free When carrying out research.	SD	D	U	A	SA
D. No, because science requires objectivity, which is contrary to the subjective socio-cultural values.	SD	D	U	A	SA

Figure 1: VOSE question 2 (Chen, 2006b).

Views on Science Questionnaires

In this study, all students' understanding of the NOS was assessed prior to the beginning of the genetics unit and again following the unit on biological evolution, approximately nine weeks apart. The Views on Science Questionnaire 1 (VSQ1) and Views on Science Questionnaire 2 (VSQ2), developed by Clough et al. (2006),

were used to evaluate students' understanding of the NOS; both are located in Appendix F. The VSQ1 contains eight questions selected from the VOSE (Chen, 2006b). The specific NOS ideas addressed by the VSQ1 can be found in Table 1. The VSQ2 contains three additional questions using the VOSE format; questions from the VSQ2 were developed to address NOS concepts not included in the VOSE. Specific NOS ideas addressed by the VSQ2 can be found in Table 2.

Table 1. NOS concepts assessed by each of the VSQ1 questions.

VSQ1 Question # and NOS Concept	Explicit in the Treatment Stories
1. influence of socio-cultural values on science	Yes
2. use of imagination / creativity in science	Yes
3. the tentative nature of scientific theories	No
4. discovery vs. invention of scientific theories	No
5. discovery vs. invention of scientific laws	No
6. relationships between scientific laws and theories	No
7. influence of personal beliefs on scientists' observations	Yes
8. multiple methodologies utilized in science	Yes

Table 2: NOS concepts assessed by each of the VSQ2 questions.

VSQ2 Question # and NOS Concept	Explicit in the Treatment Stories
1. collaboration of scientists	No
2. development of conclusions from data interpretation	Yes
3. time required for the development and acceptance of scientific ideas	Yes

The questions in the VSQ1 were taken from the VOSE, a field-tested instrument. As such, these eight questions have published reliability and validity statistics. Chen (2006b) reports that for all except two of the 85 VOSE items, more than 90 percent of the interviewees interpreted the items consistently with researchers and experts. Thus, Chen (2006b) argues the VOSE is a valid instrument. Cronbach's alphas are widely used for measuring internal consistency reliability of an instrument. An alpha coefficient of 0.7 or higher is typically considered adequate reliability (Kline, 2009). Although the Chronbach's alphas ranged from 0.34 to 0.81 for the VOSE items, Chen (2006b) asserts the instrument is reliable because the items were empirically based on respondents' viewpoints. A test-retest correlation coefficient of 0.82 provides additional support to Chen's argument that the VOSE is a reliable instrument (Chen, 2006b). Because the questions contained in the VSQ2 have not been field tested, items in the VSQ1 were analyzed separately from items in the VSQ2.

VSQ1 and VSQ2 questions were utilized because they address several of the NOS concepts addressed in the Mendel and Darwin NSF project short stories (Clough, et al., 2006). Not all NOS topics included in the VSQ1 and VSQ2 were explicitly addressed by the bolded comments and questions embedded into the two treatment group stories. Information about which VSQ1 and VSQ2 NOS concepts were explicitly addressed in the two treatment stories appear in Table 1 and Table 2, respectively.

Interest Survey

Following completion of the post test, students in the treatment group completed an interest survey about their perceptions of the two stories. The interest survey questions, found in Appendix F3, are primarily Likert-style items with scores ranging from 1 to 5. A section for students to make comments about the readings was included following the Likert-style items. The survey was utilized to determine students' interest in the stories, their preferences for the stories compared to textbook readings, and their perception of how the stories impacted their understandings of science and how it works.

Data Analyses

Research Question 1

Student responses to Likert-style items on the VSQ1 and VSQ2 were given numerical values, with a score of 5 representing the most informed view of NOS and

a 1 the least informed view. Scores for each of the item responses were added to provide a total score for each NOS component. VSQ1 questions 4 and 5 were combined to form a theory/law epistemology component, as recommended by Chen (2006a). The score ranges for each NOS component are found in Table 3.

Students' pre and post data for the VSQ1 and VSQ2 were entered into SPSS. Three separate MANCOVA were utilized to compare treatment group and control group post NOS understanding for the VSQ1 concepts addressed explicitly, non-explicit VSQ1 concepts, and VSQ2 concepts. Students' pre scores on the VSQ1 and VSQ2 were included as covariates to adjust for the preexisting differences between the treatment and control groups. Each of the three MANCOVA tested one of the following null hypotheses:

1. no significant differences between treatment and control groups' post scores on the combined explicit VSQ1 NOS components exist.
2. no significant differences between treatment and control groups' post scores on the combined non-explicit VSQ1 components exist.
3. no significant differences between the treatment and control groups' post scores on the combined VSQ2 components exist.

Subsequent ANCOVA analyses were then conducted on individual NOS component scores to determine significance of treatment and control group differences (Tabachnick & Fidell, 2001).

Table 3: Possible scores for each NOS component.

NOS Component	Questions	Possible Score
<u>Explicit VSQ1 Components</u>		
Socio-cultural Influence	VSQ1 #1	20
Use of Imagination	VSQ1 #2	25
Subjectivity of Observations	VSQ1 #7	25
Scientific Methods	VSQ1 #8	60
<u>Non-Explicit VSQ1 NOS Component</u>		
Tentative Nature of Theories	VSQ1 #3	15
Theory/Law Epistemology	VSQ1 #4 and #5	55
Theory-Law Relationship	VSQ1 #6	20
<u>VSQ2 NOS Component</u>		
Collaborative Nature of Science	VSQ2 #1	25
Drawing Conclusions from Data	VSQ2 #2	25
Time for development / Acceptance	VSQ2#3	20

Research Question 2

The interest survey results were utilized to answer the second research question. Scores on Likert-style items were compared and results were analyzed to investigate students' interest in the historical short stories, preference for short stories versus textbook readings, the effect of the readings on students' interest in pursuing science careers, and students' perceptions about the impact of the stories on their understanding of science.

Assumptions and Limitations

Several assumptions and limitations exist in this study. The student population in the school where the study took place was very homogeneous. Thus, it was assumed no significant difference existed between students in the treatment and control groups. However, this may not be the case. Although each class period was assigned randomly to either control or treatment groups, students are not randomly assigned to class periods. Students' schedules are determined by the school counselors in an attempt to meet the multiple needs of each student. Differences in the distribution of special education students, accelerated and gifted students, and students repeating the course could cause significant differences between the groups. To address this concern, MANCOVA analyses including pre-test scores as a covariate were utilized.

The homogeneity of the student population may also limit application of this study's results to more diverse settings. Such high levels of student homogeneity do not exist in the majority of schools in the United States. As such, the results of this study may not be applicable to most schools. In addition, the small sample size and the use of the intervention in only one science discipline may also limit application of the results to other courses.

The length and intensity of the treatment intervention are another limitation of this study. The study was performed over a relatively short time period and included only two historical short stories — a relatively short intervention. Moreover, the stories focused on a limited number of the NOS ideas included on the questionnaires. Thus, results and conclusions drawn must be interpreted with

caution. A longer intervention addressing more aspects of the NOS may provide more reliable and generalizable results.

The pedagogical practices and NOS understanding of the teacher may add additional limitations preventing generalizable results of this study. The teacher had extensive instruction in pedagogy and NOS during graduate level classes. As such, her pedagogical behaviors and decisions may not be congruent with the typical high school science teacher. Additionally, the involvement of a teacher-researcher may introduce unintended researcher bias. In an attempt to reduce bias class periods were randomly assigned to treatment or control groups, NOS instruction during the study was limited to use and discussion of the readings, and the teacher limited her instructional involvement during the units on genetics and evolution.

CHAPTER 4: RESULTS

Introduction

Earlier portions of this thesis discuss the importance of nature of science instruction, the rationale for including NOS instruction in secondary science courses, and what research has previously illustrated about the elements of effective NOS instruction. This section discusses results of the study designed to answer the following research questions:

1. To what extent does the use of two historical short stories in a high school biology class increase students' accurate understanding of fundamental NOS concepts?
2. What do students who complete the two historical short stories express regarding:
 - a. their interest in reading the short stories compared to reading their science textbook?
 - b. their interest in reading about scientists and how science ideas are developed?
 - c. the impact of the readings on their interest in pursuing a science career?

To address the first research question, three Multiple Analysis of Covariance (MANCOVA) tests were performed using SPSS to compare the control and treatment groups' explicit VSQ1, non-explicit VSQ1 and VSQ2 post assessment scores. Subsequent to the MANCOVA analyses, Analysis of

Covariance (ANCOVA) analyses were conducted to determine the significance of differences between control and treatment groups' performance for individual NOS components (Tabachnick & Fidell, 2001).

Research Question 1

Instrument Reliability

Initial analyses included calculating reliability indices for the VSQ1 and VSQ2 instruments. Chronbach's alphas ranged from 0.266 to 0.875 for VSQ1 items. Chronbach's alphas ranged from 0.481 to 0.762 for VSQ2 items. The VSQ1 consisted of a subset of VOSE items. VOSE items were derived from empirically based Views on Society-Technology-Society (VOSTS) items. Chen (2006) argues "the commonly used internal consistency or Cronbach's alpha is not applicable to empirically-based instruments" (p. 3). Results from the VOSE items utilized in the VSQ1 may be considered reliable "because the items originated from the respondents' viewpoints instead of experts' presumptions of reasonable responses" (Chen 2006, p. 3).

Initial MANCOVA Analyses

Multiple analysis of covariance (MANCOVA) tests were used to analyze students understanding of the NOS as measured by the VSQ1 and VSQ2 assessments (Tabachnick & Fidell, 2001). Table 4 provides a summary of the VSQ1 and VSQ2 descriptive statistics.

Table 4. Descriptive statistics for VSQ1 and VSQ2 NOS component scores.

NOS Component	Control Pre (N = 30)		Treatment Pre (N = 31) ^a		Control Post (N = 30)		Treatment Post (N = 31) ^a	
	M	SD	M	SD	M	SD	M	SD
Socio-Cultural influence VSQ1 #1 Maximum Score = 20	10.93	3.65	12.81	3.26	12.80	3.64	14.07	3.20
Use of Imagination VSQ1 #2 Maximum Score = 25	14.00	5.49	14.84	4.42	13.67	4.31	17.13	4.09
Theory Tentativeness VSQ1 #3 Maximum Score = 15	9.13	1.50	9.32	1.96	9.27	1.68	9.87	2.40
Theory/Law Epistemology VSQ1 #4 and #5 Maximum Score = 55	31.57	6.07	32.00	7.18	30.93	6.40	33.32	5.99
Theory/Law Comparison VSQ1 #6 Maximum Score = 20	9.73	2.78	10.52	2.89	10.50	2.93	10.87	2.67
Nature of Observations VSQ1 #7 Maximum Score = 25	14.83	1.60	15.10	1.99	15.07	1.57	15.52	1.93
Scientific Methods VSQ1 #8 Maximum Score = 30	15.13	2.54	15.90	3.94	15.93	3.40	18.03	3.54
Collaborative Nature VSQ2 #1 Maximum Score = 25	19.33	2.63	18.32	3.24	18.80	2.27	18.00	3.22
Nature of Data VSQ2 #2 Maximum Score = 25	17.17	2.55	17.36	2.71	17.00	1.88	18.61	2.33
Time for New Ideas VSQ2 #3 Maximum Score = 20	14.97	2.63	15.32	2.34	16.00	2.58	16.74	2.08

a. Two participants were removed from the treatment group data as outliers on multiple components. (Tabachnick & Fidell, 2001).

Initial MANCOVA analyses resulted in significant differences between the control and treatment groups for both the combined explicitly addressed VSQ1 components ($F(4, 52) = 3.803$, $p = 0.009$, Wilks' Lambda = 0.774, partial eta squared = 0.226) and for the combined VSQ2 items ($F(3, 54) = 3.398$, $p = 0.024$, Wilks' Lambda = 0.841, partial eta squared = 0.159). No significant differences between control or treatment group existed for the combined non-explicit VSQ1 components ($F(3, 54) = 0.867$, $p = 0.464$, Wilks' Lambda = 0.945, eta squared = 0.046). Results for each of the three MANOVAs are summarized in Table 5.

Table 5. Summary of MANCOVA multivariate test results.

Dependent Variable	DV components	Wilk's Lambda	F	Sig	Partial Eta Squared
Non-explicit VSQ1	Theory/Law Epistemology Tentative Nature of Theories Theory/Law Comparison	0.945	0.867 (3, 54)	0.464	0.046
Explicit VSQ1	Methodologies of Science Effect of Socio-cultural Values Use of Imagination Effect of Beliefs on Observations	0.774	3.803 (4, 52)	0.009**	0.226
VSQ2	Collaboration of scientists Conclusions from data interpretation Time required for scientific ideas	0.841	3.398 (3, 54)	0.024*	0.159

* significant at $p < 0.05$

** significant at $p < 0.01$

Subsequent ANCOVA Analyses

Subsequent ANCOVA analyses were conducted separately for the non-explicit VSQ1 components, explicit VSQ1 components, and VSQ2 components.

Although the MANCOVA results indicate no significant differences for the non-explicit VSQ1 components, information on significant differences in individual components could be useful for future studies. As expected, ANCOVA analyses indicate no significant differences for any of the three non-explicit VSQ1 components; results are summarized in Table 6.

Table 6. ANCOVA test of between-subjects effects for non-explicit VSQ1 components.

Dependent Variable	DF	Error DF	Mean Square	F	Sig.	Partial Eta Squared
Theory/Law Epistemology	1	56	66.853	2.054	0.157	0.035
Tentative Nature of Theories	1	56	3.597	0.824	0.368	0.015
Theory/Law Comparison	1	56	0.987	0.126	0.724	0.002

Table 7 presents ANCOVA results from subsequent analyses of the four explicit VSQ1 components as separate dependent variables. To adjust for increases in type I error due to multiple testing in subsequent ANCOVA analyses, p values are commonly adjusted using Bonferroni corrections. If utilizing Bonferroni corrections, the p values for the explicit VSQ1 components should be adjusted to 0.0125. Only the imagination component showed significant differences between groups at this level ($F = 11.448$, $p = 0.001$, partial eta squared = 0.172). However, even among statisticians, no consensus exists as to when Bonferroni adjustments should be applied (Nakagawa, 2004; Perneger, 1998; Royall, 1997). Bonferroni corrections

may increase the likelihood of type II error to unacceptable levels, such that “truly important differences are deemed non-significant” (Perneger, 1998, p.1236). The decrease in power to reject an incorrect null-hypothesis is increased with small sample size (Nakagawa, 2004). Because this is a preliminary study designed to determine if there may be a significant impact on students’ NOS understanding and due to the relatively low sample size it may be appropriate to disregard the Bonferroni corrections, setting significance at $p < 0.05$. Under these constraints, the component for methodologies of science also resulted in significant differences ($F = 5.671$, $p = 0.021$, partial eta squared = 0.093). Results for both the effect of socio-cultural values ($F = 0.367$, $p = 0.547$, partial eta squared = 0.007) and effects of beliefs on observations ($F = 0.0128$, $p = 0.722$, partial eta squared = 0.002) components indicate no significant differences between groups.

Table 8 presents ANCOVA results from subsequent analyses of the three VSQ2 components as separate dependent variables. To adjust for multiple testing in subsequent ANCOVA analyses, p values for the explicit VSQ1 components should be adjusted to 0.0166 using Bonferroni corrections. Of the three components, only the drawing conclusions from data component ($F = 9.351$, $p = 0.003$, partial eta squared = 0.143) had significant differences between groups. Results indicate no significant differences existed between groups for either the collaboration of scientists component ($F = 0.669$, $p = 0.417$, partial eta squared = 0.012) or the time required for scientific ideas component ($F = 1.039$, $p = 0.313$, partial eta squared = 0.018).

Table 7. ANCOVA test of between-subjects effects for explicit VSQ1 components.

Dependent Variable	DF	Error DF	Mean Square	F	Sig.	Partial Eta Squared
Use of Imagination	1	55	133.302	11.448	0.001**	0.172
Effect of Socio-cultural Values	1	55	4.039	0.367	0.547	0.007
Effect of Beliefs on Observations	1	55	1.040	0.013	0.722	0.002
Methodologies of Science	1	55	64.637	5.671	0.021*	0.093

* significant at $p < 0.05$

** significant at $p < 0.01$

Table 8. ANCOVA test of between-subjects effects for VSQ2 components.

Dependent Variable	DF	Error DF	Mean Square	F	Sig.	Partial Eta Squared
Collaboration of scientists	1	56	4.099	0.669	0.417	0.012
Nature of Data	1	56	38.462	9.351	0.003*	0.143
Time required for scientific ideas	1	56	4.662	1.039	0.313	0.018

* significant at $p < 0.01$

Research Question 2

Following the completion of the two units of study and the NOS post assessments, students in the treatment group completed an attitude and interest survey about the two short stories they read. Students were surveyed about how interesting they found the stories, their perceptions on how the stories changed their

views of science, their preference for the stories versus textbook readings, and how the stories impacted their interest in a science career. Table 9 summarizes the results of this survey. Twenty students took the opportunity to write comments about the stories in the space provided at the bottom of the survey. These comments are listed in Table 10 of Appendix G.

Students' Interest in the Stories

Interest ratings for the two stories were on a five point scale, ranging from very uninteresting (1) to very interesting (5). Most participants did not rate either story as interesting or very interesting. Figure 2 depicts students' interest ratings for each of the two short stories. Less than 21 percent of students rated the Mendel story interesting while 25 percent of students rated the Darwin story as either interesting or very interesting. However, a much larger percentage of students rated the two stories as more interesting or much more interesting than reading a textbook. Figure 3 depicts students' rating of the interestingness of the short stories compared to textbook readings. 68.75 percent of students rated the stories as more interesting or much more interesting than reading their textbooks. When students were asked how many short stories they would like to replace textbook readings in the class, less than 16 percent reported wanting to use no short stories. Over 84 percent of the students surveyed would like some short stories utilized in class to replace textbook readings; more than 40 percent of the students wanted one to two stories and more than 43 percent of the students wanted three to four stories to

replace textbook readings. Figure 4 illustrates students' preference for short stories to replace textbook readings.

Table 9. Summary of the treatment group's interest survey results showing percentage of students (N=32) choosing each response.

Question 1: Please use the following scale to rank how interesting you found the short story about Mendel.					
	1	2	3	4	5
	Very uninteresting		Neutral		Very interesting
% of students	22	19	37	22	0
Question 2: Please use the following scale to rank how interesting you found the short story about Darwin.					
	1	2	3	4	5
	Very uninteresting		Neutral		Very interesting
% of students	13	9	53	22	3
Question 3: To what extent did the short stories teach you something new about how science works?					
	1	2	3	4	5
	Not at all		Some what		Very much
% of students	6	9	41	38	6
Question 4: To what extent did the short stories change some of your views regarding how science works?					
	1	2	3	4	5
	Not at all		Some what		Very much
% of students	19	28	28	22	3
Question 5: To what extent did you find the short stories to be more interesting than readings from your textbook?					
	1	2	3	4	5
	Much less interesting		No difference		Much more interesting
% of students	16	6	9	38	31
Question 6: If short stories were to replace class readings from the textbook, how many of these short stories would you like as part of your class?					
	None	1-2	3-4	5+	
% of students	15	41	44	0	
Question 7: To what extent did the short stories impact your interest in science as a career?					
	1	2	3	4	5
	Reduced interest		No impact		Increased interest
% of students	16	6	59	13	6

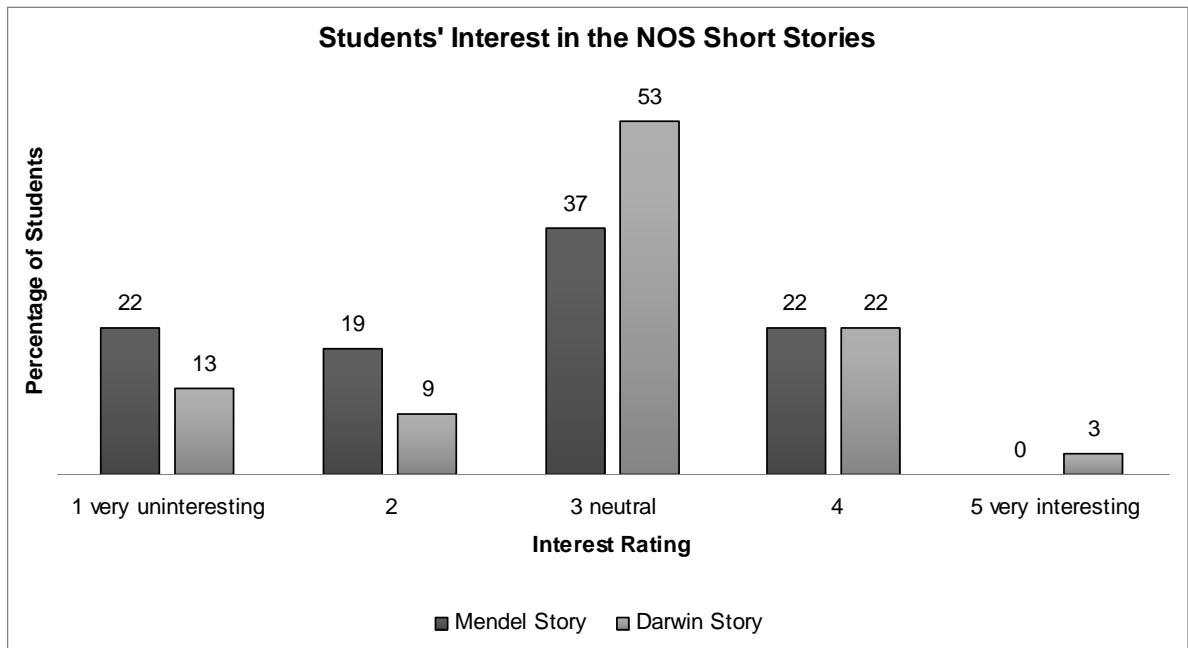


Figure 2: Summary of responses to survey questions 1 and 2.

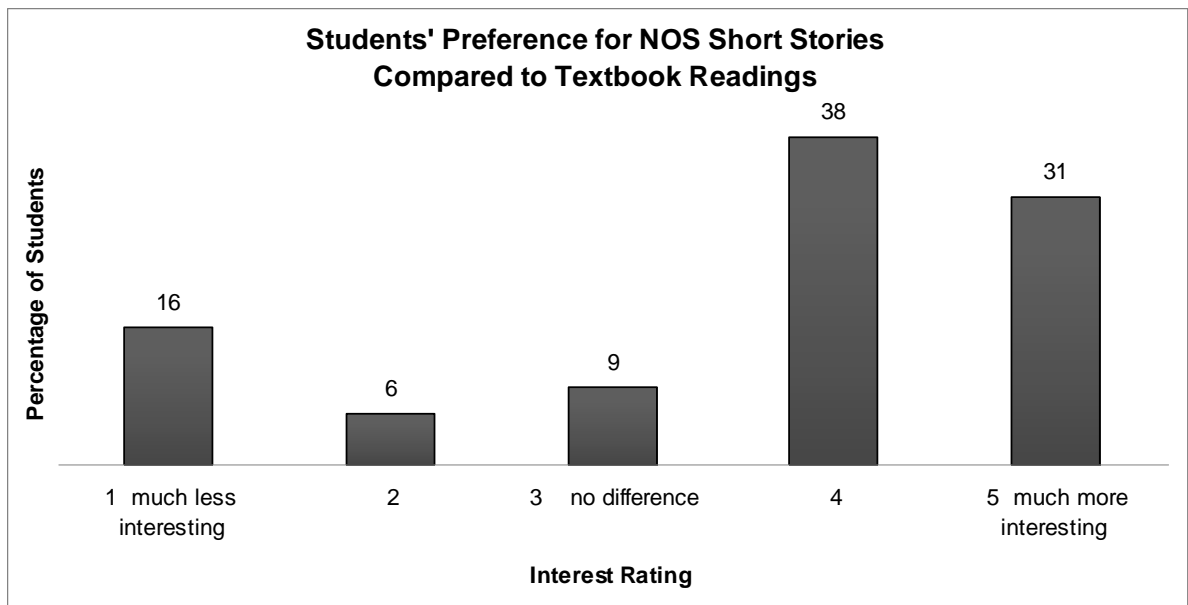


Figure 3: Summary of responses to survey question 5.

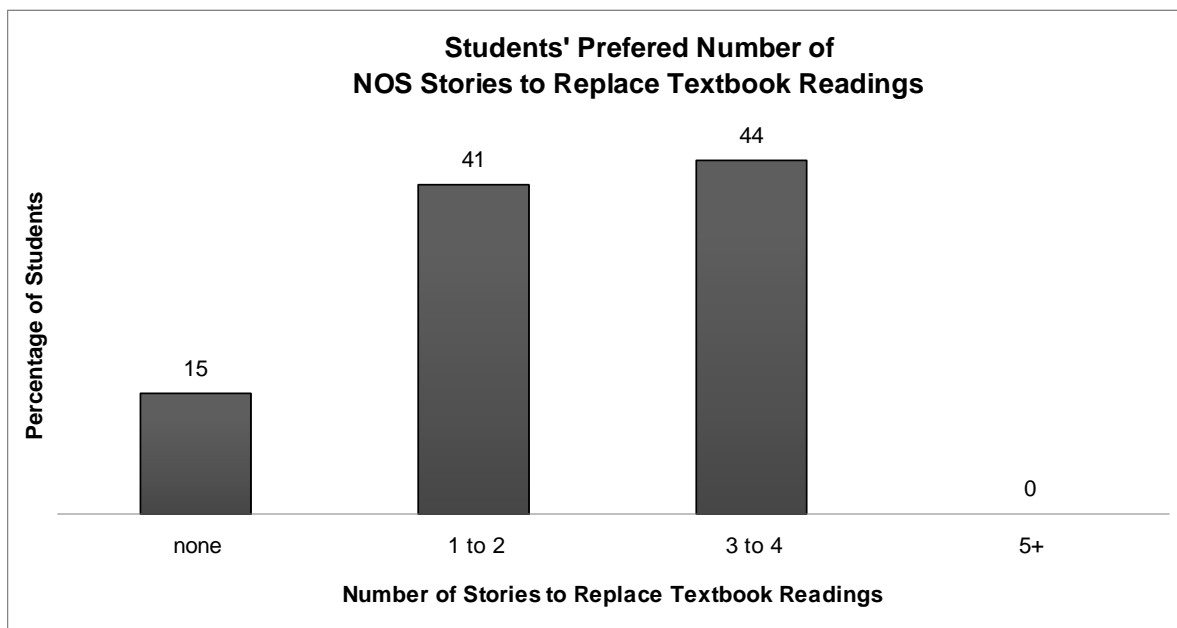


Figure 4: Summary of responses to survey question 6.

In their comments, students expressed a variety of reasons for preferring the short stories over textbook readings. Several students expressed that the stories were more interesting to read or more understandable than textbooks. Student comments to this effect include: "The stories were more interesting than reading a textbook, but not greatly entertaining. I learned from them and understood the material better than I would have had I read in the textbook", "The short stories were a lot more interesting to read then reading out of the text book. I also learned quite a bit from them", and "I thought that the short stories were a lot better than reading from the textbook. It was a lot easier to understand." Additional reasons for preferring the short stories included that the stories were descriptive, covered topics more broadly than textbooks, included questions that helped them review, and that

students could learn more from the stories. Treatment student 3 stated, "I think the stories are better than reading just from the book. The stories told me things about Mendel etc. that I never knew. I'm glad we did them."

Students who commented on why they disliked the short stories typically described the stories as boring, dull, uninteresting, or confusing. Comments to this effect include: "The stories were kind of boring and confusing.", "I don't like reading the short stories because there is nothing that interests me.", "The short stories didn't make much sense to me, it didn't keep my attention therefore I remember NOTHING about either of them.", and "The short stories were similar to reading out of a textbook, but the short stories became confusing because they seemed above my level and confusing." Another complaint made by several students was that they did not believe they learned as much from the stories as they would from a textbook. Treatment student 12 stated, "A few short stories are all right but textbooks are more helpful than short stories.", and student 10 commented, "I liked the stories better than just reading from the book, but they didn't necessarily teach me as much as the book does." Two students also commented that they disliked the background information about the scientists and would rather just read about the scientific discoveries and formation of scientific ideas. In the words of students 20 and 24, "They seemed dull and a waste of time. I felt there was too much background information. I'd rather just read about the discoveries"; "Learning about the actual people was the uninteresting part. Learning about the ideas I feel was interesting."

Students' Perceptions of the Stories' Impact on their Understanding of NOS

Survey questions 3 and 4 address students' perceptions about the impact of reading the two stories on their understanding of how science works. Figure 5 summarizes the results of these two survey questions. Survey question 3 measured students' perception of whether the stories taught them something new about how science works. Ratings for question 3 ranged from 1 to 5. A rating of 1 indicates the stories taught nothing new, a 3 indicates the stories somewhat taught something new, and a 5 indicates the stories very much taught something new. More than 40 percent of the students surveyed responded with a 3 and over 43 percent of students responded with a rating of 4 or 5. Thus, the majority of students perceived they learned something new about science from the stories. Although students reported learning something new and statistical analysis of VSQ1 and VSQ2 scores show a significant change in students' understanding of some NOS components, many students did not perceive a change in their views of science and how it works. Survey question 4 measures students' perceptions of whether reading the two stories changed their views about how science works. More than 46 percent of students surveyed responded with a rating of 1 or 2, indicating they did not believe the stories changed their views about how science works. Only 25 percent of students surveyed indicated they strongly believed the stories changed their views by responding to question 4 with a 4 or 5.

Impact of the Stories on Students' Interest in Science Careers

Survey question 7 measures how the short stories impacted students' interest in pursuing a science career; these results are summarized in Figure 6. The majority of students, more than 59 percent, indicated that the stories had no impact on their interest in science careers. However, 18.75 percent of students indicated the stories increased their interest in a science career by responding with a 4 or 5 and almost 22 percent of students responded with a 1 or 2 indicating a decreased interest in science careers.

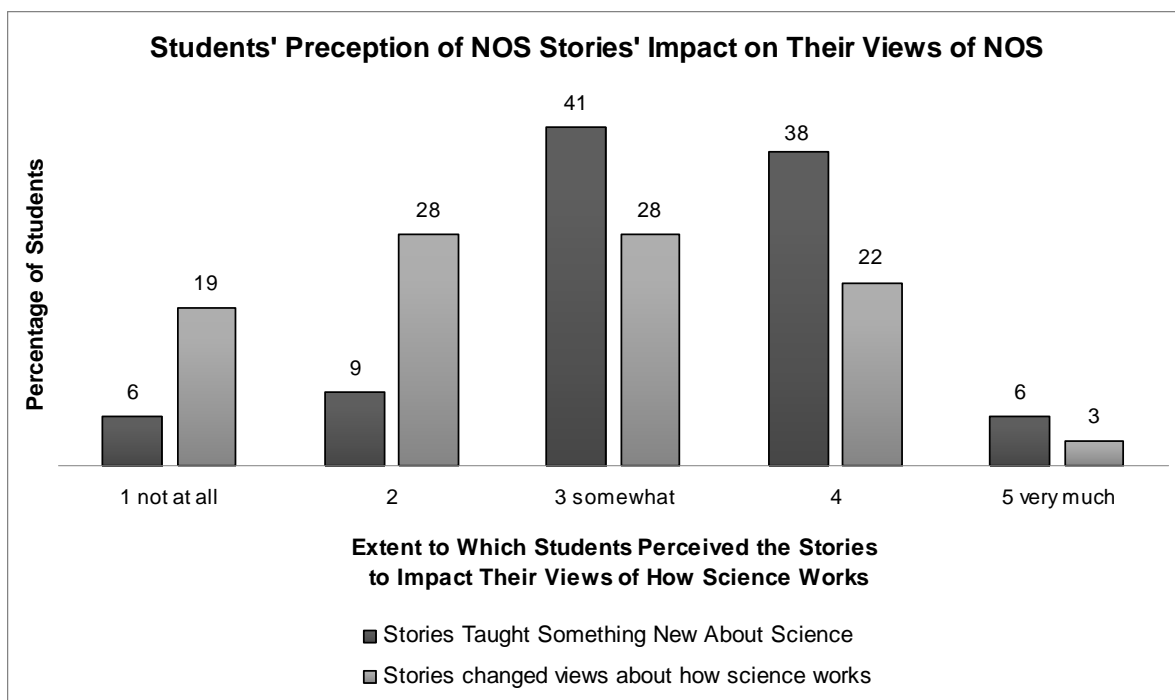


Figure 5: Summary of student responses to survey questions 3 and 4.

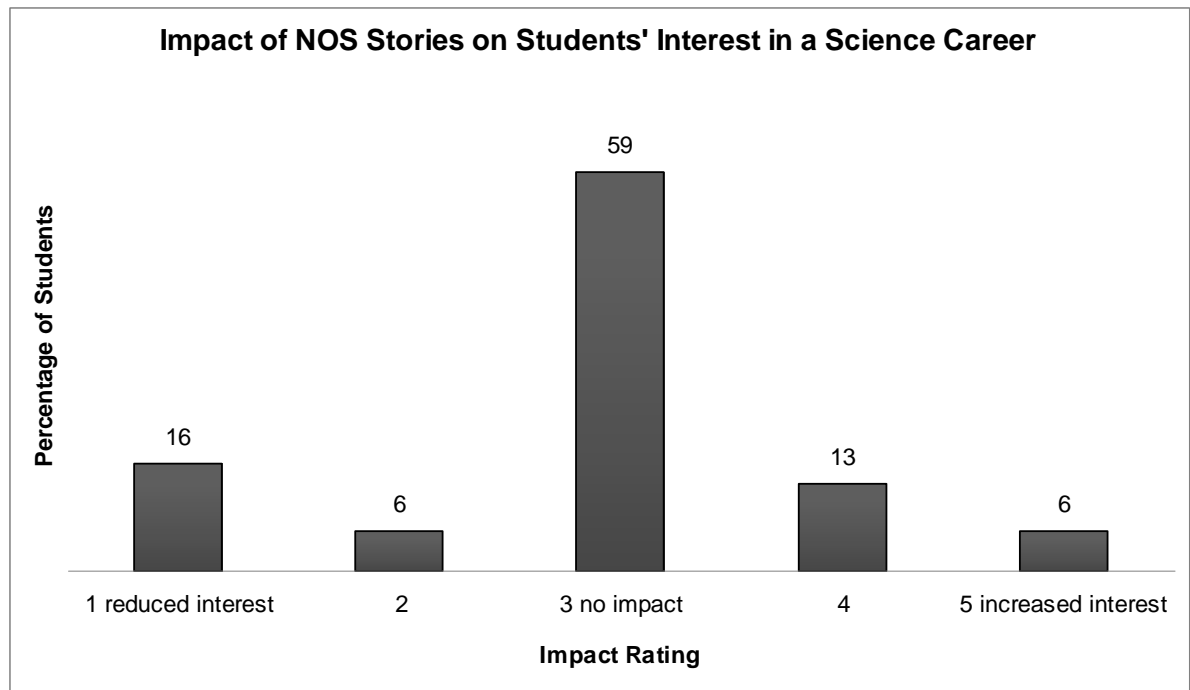


Figure 6: Summary of student responses to survey question 7.

CHAPTER 5: DISCUSSION AND CONCLUSIONS

Discussion of Research Question 1

Research question 1 relates to the extent students' accurate understanding of the NOS was impacted by the use of two historical short stories during instruction in a Biology course. Results of the three MANCOVA analyses indicate that, compared to the control group, the stories did have a significant positive impact on the treatment students' accurate understanding of the NOS in two of the three categories. A significant difference was observed for the pooled explicitly addressed VSQ1 components and the pooled VSQ2 components. Two of the three VSQ2 NOS components were explicitly addressed in the treatment stories. Differences between the treatment and control groups were not significant for the pooled non-explicit VSQ1 components. These findings support prior research which indicates explicit and reflective NOS instruction is most effective at changing students' inaccurate views of NOS (Abd-El-Khalick & Lederman, 2000; Abd-El-Khalick et al., 1998; Akerson et al., 2000; Clough, 2006; Khishfe & Abd-El-Khalick, 2002).

Subsequent ANCOVA Analysis of the Explicitly Addressed VSQ1 Components

The four explicitly addressed VSQ1 NOS components include the use of imagination in science, the effect of socio-cultural values on scientific investigations, the effect of personal beliefs on observations, and the use of multiple methodologies in science. Subsequent ANCOVA analyses only indicated a significant difference between treatment and control groups in two of these four NOS components: use of

imagination and use of multiple methodologies. The lack of significant difference between the groups on their understanding of the effects of socio-cultural values and personal beliefs may possibly be explained by the content of the control readings. While neither of the control readings use bolded comments or questions to explicitly draw students' attention to the effects of socio-cultural values and personal beliefs on scientific understandings, both readings are placed in a historical context. The Mendel reading discusses prior views of heredity and how they changed over time. The Darwin reading discusses earlier views of evolution and how they were changed over time. Additionally, both control readings included questions to draw the readers' attention to the changes in scientific views over time.

It is possible the content of the readings or the instructor's use of language during class discussions inadvertently drew attention to the importance of socio-cultural beliefs and personal beliefs when interpreting observations; this possibility is supported by the increase in mean score for the two components in both the control and treatment groups. The influence of socio-cultural views had the highest percentage of increase in score of any of the ten NOS components for the control group (+1.87 points out of a maximum score of 20; 9.35% increase) and the fourth highest percentage of increase for the treatment group (+1.26 points out of a maximum score of 20; 6.30% increase). For the treatment group, only the use of imagination (VSQ1 #2; +2.29 points out of maximum score of 25; 9.16% increase), methodological pluralism (VSQ1 #8; +2.13 points out of a maximum score of 30; 7.1% increase) and time for developing and accepting new scientific ideas (VSQ2

#3; +1.42 points out of a maximum score of 20; 7.1% increase) components had a higher percentage change in mean scores.

Subsequent ANCOVA Analysis of the VSQ2 Components

The three NOS components measured by the VSQ2 include: the collaborative nature of science, the nature data and conclusions, and the time for developing and accepting new scientific ideas. Of these three components, only the nature of data and conclusions component showed a significant difference between treatment group and control group post-scores.

The collaborative nature of science was not explicitly addressed in the treatment story, and thus was not expected to show a significant difference. Additionally, the particular topics of the two readings are not exemplars for collaboration in science. Interestingly, the collaborative nature of science component is the only one of the ten NOS components in which the treatment group demonstrated a decline in mean score between pre and post assessments (-0.32 out of a maximum of 25 points; 1.28% decrease). The collaborative nature of science component had the largest decline in mean score for the control group (-0.52 points out of a maximum score of 25 points; 2.12% decrease).

Although a significant difference did not exist between the control and treatment groups' post scores on the time for developing and accepting new ideas in science component, both groups demonstrated a relatively large increase in mean scores for this component. The treatment group demonstrated a 7.2 percent increase (+1.42 points out of a maximum score of 20) and the control group

demonstrated a 5.15 percent increase (+1.03 points out of a 20 point maximum score) between the pre to post scores on the time for new ideas component. The increase in understanding on this component may be explained by the topics of the two readings. Although the control readings did not utilize bolded comments or questions to explicitly draw students' attention to the time it takes to develop and gain acceptance for new scientific ideas, the work of both Darwin and Mendel took extensive periods of time to develop and be accepted. It is unavoidable that students reading either of these two readings would take note of the extensive time involved in the work of Darwin and Mendel.

Discussion of Research Question 2

Research question 2 involves students' interest in the two NOS historical short stories, students' perceptions of how the NOS stories impacted their views of science, and the impact of the NOS stories on students' interest in science related careers. Although few students reported finding either story interesting, the majority of students found the NOS historical short stories preferable to textbook readings. The vast majority of students reported they would like similar stories to replace at least some of their textbook readings. Student comments reveal that the primary reasons for their interest or preference for the NOS stories include that the stories were more interesting, descriptive, and easier to understand than textbook readings. It may be that students find the stories more interesting and easier to understand

because historical narratives effectively humanize and improve interest in science, as reported by prior research (Martin & Brouwer, 1991).

Analysis of students' negative comments about the stories reveals that students' conceptions of learning may be hindering their interest. This association is demonstrated by comments made by treatment students 10, 12, 20, and 24. These comments include: "I liked the stories better than just reading from the book, but they didn't necessarily teach me as much as the book does"; "A few short stories are all right but textbooks are more helpful than short stories."; "They seemed dull and a waste of time. I felt there was too much background information. I'd rather just read about the discoveries"; and "Learning about the actual people was the uninteresting part. Learning about the ideas I feel was interesting." Such comments may indicate the students' expectation that learning science requires learning facts and discoveries without any understanding of the processes of science. With this view of learning, it is understandable that students would find textbooks to be "more helpful than short stories." It is possible that the students' conceptions of learning are hindering their interest in learning from the stories; however, it is difficult to determine due to the small sample size and the limited number of participants who chose to write comments on their surveys.

Another factor which may be contributing to the negative attitude towards the stories is the reading ability of many students. The teacher had observed throughout the school year that many students enrolled in the class expressed particularly negative attitudes towards reading. Such student attitudes might explain the numerous comments about the stories being boring and confusing. Before

further research, it may be necessary to reevaluate the complexity and reading levels of the stories and the reading comprehension abilities of the students.

A third factor which may be contributing to students' reported negative attitudes towards the stories may be related to the dissonance between students' perceptions of what they learned from the stories and their actual growth in understanding the processes and nature of science. As noted in chapter 4, 47 percent of surveyed students reported the stories did not change their views of how science works. This is in contrast to the VSQ1 and VSQ2 results which indicate a significant change in students' accurate understanding of the NOS. Two students commented that they learned nothing from the stories or learned less than they would from a textbook. It is likely some students made some positive changes in their views of the NOS without perceiving they had learned anything useful; such dissonance may contribute to students' negative attitude and lack of interest in the stories.

Survey results about the stories' impact on students' interest in a science career were highly mixed. The majority of students indicated no change in their interest, almost 19 percent indicated an increase interest, and 22 percent indicated a decreased interest. It is positive to note that a number of students' interest in science careers was increased by the use of the short stories. What is not known is students' interest in science careers prior to reading the stories. It is possible that a number of students previously had a high interest in science careers and maintained a high interest after reading the stories, and thus reported no change in their views. It would be beneficial to survey students to determine their interest in science

careers before reading the stories, their interest in science careers after reading the stories, and what characteristics of the stories contributed to any changes in their interest level.

Conclusions and Suggestions for Future Research

The results of this study are sufficiently positive to warrant continued research into the use of historical short stories to teach about the NOS at the secondary level. Significant differences between control and treatment groups' scores on the VSQ1 and VSQ2 were only observed on NOS components explicitly addressed by bolded comments and questions embedded within the treatment stories. The lack of significant difference between the groups' scores on non-explicitly addressed NOS components supports the premise that the bolded questions and comments are sufficiently explicit and reflective to effectively draw students' attention to key NOS ideas embedded in the stories and the validity of the instrument. In addition to having a significant influence on students' accurate understanding of a number of NOS ideas, the stories appear to effectively engage a number of students and increase their interest in science careers.

However, this study was highly limited in size, scope, length of intervention, and number of NOS components addressed. Further research is needed to determine the feasibility and effectiveness of using historical short stories to teach about the NOS in secondary science courses. To determine the effectiveness of this approach, it is necessary for research to be done with larger groups of students with

a longer and more intensive treatment including more stories addressing more NOS components. Research supporting the use of this approach to teach the NOS should also include samples from science disciplines and grade levels.

Additionally, it would be beneficial for future research to determine what factors contribute to this approach being used effectively to teach about the NOS to some students but not others. Students' conception of learning, reading ability, and attitudes towards reading may contribute to students' positive and negative attitudes towards the use of short stories. Teachers' pedagogical approaches, conceptions of learning, and accurate understanding of the NOS also likely contribute to the successful use of the stories. Further research is needed to determine in what situations and with what students this approach to NOS instruction can be effectively used in secondary science classrooms.

APPENDIX A: INFORMED CONSENT DOCUMENTATION

INFORMED CONSENT DOCUMENT

Title of Study: Historical Science Short Stories in High School Science

Investigators: Jennifer A. R. Smith, B.S.

Michael P. Clough, Ph.D.

FOR PARENTS:

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

FOR STUDENTS:

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

INTRODUCTION

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

DESCRIPTION OF PROCEDURES

If you agree to participate in this study, your participation will last for a two-month period during the spring 2009 semester. Participation means that your scores on a nature of science questionnaire may be used for data analysis. The content of the course will in no way be altered by this study; all homework, quizzes, tests, lectures, laboratory activities and other classroom activities, including the questionnaire, are designed to meet pre-determined learning objectives for the course.

RISKS

No foreseeable risks exist for participation in the study.

BENEFITS

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

COSTS AND COMPENSATION

You will not have any costs from participating in this study. You will not be compensated for participation in this research.

CONFIDENTIALITY

Records of participation in this research will be maintained and kept confidential to the extent permitted by law and will not be released without your prior authorization unless ordered by a court of law. Identification numbers will be used to identify subjects in the study. In the event of any report or publication from this study, the identity of participants will not be disclosed.

VOLUNTARY PARTICIPATION

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

QUESTIONS OR CONCERNS

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

Jennifer Smith, Iowa State University, Ames, IA

Dr. Michael Clough, Iowa State University, Ames, IA (515) 294-1430

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

PARTICIPANT SIGNATURE

Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant's Name (printed) _____

(Participant's Signature)

(Date)

(Signature of Parent/Guardian or Legally Authorized Representative)

(Date)

INVESTIGATOR STATEMENT

I certify that the participant has been given adequate time to read and learn about the study and all of their questions have been answered. It is my opinion that the participant understands the purpose, risks, benefits and the procedures that will be followed in this study and has voluntarily agreed to participate.

(Signature of Person Obtaining Consent)

(Date)

APPENDIX B: MENDEL TREATMENT STORY

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, who was representing a French seed company. While touring Central Europe, Eichling had been urged to visit Mendel's collection of pea plants at his monastery in the town of Brno (which is in what is now called the Czech Republic). 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 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 no one believed Mendel's experiments were more than the work of a "charming putterer." At the age of 56, Mendel had been removed nearly five years from his scientific work with pea plants, having become so preoccupied with the daily operations of a large monastery that he could only spend rare free hours in his garden. About 20 years later, this "charming putterer" would be recognized for developing two ideas that we now accept as fundamental laws of inheritance; he is now often referred to as the father of modern genetics.

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

Born Johann Mendel in 1822 in a small village (also in what is now the Czech Republic), he lived a peasant's life for many years. In grade school he was pointed out as a gifted child, and sent off to a boarding school in a German speaking town. His parents could barely afford the bill, and his occasional gifts from home came in the form of bread loaves. To pay for housing, Mendel tutored other students. Through a great deal of self-discipline, Mendel earned top grades in school. However, he returned home and spent a year on his parents' farm after being unable to secure a job as a full-time teacher following graduation. In 1841 he was accepted to the University of Olomouc, in a Czech speaking town. The decision to attend University was tough for Mendel—in addition to hardly speaking a word of Czech, his father had been injured and the family farm was in real danger of collapsing. Mendel chose to continue his education.

At the university, Mendel pursued a degree that included work in mathematics, physics, philosophy and ethics. He developed good relationships with his professors and again earned top marks. After his two year degree, his life went into a very different direction than he had expected. When Mendel had decided to leave the family farm, his sister took charge. While he was away at school, his sister married and her new husband gained control of the farm. The contract handing over control of the farm to Mendel's new brother-in-law stipulated that Johann would receive a handsome annual sum of money in return for entering the priesthood. Luckily for Johann, his physics professor had been a member of an Augustinian Monastery. With his good grades and his teacher's reference, in 1843 Johann

was accepted at the Augustinian Monastery in Brno without so much as meeting the elders. At the monastery he would be named “Gregor,” and as long as he performed his clerical duties, he was free to study whatever he wished.

2. 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. Why would scholarly work be considered a leisure activity at that time?

The popular image of monastery life is painted such that monks are quiet, reserved creatures that pray the whole day and interact little with the outside world. This was not the case at Brno. Mendel's duties involved visits with the sick and poor and attending regular church services. Furthermore, the Brno monastery had an extensive collection of rocks, minerals, and plants collected by monks while on their travels. Most important, the monastery had an excellent library, stocked with books of all types. Mendel used these resources extensively, hoping to earn a certificate and become a full-time teacher. While praised for his classroom teaching, he couldn't pass the very tough certification exams mostly because he limited his studies to what was on hand at the monastery. By 1851, Mendel had resigned himself to being a substitute teacher in a monastery. However, later that year the natural history teacher at Brno Technical School took ill, and Mendel stepped in. He taught over a hundred students a day and did so well that he was hired on full-time. When the Abbot of the Brno monastery later learned that Mendel hadn't passed the certification exams, he decided to send Mendel to the University of Vienna to sharpen his education.

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

At the time Mendel began his scientific work and investigations into heredity in 1856, discussions regarding inheritance had already been very active for a century. Many well known figures in science had all speculated on the subject. Early investigations into heredity were done with animals. Plants were not used in hybridization experiments until the 1700s. This was likely due to the difficulty natural scientists had in accepting that plants sexually reproduced. Linnaeus, a devout Christian, was willing to accept that God's creatures could breed and make new species. He noted that plants also had sexes, and that when two different kinds of plants produced a new offspring (or 'hybrid'), it was good enough to be considered a new species. The notion that humans could artificially create new species came as a shock to eighteenth-century naturalists. Nature was supposed to be orderly and harmonious, but if humans could indeed make a new species whenever desired by simply crossbreeding existing species, chaos would follow. So at the time Mendel began his work, scientists were thinking about inheritance and were considering the idea that new species might result from reproduction and breeding. However, precisely how characteristics were transferred from parents to offspring remained a complete mystery.

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

What stimulated Mendel and others to begin investigating how heredity occurred was prior work regarding the fertility of hybrids. Almost 100 years earlier, around 1760, Joseph Koelreuter, a German, began mating hybrids with other hybrids. He filled all the space he could spare with potted plants acquired from all corners of the globe, even obtaining seeds from Linnaeus. Koelreuter made two important observations. The first was that not all hybrids could produce offspring, 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 explanation: in nature, species remain unchanged and parents give birth to offspring like themselves, but when humans interfere is when the 'unnatural' crosses (new species) appear.

While Koelreuter's explanation is no longer accepted, his work was important because it questioned one of the major ideas regarding heredity at the time, called "preformation." Preformation stated that an exact miniature replica of the parent existed inside sperm cells or egg cells. Therefore, exact blueprints were passed on in each generation. The idea of preformation had survived to Koelreuter's day even though the microscope had been invented almost one-hundred years earlier. Despite failure to see the miniature replicas of parents in the sex cells, the preformation idea lived on because it could explain why so many species had more or less identical offspring. Taking many observations and measurements of his hybrid plants, Koelreuter argued that his results could only occur if both the male and female were involved in heredity. Mendel had extensively read Koelreuter's work, and it influenced the way he thought about heredity. Franz Unger, a professor at Vienna, was yet another influence on Mendel's thinking. Unger rejected the idea that species were unchanging. In contrast to Koelreuter, Unger proposed that new variations arise even in natural populations – without interference from humans.

So at the time Mendel graduated from the University of Vienna, his thinking regarding heredity 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.

In the summer of 1856, in between clerical duties and teaching, Mendel began his research on pea plants of the genus *Pisum*. He favored these plants for their purity and easily observed characteristics. Mendel's experiments followed from his idea (an idea that no one had previously considered) which was to predict "the number of different forms that would result from the random fertilization of two kinds of 'egg cells' by two kinds of pollen grains." In other words, Mendel assumed there were different forms of what he called "factors" for each trait in an organism. He suspected that the factors responsible for different forms of a trait would not occur together in the same sex cell (sperm or egg). For example – there would be a "factor" that causes long stems and a different "factor" causing short stems. One sex cell could only contain one of these factors at a time, not both. Mendel does not know what these factors are, but his idea has observable consequences as illustrated in figure 1.

Figure 1. Ratio of offspring expected from the random cross of two kinds of egg cells and two kinds of pollen grains (which contain the male sex cells).

	T egg	t egg
T pollen	TT Tall offspring	Tt Tall offspring
t pollen	Tt Tall offspring	tt Short offspring

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

4. Explain how Mendel's thinking shows both a gradual progression from prior ideas about 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 (allowing pollen from a plant to fertilize an egg from the same plant) crosses, he determined that particular plants were "true-breeding" (only contained one factor) for certain traits. 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 F1 generation) were all tall. Mendel did not know what in the sex cells caused pea plants to have long or short stems, but proposed that whatever caused the plants to have long stems somehow overpowered whatever caused pea plants to have short stems. That is, the long stem factor was dominant and dwarfness, which did not show up in this F1 generation, was caused by a recessive factor.

The tall hybrid plants from the F1 generation were then self-fertilized, to create the next or F2 generation. When the F2 offspring matured, most were tall, but some were short. This was just what others had observed, but unlike previous explanations for this phenomenon, Mendel was interested in how the number of each compared. Upon counting the members of this F2 progeny, Mendel interpreted the numbers as exhibiting a certain constancy, averaging three tall 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 F₂ experimental results:

Characteristic	Number of F ₂ Offspring		Ratio
Seed shape	Round5,474	Angular1,850	2.959 : 1
Cotyledon color	Yellow6,022	Green2,001	3.010 : 1
Seed coat color	Colored705	White224	3.147 : 1
Pod shape	Inflated882	Constricted ...299	2.950 : 1
Pod color	Green428	Yellow152	2.816 : 1
Flower position	Axial651	Terminal207	3.145 : 1
Stem length	Tall787	Short277	2.841 : 1
Total	Dominant...14,949	Recessive 5,010	2.948 : 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. Historians Fairbanks and Rytting write that when Mendel noted that one of his crosses yielded results he thought were not in line with the predicted ratio, "he repeated the experiment and obtained results that were more acceptable to him." Some ambiguity (uncertainty) is part of all scientific work, and those who do research must make judgments to make sense of that ambiguity. 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.

- **Mendel wasn't fudging his data. Scientists must make sense of data, and this requires making judgments when interpreting data, 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; this reduces, but does not eliminate, the amount of subjectivity in science.**
5. **How does Mendel's work illustrate that observation and data analysis is not objective, but is subjective and influenced by their expectations and their perception of the world?**
 6. **Many students today choose not to pursue science careers, thinking that science does not require creativity. How does Mendel's original idea, approach to testing that idea, and his analysis of data illustrate that science is a creative endeavor?**

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

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

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

In 1900, Mendel's work was 'rediscovered.' While it had never really been lost, his results resonated with some vocal scientists. They hailed him as being the discoverer of what they now called 'genes,' the microscopic 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.

7. Mendel's ideas involved:

- **some "factors" determining particular traits in life forms**
- **the application of mathematics and probability to life forms**

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

APPENDIX C: DARWIN TREATMENT STORY

Charles Darwin: A Gentle Revolutionary

Most everyone recognizes the name of Charles Darwin. His near legendary status has made him seem larger than life, but few people accurately understand the events in his life, his motives, and his contributions to our understanding of biology. Born in 1809, Charles Darwin had a family history of interest and work in science. His grandfather had been a successful physician and naturalist. His father had also been a successful physician. 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 doctor. In 1825 he enrolled at Edinburgh University to obtain his medical degree. However, much like students today, he found the lectures boring, and he recoiled in disgust from his anatomy classes, unable to stomach working with human cadavers. 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 join the clergy took the same challenging classes as those studying to be scientists. While at Cambridge, Darwin met scientists who contributed to his attitude and efforts toward investigating nature. They encouraged a balance of observation and experiment, and taught Darwin that successful scientific theories draw from many fields of research. Thus, along with being well versed in religious studies, Darwin became a keen observer and important researcher in the fields that we now call geology (the study of the earth's structure and its history) and zoology (the study of animals). Although Cambridge infused Darwin with a scientific spirit, he again found the classes boring and livened his days by gathering and inspecting beetles he found in the courtyards. He wrote:

But no pursuit at Cambridge was followed with nearly so much eagerness or gave me so much pleasure as collecting beetles. It was the mere passion for collecting, for I did not dissect them, and rarely compared their external characters with published descriptions, but got them named anyhow. I will give a proof of my zeal: one day, on tearing off some old bark, I saw two rare beetles, and seized one in each hand; then I saw a third and new kind, which I could not bear to lose, so that I popped the one which I held in my right hand into my mouth. Alas! it ejected some intensely 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 formed swiftly through epic hurricanes, earthquakes or floods. Sedgwick advocated this idea to Darwin on the trip to Wales. Darwin had his reservations about this idea, 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.

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

Later, in 1844, Robert Chambers also put forth a popular evolutionary idea. In his book, *Vestiges of Natural Creation*, Chambers combined astronomy, geology, theology, and biology 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 up-to-date works on evolution and developed a very influential argument that many in the public took as the best explanation of evolution.

- **Note that ideas regarding the evolution of species did not originate with Darwin. Moreover, people, like Darwin, who believed in God, were often promoting ideas regarding the evolution of species.**
1. **Summarize both Lamarck’s and Chamber’s views on how species evolve and how these two ideas differ from each other.**

Darwin would have read all of these works—one could not be a naturalist in his day without being familiar with Lamarck and Chambers’ writings (the latter he would have read in 1844, seven years after his return on the *Beagle*). However, on this expedition Darwin made two important observations. The first had to do with geology. In England, Sedgwick had trained Darwin’s eye to see geological formations as happening all at once. However, Darwin couldn’t accept this view once he viewed the rugged and varied landscapes of South America. Before leaving England, Darwin had acquired a copy of the geologist Charles Lyell’s new book *Principles of Geology*, which would become a classic throughout science.

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. The solid rock that Darwin observed was granite, which geologists thought formed under great pressure, such as under the ocean. Darwin couldn't conceive of the granite being produced under an ocean and then exploding up all at once. Instead, he thought it more likely that such a vast landscape had been slowly built up over time. He made many more of these geological observations. They were very important because he began to apply this idea of gradual change to his second important group of observations he made on the trip: living organisms.

As the *Beagle* skirted the South American coast and pulled in at 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 short flying birds (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 very distant locales with very similar environments, such as Africa and South America, have completely different flora and fauna? 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 became a staple of Darwin's evolutionary theory.

2. 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 the specimens he had collected. 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. Roughly 40 years earlier, the clergyman Thomas Malthus had published an *Essay on the Principle of Population*, stating that mankind's 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 into new species. Darwin applied the term "struggle for existence" to species fighting for limited resources. Perhaps some species might have an adaptive advantage over others, and that would partially explain why so much variety existed. The importance of his insight is illustrated by his own words:

In October 1838...I happened to read for amusement "Malthus on Population," and being well prepared to appreciate the struggle for existence which everywhere goes on from long-continued observation of the habits of animals and plants, it at once struck me that under these circumstances favourable variations would tend to be preserved, and unfavourable ones to be destroyed. The result of this would be the formation of new species. 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 forming of a new species, 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" (branched off from each other), or in other words why so many varied species existed.

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

Darwin's ongoing work included, but was not limited to, studying pigeon breeding, the geographical distribution of organisms, and barnacles. Darwin knew that animal breeders carefully paired males and females possessing desired traits to emphasize those traits in the offspring. Darwin knew, of course, that humans were artificially selecting and breeding animals for desired traits. This provided an analogy for how nature, given far more time, might select for traits and result in organisms adapted to their environment. Darwin reasoned that the random variation from which breeders select their traits must also exist in nature. This *natural* selection is analogous to artificial selection, but **natural selection** is far more pervasive and creative than artificial selection 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. Darwin felt that studying variation in the crustaceans could help him understand why *all* species undergo change. Popular ideas regarding evolution accounted for wide variation in 'advanced' life forms like birds or apes or humans, but it would not be expected in the 'primitive' barnacles. Nonetheless, there was variation and Darwin wanted to understand what caused it. After years of study and reflection, in November, 1854 he outlined his **principle of divergence** that stated divergence and eventual speciation would occur in locations where competition for resources was intense.

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

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

For Darwin, another challenge loomed on the horizon—convincing scientists that his ideas had merit. Fearing the readers of the Victorian age would ruin his life by labeling him a ‘materialist’ or an ‘atheist,’ he had withheld from publishing his ideas. However, he had long been forging friendships with scientists dissatisfied over the older evolutionary theories. Alfred Russel Wallace was one of these colleagues. 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 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*, he drew upon extensive research he had conducted during the past twenty years. In the closing days of November 1859, the first printing of his *On the Origin of Species* appeared in London’s bookstores. Darwin’s work was rewarded with a first-day sell-out of 1250 copies, a very large printing for the time.

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

Charles Darwin was a complex man who put a lifetime of work into his theory of evolution. Very much a man of his time, he infused his understanding of morality, order, theology, economics, geology, and zoology into his theory. Many scientists and public officials gradually accepted Darwin’s ideas on evolution, but Darwin’s primary mechanism, natural selection, was widely rejected by scientists for many years. Many scientists refused to abandon the idea that evolution progressed toward some proper end. As with most all advancement in science, change was slow and no single piece of evidence brought about our current understanding of evolution. Darwin’s *Origin* led to a scientific debate that continued for decades. Once published, his theory of evolution by natural selection 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. During the past 100 years, overwhelming evidence has continued to support Darwin’s most fundamental ideas regarding biological evolution.

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

Darwin’s theology at any given time in his work is much debated. While he was never an atheist, Darwin’s religiosity had faded by the time of his death due to his witnessing the painful and early deaths of his daughters. However, believing that ultimately some higher

power must be in charge, Darwin died an agnostic. Recognizing his significant contributions to science, the powers of the time, including the Church, made sure he was buried in London at Westminster Abbey. Charles Darwin was buried next to another icon in science, Sir Isaac Newton.

- **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.**
6. **How might you account for the prevalence of these two significant misconceptions regarding how science research is done?**
 7. **How might the public's adherence to these misconceptions cause them to reject biological evolution?**
- **Science explains events in the universe without reference to the supernatural. Individual scientists often have a deep personal faith in a supernatural being, but when doing science, 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.**
8. **How would permitting supernatural explanations in science interfere with the quest to develop explanations humans can understand and use?**

APPENDIX D: MENDEL CONTROL READING



Exerpts from the Field Museum: <http://www.fieldmuseum.org/mendel/>

Gregor Mendel's story is remarkable: A 19th-century friar and high school science teacher, he designed a brilliant experiment with ordinary peas that revealed the laws of heredity. His work was ignored for thirty years—only to be rediscovered after his death and launch the science of modern genetics.

Gregor Mendel's Story

In 1865, Gregor Mendel reported the results of plant hybridizing experiments and laid out the basic laws of inheritance—offering an insightful sketch of how physical traits are passed from one generation to the next. This ground-breaking work was ignored until the turn of the century, when it was rediscovered and confirmed by other researchers.

Since then, Mendel has come to be recognized as the father of genetics, although the story of how he accomplished that remains relatively unknown today.

Heredity Science Before Mendel:

The causes of heredity remained a mystery for centuries—until Gregor Mendel.

The timeline below shows key developments in how people thought about heredity before Mendel.

8000 BC – Neolithic farmers select plants and animals with desirable traits—the highest-yielding vegetable, the sweetest fruit, or the fattest cow—to crossbreed.

400 BC – Greek philosopher **Hippocrates** proposes that tiny particles from every part of the body of each parent became blended, producing an individual with the characteristics of both.

350 BC – **Aristotle** dismisses Hippocrates' theory, noting that children do not always resemble parents. But Aristotle's thinking about heredity still centers on a mixing of "fluids" from each parent.

1700s – Scientific thinking about reproduction is dominated by "preformation": the idea that an organism contains all of its future descendants, encased in increasingly miniature forms, like Russian nesting dolls.

1760s – **Joseph Kölreuter** pioneers the scientific study of plant hybrids (a “cross” between parents of different varieties).

1780s – English livestock breeder **Robert Bakewell** pioneers the systematic breeding of sheep and cattle to obtain higher quality wool and fatter beef.

1800s - The idea of heredity as a “blending” process continues to dominate scientific thought until the late 1800s.

1856 - An inquisitive friar named **Gregor Mendel** began conducting experiments that held the answer to the riddle.

1. Explain how the actions of the Neolithic farmers (8000 BC entry on time line) relate to genetics.
2. How is Hippocrates’ view (400 BC) of inheritance different than the modern view?
3. What is performance (1700s), and how does it differ from current views of inheritance?
4. Explain what is meant by the term “hybrid”?

Gregor Mendel’s Life:

In an abbey garden, Mendel planted the seeds for the science of heredity.

Born to poor tenant farmers in the Austro-Hungarian Empire, Gregor Mendel joined the Abbey of St. Thomas in 1843, at age 21. The Abbey was a dream come true for a budding scientist. A vibrant center of research, its friars were active in the sciences, linguistics, literature and philosophy. The Abbey made it possible for Mendel to attend the University of Vienna and to read widely in a library that contained 30,000 books. Mendel had diverse interests—astronomy, meteorology, physics, botany, and mathematics. He was one of the first scientists to use rigorous experiments and mathematical analysis as a means to study biology.

In 1856, Mendel launched an ambitious series of experiments with *Pisum sativum*—the garden pea. Eight years and approximately 28,000 pea plants later, Mendel published the results of his grand experiment. His methods were so advanced and his results so groundbreaking that no one realized how his discovery would eventually revolutionize science.

After being elected Abbot in 1868, Mendel had little time for science. He may have been disheartened by the lack of reaction to his pea paper, but he knew that his discovery was important. Not long before his death in 1884 he told a scientific colleague, “My time will come.”

Mendel was right. In 1900 three European botanists rediscovered his work and set off a scientific explosion. The field of genetics was born and Mendel is considered its founding father.

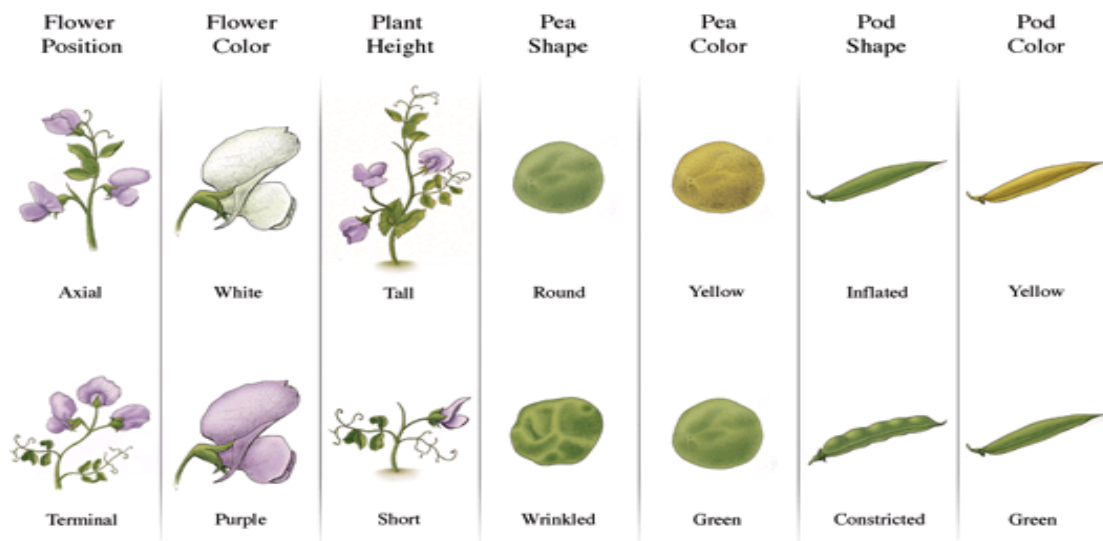
5. **What advantages did Mendel experience by living at the monastery (Abbey)?**
6. **What species of plant did Mendel use for his genetics experiments? Why might this be a good choice for experimenting?**

The Famous Pea Experiment:

Mendel's results depended on a lot of peas—and a lot of patience

Prior to Mendel, naturalists and scientists tried to understand heredity by crossbreeding different varieties of plants or animals. Nevertheless, Mendel was the first to conduct broad, thorough, systematic, and sufficiently rigorous experiments to discern any universal laws governing inheritance.

Mendel began by identifying seven pairs of contrasting traits found among garden peas:



For two years, the scientist grew different varieties of peas to make sure that their offspring were always the same (pure-breeding plants). Then he began breeding different varieties together to make hybrids. He brushed the pollen off pure-breeding pea plants with yellow pods and put it on pure-breeding pea plants with green pods, and did the same for plants with each of the seven pairs of traits. He then grew generation after generation of hybrids and tracked the inheritance of the traits.

Mendel noticed that some traits disappeared in the first generation of hybrids. He called these traits “recessive.” He called those that did appear “dominant.” In later generations the recessive traits reappeared—and in a mathematically predictable pattern. For example, later generations of plants had one green pea for every three yellow peas. The same ratio

appeared for all seven pairs of traits.

Mendel grew an estimated 28,000 pea plants over eight years. In 1864 he published the results of his experiment.

7. **In what ways was Mendel's approach to studying biology different than prior scientific work?**
8. **In what ways do pure-breeding and hybrid plants differ?**
9. **Make a Punnett square showing the cross between pure-breeding yellow pea plants and pure-breeding green pea plants (assume green pea pods are dominant).**
10. **How did Mendel differentiate "recessive" and "dominant" traits?**

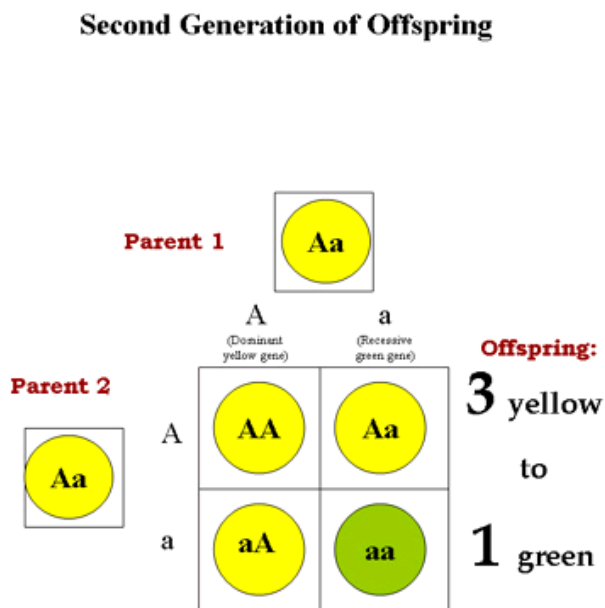
What Mendel Discovered:

Mendel's mathematical mind allowed him to "see" hidden patterns of heredity.

Earlier scientists had noticed the disappearance and reappearance of traits in hybrid plants. What Mendel did differently was count. And count. And count. Mendel used mathematics to draw conclusions about what was happening deep inside the cell.

Mendel concluded that every trait must be controlled by two "elements" (what we now call genes) that are present in every pea plant. As part of sexual reproduction, these elements separate and only one is passed down to the offspring. Whether a plant has green or yellow peas depends on the combination of elements that it received from its parents. If a plant receives two dominant elements, its trait will be dominant (i.e. yellow peas). If it receives two recessive elements, its trait will be recessive (i.e. green peas). If it receives one of each element, the dominant trait will mask the recessive trait. This is what caused all the green peas to disappear in Mendel's first generation of plants.

Mendel went on to cross plants that differed in more than one trait—round-yellow peas with wrinkled-green ones, or tall, violet-blossomed plants with short, white-blossomed ones.



As in his initial experiments, the traits appeared in predictable ratios. This told Mendel that the elements governing traits were not linked, but passed separately to the offspring.

Mendel's results were published in a local scientific journal in 1866, but other scientists did not understand the importance of his work for several decades.

11. **Why did the green peas disappear in the offspring when a pure-breeding plant with yellow peas and a pure-breeding plant with green peas were crossed?**
12. **Why did green peas “reappear” in future generations when the offspring from the cross in #11 were mated? Use a Punnett square to support your answer.**
13. **Summarize 3 main ideas Mendel learned from his experiments with pea plants.**

The Rise of Genetics:

As the 20th century dawns, Mendel's work is rediscovered and a new science is born.

In 1900 botanists Carl Correns, Hugo de Vries, and Erich von Tschermak each referred to Mendel's experiments in their own articles on hybridization. At last, thirty-four years after its publication, Mendel's work was pulled from obscurity.

By this time, improved microscopes had revealed deeper insights into the world of the cell, including the discovery of chromosomes and DNA. Some scientists saw clues to heredity in chromosomes' patterns of division, and by 1903 they made the connection between the action of chromosomes and Mendel's findings. In 1905 a British scientist coined the term “genetics” as the name for this new science of heredity and variation. Within four more years, scientists renamed Mendel's “elements” as genes.

Further discoveries occurred in Thomas Hunt Morgan's “fly room” at Columbia University. Morgan looked at characters—such as eye color and wing size—over generations of fruit flies, connecting certain traits with individual chromosomes, and eventually “mapping” genes on the chromosome itself.

The biggest biological discovery since Mendel's came in 1953 when scientists discovered the molecular structure of DNA. Maurice Wilkins and Rosalind Franklin at King's College photographed DNA using a technique called “x-ray crystallography.” Meanwhile, at Cambridge University, Francis Crick and James Watson attempted to create DNA models of cardboard and metal. It was only when Wilkins shared Franklin's x-ray photograph of DNA that the structure—a double helix, like a twisted ladder—clicked for Watson and Crick.

This discovery marked a new era in genetics, and opened the door for the next generation to make more dramatic discoveries about the natural world.

14. **Why might it have taken so long for Mendel's work and contributions to our understanding of inheritance to be recognized?**
15. **How does the discovery of DNA help support Mendel's ideas?**

APPENDIX E: DARWIN CONTROL READING



Exerts From The American Museum of Natural History: <http://www.amnh.org/exhibitions/darwin/>

Introduction:

Two centuries after Charles Darwin's birth, nearly everyone knows his name. **What did Darwin do**, and why does he still matter so much? Keenly observing nature in all its forms—from fossil sloths to mockingbirds, primroses to children—Darwin saw that we all are related. **Every living thing shares an ancestry**, he concluded, and the vast diversity of life on Earth results from processes at work over millions of years and still at work today. Darwin's explanation for this great unfolding of life through time—the theory of evolution by natural selection—transformed our understanding of the living world, much as the ideas of Galileo, Newton and Einstein revolutionized our understanding of the physical universe.

Darwin's theory of evolution by natural selection underlies all modern biology. It enables us to decipher our genes and fight viruses, and to understand Earth's fossil record and rich biodiversity. Simple yet at times controversial, misunderstood and misused for social goals, the theory remains unchallenged as the central concept of biology. Charles Darwin profoundly altered our view of the natural world and our place in it.

1. What does it mean to say that “every living thing shares an ancestry”?

The World Before Darwin:

The Nature of Species: Before Darwin was born, most people in England accepted certain ideas about the natural world as given. **Species were not linked in a single “family tree.”** They were unconnected, unrelated and unchanged since the moment of their creation. And Earth itself was thought to be so young—perhaps only 6,000 years old—that there would not have been time for species to change. These attitudes reflected a broader **view of the world as stable and unchanging.** There was a natural order to things.

By 1800, European naturalists knew a great deal about plants and animals. They collected specimens, carefully studied them and even classified similar species in groups. But only a few bold thinkers speculated that species had evolved—that is, that all life shared a common ancestor.

Evolution Before Darwin: Early evolutionists like Jean-Baptiste Lamarck had difficulty explaining how new species arose. Lamarck saw that many animals seemed to have acquired useful adaptations. The giraffe's long neck, for instance, was perfect for feeding on high leaves. But how did the giraffe get its neck? Lamarck thought it resulted from the constant effort of reaching for food. Constant use of a body part, he argued, made it larger and stronger. But there was one key problem. Can changes produced during an animal's lifetime be passed on to its offspring? Does a father lifting weights produce a muscular

baby? Lamarck argued that such acquired traits could be inherited, but few others were persuaded. A convincing mechanism for evolution had yet to be discovered.

How Old is Earth? Could life on Earth have evolved? Before 1800, only a handful of naturalists in England and France had given this idea serious consideration. And even they couldn't see how there could have been enough time for evolution to occur. Relying on interpretations of the Bible, most people in England believed that Earth was only about 6,000 years old—not nearly old enough for countless species to have evolved. Today, we know from radiometric dating that Earth is about 4.5 billion years old. Had naturalists in the 1700s and 1800s known Earth's true age, early ideas about evolution might have been taken more seriously.

2. **Why did people in the 1700s and 1800s find it difficult to accept that life on earth might change over time?**
3. **What was Lamarck's view of how biological evolution could occur?**

Young Naturalist:

Darwin's father sent him to Edinburgh University in Scotland to study medicine, like his father and grandfather before him. When **Charles showed no interest in becoming a doctor**, His father next sent Charles to the University of Cambridge to prepare for a career in the church. Charles had no objection. A quiet country parish might be just the place to pursue his interest in natural history.

At the University of Cambridge, Darwin's interest in natural history blossomed into far more than a hobby.. He became the particular protégé of the Reverend J. S. Henslow, a brilliant and charismatic botanist. Encouraged by Henslow, Darwin developed a "burning zeal to add even the most humble contribution to the noble structure of natural science." To help him brush up on his geology, Henslow introduced Darwin to Adam Sedgwick, one of Britain's preeminent geologists. Reverend Sedgwick took Darwin on a geological expedition through Wales.

A Trip Around The World:

In 1831, Charles Darwin received an astounding invitation: to join the HMS *Beagle* as ship's naturalist for a trip around the world. For most of the next five years, the *Beagle* surveyed the coast of South America, leaving Darwin free to explore the continent and islands, including the Galápagos. He filled dozens of notebooks with careful observations on animals, plants and geology, and collected thousands of specimens, which he crated and sent home for further study. When he set out, 22-year-old Darwin was a young university graduate, still planning a career as a clergyman. By the time he returned, he was an established naturalist, well-known in London for the astonishing collections he'd sent ahead. The *Beagle* voyage would provide Darwin with a lifetime of experiences to ponder—and the seeds of a theory he would work on for the rest of his life.

The captain and crew of the HMS *Beagle* originally planned to spend two years on their trip around the world. Instead, the voyage took nearly five years, from December 1831 to October 1836. While the ship systematically measured ocean depths, Darwin went ashore

to explore and collect specimens. In fact, two-thirds of Darwin's time was spent on dry land, largely in the South American wilderness of Brazil, Argentina, Chile and remote areas such as the Galápagos Islands. He brought back specimens of more than 1,500 different species, hundreds of which had never before been seen in Europe.

Throughout his trip, Darwin saw ample evidence that Earth had undergone vast changes. Mountains had risen from the sea. Climates had changed. Many species had gone extinct, leaving fossils as evidence. But how, Darwin wondered, had these changes occurred? Darwin's geological studies left him increasingly convinced that most of these changes had happened over a very long time. Darwin experienced an earthquake that leveled the Chilean town of Concepción. To his amazement, the earthquake had elevated a bank of mussels about eight feet above the sea. If that could happen in one day, Darwin wondered, why couldn't the same process, repeated over millions of years, raise entire mountains?

Darwin was especially interested in where he found each fossil. Studying the geology of the rocks, shells and fossils around it could reveal when the fossilized plant or animal lived. Fossils could also reveal how an environment had changed over time. For example, petrified wood had to start as living trees in a forest habitat, then spend time buried and later rise to its present elevation. Thus a single fossil could tell the story of a slowly changing landscape. Even after the original material has been replaced by stony minerals, fine details of petrified wood are sometimes minutely preserved, down to the structure of individual cells.

Fossils and Living Species: Fossils raised many questions about the origin of species—and not just for Darwin. Discoveries in geology had already challenged the idea that the world and all its species had been created at the same time a few thousand years ago. Fossils clearly showed that in past ages, the world had been inhabited by different species from those existing today. Old species had died out, and new species had appeared at many different times in Earth's history. Fossils also revealed another intriguing pattern: new species tended to appear where similar species had previously lived. Why would one species replace a similar one in the same location? Or perhaps, Darwin would eventually wonder, had the older species somehow given rise to the new ones? Back in London, the relationship between old and new species, as shown in fossils, would become one of the main lines of evidence leading to Darwin's theory of evolution.

Ancient Shells: On the windswept Falkland Islands little grew except "withered grass" and "a few very small shrubs." But Darwin perked up when he cracked some "primitive looking rocks" with his hammer and found fossils. The Falklands were full of brachiopods—two-shelled animals that were once among the most abundant species on Earth. With 35,000 species living at different times over the past 570 million years, brachiopods are excellent for dating the rocks they are found in: Since rocks from different eras contain their characteristic species of brachiopods, one can determine the age of a rock layer by the type of brachiopod fossils found in it. Modern dating methods confirm the accuracy of this technique.

Armored Ancestors? Darwin was delighted by the armadillos he saw scurrying about in Argentina. But most intriguing was the striking similarity of these small, armored mammals to some of the fossils he was unearthing. One such fossil was a glyptodont, an immense shelled animal that looked like a giant armadillo. In fact, to Darwin, many ancient, extinct species seemed to be giant versions of living species. Why had so many species gone extinct, only to be replaced by similar ones? And not just once, but again and again? Perhaps the newer species were better suited to the changing environment, he reasoned.

All around him, he was seeing evidence of slow, gradual, geological changes. But if Earth's changes were slow and gradual, what did that mean for the changes in species? Over long periods of time, could older species have evolved into new ones?

4. **What evidence did Darwin find that convinced him that the Earth may be very old?**
5. **What information did Darwin gain from fossils during his trip?**

During his voyage, Darwin filled numerous notebooks, including the ones on display, with detailed observations on geology, plants and animals. These notebooks contain his notes from the Cape Verde Islands to Rio de Janeiro, Brazil, and from Buenos Aires, Argentina, to the Chilean Andes. Darwin was a precise and patient observer of animals, but his main interest at the time was geology. Over the course of the voyage, he made 368 pages of notes about animals but filled 1,383 pages with geology.

Evidence for Evolution: Neighboring Species: The puzzling distribution of plants and animals in South America and the Galápagos would later make Darwin question how species originated. If each plant and animal was created to match its habitat, why didn't the same species appear in similar environments? Why create the ostrich in Africa and a different running bird, the rhea, in America? And why, within each continent, were there so many variations? One rhea might have been sufficient in South America—yet there were two distinct species, living in adjacent regions. If the two species had arisen from a single common ancestor, it would make sense for them to live close together. When Darwin returned to England and began to examine the origin of species in earnest, the distribution of species would provide some of his more persuasive evidence. The pattern of geographic separation he observed was exactly what one would predict if new species evolved from existing ones.

While exploring the hot, dry "devil's country" near Bahia Blanca, on the coast of Patagonia, Darwin roamed for days on horseback with local cowboys, or gauchos. The gauchos ate whatever they could shoot. A popular meal was the greater rhea, a large, flightless bird Darwin compared to an ostrich. But the gauchos also told Darwin of a second, smaller rhea, which turned out to be not just a smaller variety, but a distinct species, with different coloring, shorter, more feathery legs and blue-tinted eggs. Darwin was anxious to find this lesser rhea, but only after the Beagle sailed several hundred miles down the coast did he finally find one. He later learned that that the lesser rhea lived primarily south of the Rio Negro, and the greater rhea to the north. Why, Darwin wondered, did two such similar species live in neighboring regions? Why was there more than one rhea? In the months and years to come, Darwin eventually would ask himself: could the two rheas perhaps have originated from a common ancestor?

6. **How do the ostriches of Africa and the rheas of South America support the idea of evolution?**
7. **How do the differing species of rhea support the idea of common ancestry?**

Evidence for Evolution: Island Species: The strange plants and animals of the Galápagos Islands puzzled Darwin. Many lived only on the Galápagos—and sometimes only on one specific island. How had these species gotten there? And why weren't they the same as those on similar islands around the world? Instead, in countless details, they were more like species from the mainland of South America. That would make sense if they were migrants. But while many birds, plants, insects, reptiles, and even mollusks on the Galápagos resembled South American species, they were also slightly different. Darwin wondered if species from the mainland had reached the Galápagos, and then changed—as they adapted to this new environment. Over time, could species change?

Different on Each Island: Of all the unusual creatures on the Galápagos Islands, the most impressive are the huge Galápagos tortoises. Darwin was startled to discover that each Galápagos island was "inhabited by a different set of beings." For example, the tortoises on each island were slightly different. Minor differences distinguish the Galápagos tortoises on each island. But there are also two basic types, adapted for different feeding habits. Tortoises from Pinzón (formerly Duncan Island) are "saddle-backed," meaning that their shells rise in the front, like a saddle. This adaptation makes it easier for them to lift their necks and feed on taller cactus. Tortoises from Santa Cruz have "dome-shaped" shells. Animals with these shells live on islands where most of the vegetation is close to the ground, making it unnecessary to raise their heads to feed.

Giant Daisies: On the Galápagos, Darwin found plants that were related to daisies and sunflowers—but grew to the size of trees. Like the marine iguanas, these island residents seemed to have adapted to their environment: with plenty of sun and little competition, daisies and cactuses could grow to the size of trees. Darwin noticed another "truly wonderful fact" about these giant daisy relatives. He had found six species, now classified in the genus *Scalesia*, and remarkably, "not one of these six species grows on any two islands." It was not enough that they were found only on the Galápagos—each species was found on only one island. The same was true of dozens of other plants. What could account for this diversity?

Birds of a Feather: Darwin was intrigued that almost all the birds on the Galápagos resembled birds from the mainland. The chief difference was in their coloring. Most tropical birds have bright plumage, but on the grim Galápagos islands, the birds were "generally more dusky colored." Like the iguanas, they seemed to have adapted to match the dark lava around them. A rare exception was the brightly colored vermilion flycatcher. Perhaps it was not a true Galápagos bird, Darwin thought: "It is worthy of remark, that the only land-bird with bright colours, is that species of tyrant-flycatcher, which seems to be a wanderer from the continent." It appeared that only species found solely on the Galápagos were colored to match its lava backdrop.

Winging It: Though it is related to the 35 other cormorant species around the world, the flightless cormorant lives only the Galápagos Islands. And while all other cormorants can fly, this one cannot. Its wings are, however, perfectly suited to swimming—much more useful than flying when searching for octopus, its favorite food. Before humans arrived on the Galápagos, the cormorant had no natural predators, so it had no need to fly. It was wonderfully adapted to its isolated environment. But when people came, bringing dogs, cats and pigs with them, the defenseless birds were at their mercy. Their numbers have dropped dramatically, and now they are rare.

A Long Way from the South Pole: When most people think of penguins, they think of Antarctica, where these flightless seabirds waddle over the ice and dive for fish and krill. But some penguins live on the coast of South America, thanks to a cold, north-flowing ocean current, and one tiny penguin lives in the tropics. Instead of huddling for warmth, it must battle the blazing heat of the sunbaked Galápagos Islands. The Galápagos penguin is not only the smallest penguin, and the only one found near the equator, but it is probably the only penguin that has to hold its wings outstretched over its webbed feet to prevent sunburn. Once again, Darwin had found an example of a unique species that lived only in the Galápagos, but which seemed to be a modified version of a species from somewhere else—as if it had somehow become specially adapted to its island environment.

Solving a Mystery: Many corals form rocky reefs that rise from hundreds of feet beneath the sea. Before Darwin, how these large reefs formed remained a mystery. The animals that build coral reefs live only near the sunlit surface. They cannot survive in the dark water at the base of the reef—making it impossible to build a large reef from the bottom up. But clearly they could not build from the top down! So how did they do it? Ironically, the answer occurred to Darwin while he was thinking about the rise of the Andes Mountains. If land could slowly rise over millions of years, as geologist Charles Lyell argued, it could also sink. Suppose a coral reef was growing in shallow water. What if the sea floor began to sink? The reef would grow upward to stay near the sunny surface. The more the sea floor lowered, the taller the reef would grow. Eventually, a huge reef would form, with the bottom anchored in the dark depths—even though the entire reef was built by animals living near the surface.

Reaching for the Sun: Coral reefs are made by living animals. The main reef-builders are colonies of tiny coral polyps, which secrete layer after layer of limestone. Over many years, this limestone can form an immense reef. Reef-building corals live only in clear, shallow water, because their bodies contain living, photosynthetic algae that need light to grow. The coral cannot survive without these algae. So like plants spreading their leaves, they grow up and out to capture more sunlight.

A New Perspective: At the beginning of his voyage, Darwin saw animals like the iguana as unique marvels. But by the end, he was looking at species in a different way: He was becoming interested in how species might be related to one another. Green iguanas were common on the mainland, but they were absent on the Galápagos; instead these islands had their own unique species. Why? Where had these species come from? Eventually Darwin would wonder: Could species from the mainland have reached the Galápagos and somehow changed into the species he found there?

The Idea Takes Shape:

Darwin was something of a **scientific celebrity** when he got back to England. The strange fossils and unfamiliar animals he had shipped home gained him entry into London's learned circles. Determined to earn the respect of the men he called the "great guns," Darwin threw himself into work. **Sorting his *Beagle* specimens and arranging for experts to analyze them** were his first priority. What these authorities told him about his specimens—particularly the fossils and the birds—would profoundly affect his developing theories.

Galápagos finches: Darwin's Galápagos birds told an amazing story. A group of Galápagos specimens he had thought included many different birds were actually all

finches. They were just finches that looked remarkably different from one another—almost as if, he would later write, "one species had been taken and modified for different ends." Did islands—and isolation—somehow give rise to new species? Had all these diverse-looking finches, and these species of mockingbirds, diversified from South American ancestors? These Galápagos birds show a wide range of beak shape and size, but they are all finches. Seeing this kind of variation among birds of the same kind made Darwin question the idea that species are fixed and unchanging.

8. Discuss at least three forms of evidence for evolution and common ancestry that are supported by Darwin's observations in the Galapagos Islands.

Darwin relied on his notebooks. The notebooks reveal a great mind homing in on a great idea: plants and animals are not fixed and unchanging. Instead, **all species are related through common ancestry, and they change over time.** He drew a crude—but unmistakable—**evolutionary tree**. This drawing, with the most ancient forms at the bottom and their descendants branching off irregularly along the trunk, reveals that Darwin understood all plants and animals are related.

Darwin's Evidence: Structure: Limbs that look very different and serve different functions—"the hand to clasp, the bat's wing to fly . . . the porpoise to swim"—are often much alike in skeletal design. For Darwin, this resemblance was further evidence that large classes of organisms, such as mammals, shared a common ancestry. Here, each of the bones in this bat wing has a counterpart in the bones of a human hand.

9. Explain how skeletal structure can provide support for common ancestry.

Infinite Variety: Darwin knew that starlings looked like other starlings, of course, and moles like other moles. And Darwin also knew that within a nest or a litter, no two individuals look exactly alike. But Darwin, unlike anyone else, was absorbed in thinking about evolution, and he started to wonder about the **small differences between individuals of the same kind.** Why did they exist? Could they be useful? A country gentleman by birth, Charles knew a lot about domesticated animals. He was aware that people often bred animals with desirable traits, and that over time such breeding exaggerated small differences. Horses were horses, but one bred for hunting looked very different from one bred to pull heavy loads. Dogs were dogs, but a tiny lap dog and a large, lean greyhound looked nothing alike. Somehow, Darwin thought, variation is the key to understanding how species change.

"A Theory by Which to Work": Darwin always read widely, on the lookout for new ideas. In late September 1838 he found himself reading—"for amusement," he later recalled—the "Essay on Population" by political economist Reverend Thomas Malthus. In this essay, Malthus argued that human population could quickly outstrip the food supply: competition for food or space was a constant force keeping population in check.

Darwin immediately saw how the idea could be applied to the natural world. **More animals were born than could survive.** They constantly struggled against one another for food or room to grow, he thought. That meant any plant or animal with a competitive edge—drought tolerance, a thicker-than-average coat—could live longer and leave more offspring than its

fellows. The presence of such adaptations controlled, in effect, which individuals would represent the species in the next generation. Now Darwin could see how variation could make a difference: **individuals with useful traits would, on average, survive to reproduce and pass along those traits.**

Adding it Up: By the late summer of 1842 Darwin felt ready to commit an outline of his theory to paper. The main points were clear: plants and animals with useful—and heritable—variations were likely to live longer. That meant they could leave more offspring, some of which would carry the new trait. Over time, **species could change through this process of "natural selection,"** a term Darwin first uses here.

Darwin's rough sketch of his argument is almost a miniature version of his future masterwork, the *Origin of Species*. Yet he kept his ideas under wraps for nearly two decades more. Darwin wasn't finished thinking: some critical details were still to come. And he knew he needed to amass a great deal of evidence to convince others of such a radical idea. It took a letter from the Malay Archipelago—a letter outlining another man's version of natural selection—to push him into print. Shutting himself in his study, working feverishly, Darwin finally produced the *Origin of Species*.

The letter delivered in June 1858 was shocking. Sent by the young naturalist Alfred Russel Wallace, it outlined a theory of evolution by natural selection eerily like Darwin's own. Darwin was distraught: after all the years of work and worry, someone else would get the credit. But Darwin's friends, botanist Joseph Hooker and geologist Charles Lyell knew Darwin had written an essay containing those ideas nearly 15 years ago, so clearly he had developed the theory first. Hooker and Lyell arranged a compromise: Wallace and Darwin would both have papers on the theory presented at the Linnean Society in London. In little more than a year, he would publish his greatest book, *On the Origin of Species by Means of Natural Selection*.

10. What are the main ideas at the base of Darwin's work, *On the Origins of Species*?

How Does Natural Selection Work?: Natural selection is a mechanism by which populations adapt and evolve; those individual organisms who happen to be best suited to an environment survive and reproduce most successfully, producing many similarly well-adapted descendants. After numerous such breeding cycles, the better-adapted dominate. Nature has filtered out poorly suited individuals and the population has evolved. Natural selection is **a simple mechanism that causes populations of living things to change over time.** In fact, it is so simple that it can be broken down into five basic steps, abbreviated here as V.I.S.T.A.: Variation, Inheritance, Selection, Time and Adaptation.

Variation and Inheritance: Members of any given species are seldom exactly the same, either inside or outside. Organisms can vary in size, coloration, ability to fight off diseases and countless other traits. Such variation is often the result of random mutations, or "copying errors," that arise when cells divide as new organisms develop. When organisms reproduce, they pass on their DNA—the set of instructions encoded in living cells for building bodies-to their offspring. And since many traits are encoded in DNA, **offspring often inherit the variations of their parents.** Tall people, for example, tend to have tall children.

Selection, Survival, and Reproduction: Environments cannot support unlimited populations. Because resources are limited, more organisms are born than can survive: some individuals will be more successful at finding food, mating or avoiding predators and will have a better chance to thrive, reproduce and pass on their DNA. **Small variations can influence whether or not an individual lives and reproduces.** Differences in color, for instance, aid some individuals in camouflaging themselves from predators. Sharper eyes and claws help an eagle catch its dinner. And brighter coloration improves a male peacock's chances of attracting a mate.

Time and Adaptation: In generation after generation, advantageous traits help some individuals survive and reproduce. And these traits are passed on to greater and greater numbers of offspring. After just a few generations or after thousands, depending on the circumstances, such traits become common in the population. **The result is a population that is better suited—better adapted-to some aspect of the environment than it was before.** Legs once used for walking are modified for use as wings or flippers. Scales used for protection change colors to serve as camouflage.

How Do We Know Living Things are Related? Overwhelming evidence shows us that all species are related—that is, that they are all descended from a common ancestor. One hundred and fifty years ago, Darwin saw evidence of these relationships in striking anatomical similarities between diverse species, both living and extinct. Today, we realize that most such resemblances—in both physical structure and embryonic development—are expressions of shared DNA, the direct outcome of a common ancestry.

11. Summarize how the process of natural selection works.

APPENDIX F: ASSESSMENT INSTRUMENTS

F.1: Views on Science Questionnaire 1 (VSQ1)

Views on Science Questionnaire 1

Instructions:

Each question in this questionnaire starts with a statement about the nature of science. Most statements adopt a certain stance. You may strongly agree with it, strongly disagree with it, or have other thoughts about it. Each statement is followed by several responses. Please read all of the responses first, then circle your opinion on the right side (SD, D, U, A, SA) of each response according to your knowledge of the scientific activities or scientists. There is no right or wrong answer, but your accurately reporting your opinion is important. Thank you.

SD	=	Strongly Disagree
D	=	Disagree
U	=	Uncertain or No Comment
A	=	Agree
SA	=	Strongly Agree

1. Scientific investigations are influenced by socio-cultural values (e.g. society's current trends, values).					
A. Yes, socio-cultural values influence the direction and topics of scientific investigations.	SD	D	U	A	SA
B. Yes, because scientists participating in scientific investigations are influenced by socio-cultural values.	SD	D	U	A	SA
C. No, scientists with good training will remain value-free when carrying out research.	SD	D	U	A	SA
D. No, because science requires objectivity, which is contrary to the subjective socio-cultural values.	SD	D	U	A	SA
2. When scientists are conducting scientific research, will they use their imagination?					
A. Yes, imagination is the main source of innovation.	SD	D	U	A	SA
B. Yes, scientists use their imagination more or less in scientific research.	SD	D	U	A	SA
C. No, imagination is not consistent with the logical principles of science.	SD	D	U	A	SA
D. No, imagination may become a means for a scientist to prove his/her point at all costs.	SD	D	U	A	SA
E. No, imagination lacks reliability	SD	D	U	A	SA
3. Even if scientific investigations are carried out correctly, the theory proposed can still be disproved in the future.					
A. Scientific research will face revolutionary change, and the old theory will be replaced.	SD	D	U	A	SA
B. Scientific advances cannot be made in a short time. It is through a cumulative process; therefore, the old theory is preserved.	SD	D	U	A	SA
C. With the accumulation of research data and information, the theory will evolve more accurately and completely, not being disproved.	SD	D	U	A	SA
4. Is a scientific theory (e.g. natural selection, atomic theory) discovered or "invented" by scientists from the natural world?					
A. Discovered, because the ideas was there all the time to be uncovered.	SD	D	U	A	SA
B. Discovered, because it is based on experimental facts.	SD	D	U	A	SA
C. Some scientists discover a theory accidentally, but other scientists may invent a theory from their known facts.	SD	D	U	A	SA
D. Invented, because a theory is an interpretation of experimental facts, and experimental facts are discovered by scientists.	SD	D	U	A	SA
E. Invented, because a theory is created or worked out by scientists.	SD	D	U	A	SA
F. Invented, because a theory can be disproved.	SD	D	U	A	SA

Views on Science Questionnaire 1 (continued)

5. Is a scientific law (e.g. gravitational law) “discovered” or “invented” by scientists from the natural world?					
A. Discovered, because scientific laws are out there in nature, and scientists just have to find them.	SD	D	U	A	SA
B. Discovered, because scientific laws are based on experimental facts.	SD	D	U	A	SA
C. Some scientists discover a law accidentally, but other scientists may invent a law from their known facts.	SD	D	U	A	SA
D. Invented, because scientists invent scientific laws to interpret discovered experimental facts.	SD	D	U	A	SA
E. Invented, since there are no absolutes in nature, therefore, the law is invented by scientists.	SD	D	U	A	SA
6. In comparison to laws, theories have less evidence to support them.					
A. Yes, theories are not as definite as laws.	SD	D	U	A	SA
B. Yes, if a theory stands up to many tests it will eventually become a law, therefore, a law has more supporting evidence.	SD	D	U	A	SA
C. Not quite, some theories have more supporting evidence than some laws.	SD	D	U	A	SA
D. No, theories and laws are different types of ideas. They cannot be compared.	SD	D	U	A	SA
7. Scientists’ observations are influenced by personal beliefs (e.g. personal experiences, presumptions); therefore, they may not make the same observations for the same experiment.					
A. Observations will be different, because different beliefs lead to different expectations influencing the observation.	SD	D	U	A	SA
B. Observations will be the same, because the scientists trained in the same field hold similar ideas.	SD	D	U	A	SA
C. Observations will be the same, because through scientific training scientists can abandon personal values to conduct objective observations.	SD	D	U	A	SA
D. Observations will be the same, because observations are exactly what we see and nothing more. Facts are facts. Interpretation may be different from one person to another, but observations should be the same.	SD	D	U	A	SA
E. Observations will be the same. Although subjectivity cannot be completely avoided in observation, scientists use different methods to verify the results and improve objectivity.	SD	D	U	A	SA
8. Most scientists follow the universal scientific method, step-by-step, to do their research (i.e. state a hypothesis, design an experiment, collect data, and draw conclusions).					
A. The scientific method ensures valid, clear, logical and accurate results. Thus, most scientists follow the universal method in research.	SD	D	U	A	SA
B. Most scientists use the scientific method because it is a logical procedure.	SD	D	U	A	SA
C. The scientific method is useful in most instances, but it does not ensure results; therefore, scientists invent new methods.	SD	D	U	A	SA
D. There is no so-called scientific method. Scientists use any methods to obtain results.	SD	D	U	A	SA
E. There is no fixed scientific method; scientific knowledge could be accidentally discovered.	SD	D	U	A	SA

F.2: Views on Science Questionnaire 2 (VSQ2)

Views on Science Questionnaire 2

Instructions:

Each question in this questionnaire starts with a statement about the nature of science. Most statements adopt a certain stance. You may strongly agree with it, strongly disagree with it, or have other thoughts about it. Each statement is followed by several responses. Please read all of the responses first, then circle your opinion on the right side (SD, D, U, A, SA) of each response according to your knowledge of the scientific activities or scientists. There is no right or wrong answer, but your accurately reporting your opinion is important. Thank you.

SD	=	Strongly Disagree
D	=	Disagree
U	=	Uncertain or No Comment
A	=	Agree
SA	=	Strongly Agree

1. When doing science, scientists usually collaborate with other scientists.					
A. Yes, because scientists develop better ideas when considering other scientists' thinking or work.	SD	D	U	A	SA
B. Yes, because scientists are required to "check" each other's ideas for their validity.	SD	D	U	A	SA
C. No, working with other scientists increases the chance that cultural and other subjective factors will influence the work being done.	SD	D	U	A	SA
D. No, scientists do not want to risk sharing the glory of discoveries with other scientists.	SD	D	U	A	SA
E. No, scientific ideas are usually due to the work of one great mind.	SD	D	U	A	SA
2. How do scientists make conclusions from their data?					
A. Data clearly points to a valid conclusion.	SD	D	U	A	SA
B. Scientists have to interpret data to make sense of it.	SD	D	U	A	SA
C. When scientists are objective, data speaks for itself, it doesn't require interpretation.	SD	D	U	A	SA
D. Good scientific data leads clearly to valid conclusions.	SD	D	U	A	SA
E. Scientists create ideas to be consistent with data.	SD	D	U	A	SA
3. How much time is required for scientific ideas to be developed and accepted?					
A. Most scientific ideas that end up being accepted are developed rather quickly (in days to a few weeks).	SD	D	U	A	SA
B. Once developed, little time is required for scientific ideas to be conclusively accepted (days to weeks).	SD	D	U	A	SA
C. Most scientific ideas that end up being accepted are developed over long periods of time (years to decades).	SD	D	U	A	SA
D. Once developed, much time is required for scientific ideas to be conclusively accepted (years to decades).	SD	D	U	A	SA

F.3: Attitude and Interest Survey

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. Please use the following scale to rank how interesting you found the short story about Mendel.

1	2	3	4	5
Very Uninteresting		Neutral		Very Interesting

2. Please use the following scale to rank how interesting you found the short story about Darwin.

1	2	3	4	5
Very Uninteresting		Neutral		Very Interesting

3. To what extent did the short stories teach you something new about how science works?

1	2	3	4	5
Not at all		Somewhat		Very much

4. To what extent did the short stories change some of your views regarding how science works?

1	2	3	4	5
Not at all		Somewhat		Very much

5. To what extent did you find the short stories to be more interesting than readings from your textbook?

1	2	3	4	5
Much less interesting		No difference		Much more interesting

6. If assigned short stories were to replace class readings from the textbook, how many of these kinds of short stories would you like as part of your class?

None _____ 1-2 _____ 3-4 _____ 5+ _____

7. To what extent did the short stories impact your interest in science as a career?

1	2	3	4	5
Reduced Interest		No Impact		Increased Interest

We would very much appreciate your constructive comments about the shorts stories. Please write your comments on the back of this sheet. Thank you for your time and input into this project.

APPENDIX G: STUDENT COMMENTS ABOUT THE STORIES

Table 10. Students' comments about the stories from the treatment group survey.

Student ^a	Comments
2	I don't like reading the short stories because there is nothing that interests me. Most of us just look for key words just to answer the questions. We forget stuff right away.
3	I think the stories are better than reading just from the book. The stories told me things about Mendel etc. that I never knew. I'm glad we did them.
4	The stories were more interesting than reading a textbook, but not greatly entertaining. I learned from them and understood the material better than I would have had I read in the textbook.
5	The stories were kind of boring and confusing.
6	Most of the stories were interesting because they covered the topics broadly.
7	I liked the stories because of the questions during the reading helped me review. Easier to understand than the book.
8	The stories did not impact me and I'd much rather have had a different assignment, because it was boring.
9	The short stories didn't make much sense to me, it didn't keep my attention therefore I remember NOTHING about either of them.
10	I liked the stories better than just reading from the book, but they didn't necessarily teach me as much as the book does.
11	I liked the short stories a lot more than reading out of the books. They were much more interesting.
12	It didn't really impact my opinions. A few short stories are all right but textbooks are more helpful than short stories.
13	The short stories were a lot more interesting to read then reading out of the text book. I also learned quite a bit from them.
14	The short stories were similar to reading out of a textbook, but the short stories became confusing because they seemed above my level and confusing.
15	I didn't like them at all and did not understand any of them.
17	I liked how they were very descriptive.
20	They seemed dull and a waste of time. I felt there was too much background information. I'd rather just read about the discoveries.
24	Learning about the actual people was the uninteresting part. Learning about the ideas I feel was interesting.
27	I thought that the short stories were a lot better than reading from the textbook. It was a lot easier to understand.
32	Just felt like any other reading

a. 32 of 33 students in the treatment group completed the survey.
19 of these students wrote comments related to the use of the stories.

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