Using the History of Research on Sickle-Cell Anemia to Affect Preservice Teachers’ Conceptions of the Nature of Science

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USING THE HISTORY OF RESEARCH ON SICKLE-CELL ANEMIA TO AFFECT PRESERVICE TEACHERS' CONCEPTIONS OF THE NATURE OF SCIENCE

by

Eric M. Howe

A Dissertation
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Preservice elementary teachers enrolled in an elective biology course participated in an eight-class unit of instruction based on the history of research in understanding the disease sickle-cell anemia. Students were introduced to the disease as a “mystery” for them to solve, and subsequently developed an understanding of the disease from several disciplines in biology (e.g., genetics, ecology, evolution, molecular biology). The unit involved open-ended problems in which students examined evidence and developed explanations in a manner analogous to the reasoning used by Anthony C. Allison and his colleagues during the early to middle part of the twentieth century.

Throughout the unit, students were challenged to explicitly and reflectively connect their work with the historical material to more general conclusions about aspects of the nature of science. These aspects included (a) the nature of scientific theories, (b) the tentative nature of science, (c) the difference between scientific theories and laws, (d) the validity of observational methods in science, and (e) the subjective (theory-laden) nature of science. The research measured students’ pre- and post-instruction views by using both an open-ended survey (VNOS) and follow-up, semi-structured interviews.

The results indicated that an appreciable number of students underwent a change or enrichment in their views for some of the nature of science aspects. Moreover, change or enrichment in students’ views was directly attributable to their work in the sickle-cell unit as evidenced from the specific examples students articulated in their post-
instruction responses in support of their more informed views. In general, the findings of this research lend empirical support to the value of having students actively recapitulate the history of science to improve their nature of science conceptions. This is facilitated when the lessons challenge students to *explicitly and reflectively* develop views of the nature of science in tandem with their examinations of the problems taken from the history of science.
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The success of this project simply would not have been possible without the critical insights offered by my committee members. Though for the majority I incorporated their suggestions, there were a few instances in which I kept to my original prose and line of thought. In the unlikely event that this weakens my argument or the conclusions that I draw, the fault is entirely mine.

Finally, special regards should go to two fellow graduate students, Robert Keys and Uric Geer for their support and fruitful discussions regarding graduate work. Particular thanks goes to Uric for his collaboration in the data collection of this project.

Eric M. Howe
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CHAPTER 1

INTRODUCTION

Having students achieve a more informed understanding of various aspects of the nature of science has been a goal of science educators for over a century (DeBoer, 1991). Though there is no consensus among stakeholders (e.g., science educators, historians and philosophers of science, practicing scientists) as to what constitutes the nature of science\(^1\), recent science education reform documents explicitly characterize several aspects (e.g., Appendix A) and further stress the importance of having students learn about the nature of science in addition to learning science content (AAAS, 1990, 1993; National Research Council, 1996). Support for this position rests on the recognition that a genuine understanding of science involves learning about methodology and epistemology of science in addition to science content. This stands in contrast to a more naïve view often held by students that science is merely a body of factual “truths” to be memorized.

One difficulty faced by science educators is that naïve beliefs about the nature science held by their students are quite tenacious and resistant to change (Abd-El-Khalick & Lederman, 2000). Research on conceptual change documents that the tenacity of alternative conceptions complicates efforts to move students from a naïve to a more informed view (Posner, Strike, Gertzog, & Hewson, 1982; Strike & Posner, 1992). The challenge to teachers is how to best adopt methods or structure their lessons such that students improve their conceptions of the nature of science while at the same time ensuring that students develop a robust conceptual understanding of the material.

\(^1\) For this reason, some (e.g. Abd-El-Khalick, 1998; Lederman & Abd-El-Khalick, 2000) suggest referring to the issues as “Nature of Science” instead of “The Nature of Science”.
Several researchers claim that one way to foster an understanding of aspects of the nature of science is to more heavily integrate the history and philosophy of science into the lessons (e.g., Brush, 1989; Conant, 1951; Duschl, 1990; Klopfer, 1964; Mathews, 1994; Monk & Osborne, 1997; Wandersee, 1992). The advantages of using the history of science to teach science have been argued from different perspectives. Moreover, there are several suggested methods for how history can best be incorporated to improve students’ learning of science (e.g., Allchin, 2000; Hagen, Allchin, & Singer, 1996; Mathews, 1994; Roach & Wandersee, 1993; Solomon, Duveen, Scot & McCarthy, 1992).

The project described in this study empirically measured how students’ conceptions of certain issues associated with the nature of science were affected by an historical and subdisciplinary approach to learning about the disease sickle-cell anemia. As part of a three-unit sequence of an introductory biology course for elementary education majors, the final unit consisting of eight lesson invited students to explore a “mystery disease” (sickle-cell anemia) from the perspective of six different subdisciplines of biology. Students recapitulated the reasoning done by Anthony C. Allison (and his colleagues) during the 1940’s and 1950’s that led to recognition of how sickle-cell anemia can be understood from the standpoint of molecular biology, genetics, cell biology, physiology, ecology, and evolution. In so doing, students were challenged to construct and test their own provisional theories for why an otherwise debilitating disease is prevalent in central Africa and other malaria infested regions.

The lessons incorporated open-ended problems in which students were challenged to propose and defend their theories in light of the available evidence. A significant portion of each class used group problem solving and discourse. The
instructor facilitated these sessions by leading explicit discussions, particularly when the lessons highlighted the targeted aspects of the nature of science that students' should have been considering. In this way, aspects of the nature of science were considered as planned, instructional activities in which students were challenged to reflect on their own how the significance of their work on the sickle-cell phenomenon related to more general interpretations of the nature of science.

The efficacy of this unit in helping participants develop a more robust understanding of the nature of science was assessed by means of an open-ended survey and semi-structured interviews. Analysis of the results of these instruments suggested that the use of an historical and subdisciplinary approach to teaching can lead to appreciable change or enrichment in student understanding of the nature of science.

Rationale for the Study

In the absence of an understanding of the nature of science, students often believe science is a body of factual knowledge that is to be memorized rather than think about science as a process to generate understanding about the world. Moreover, even when they acknowledge the existence of a process by which scientific knowledge is generated, they often have naïve views about the process of science. Various science educators, historians, philosophers and sociologists of science, and practicing scientists have for some time been concerned with how to best conduct the teaching of science such that this naïve conception is addressed. A general approach many of these stakeholders advocate emphasized the potential of incorporating the history and philosophy of science into the teaching of science (e.g., Matthews, 1994; Monk & Osborne, 1997; Palmquist & Finley, 1997; Wandersee, 1992) to affect or improve students' conceptions of the nature of science. The goal of the present study is to examine the efficacy of a unit developed from a specific episode in the history of
science to improve preservice teachers' conceptions of certain aspects of the nature of
science.

One reason for doing this study is to add to the research literature on using the
history and philosophy of science for the teaching of science. From a theoretical
standpoint, there have been a number of reasons suggested why using history can
improve students' understanding of science (e.g., Matthews, 1994). These range from
the affective dimension (that students will appreciate the humanistic side of science) to
the epistemological dimension (that using history can give insight into how knowledge
is constructed, validated, and evaluated). This research is aimed more toward promoting
students' epistemological understanding of science. From a practical standpoint, this
research will provide insight into one method of developing an historically-based
science unit and the effectiveness of this method in teaching to targeted aspects of the
nature of science. This method can be contrasted with other suggested approaches for
using history in the classroom.

More generally, the results from this study add to our current understanding of
the alternative conceptions that students possess about targeted aspects of the nature of
science. This is important because in the absence of a comprehensive awareness of
student alternative conceptions, preservice elementary education students who go on to
teach (the population being studied in this study) will themselves be far less effective in
identifying antecedent naïve views and will therefore be less effective in facilitating
conceptual change in their own classrooms.

The timing of this study is very appropriate when considering the recent
attention given by science education reform documents in calling for the need to
increase student awareness of the nature of science (e.g., AAAS, 1990, 1993; NRC,
1996). Despite doing a laudable job of identifying what aspects of the nature of science
are important for teachers (and students) to consider, there has been less attention given
on how to specifically facilitate such an understanding through lesson design or pedagogical delivery. A review of the literature indicates that the research is clearly in the formative stage, as evidenced by the increasing number of empirical studies done in the last fifteen years designed to address various aspects of learning about the nature of science.

Theoretical Framework

The theoretical framework for this study draws from several sources. As such, the conclusions from this research will contribute to multiple domains. The reason for the composite framework is that an informed understanding of students’ learned conceptions of the nature of science requires a multifaceted approach in which we must consider how students formulate and develop their conceptual understandings (issues of cognition and conceptual change) and how use of history and philosophy in the classroom can affect those understandings. What follows is a brief introduction to the theoretical domains.

With respect to cognition, the theoretical framework of this study derives from two areas, constructivist theory and the theory of conceptual change. Constructivism is based on the claim that students’ learning is largely the product of how they develop personal meaning through a process of taking new conceptual information and assimilating or accommodating it into their own knowledge frameworks (Piaget, 1959). These ideas are further developed by Ausubel (1960, 1968) in his claims of meaningful learning.

Conceptual Change Theory (Wandersee, Mintzes & Novak, 1994) seeks to explain how and why students adopt alternative conceptions that are themselves highly resistant to change. Included in this theory is a model of conceptual change (Posner, Strike, Gertzog & Hewson, 1982; Strike & Posner, 1992) that describes a method for
facilitating students to abandon alternative or naïve conceptions in favor of more informed ones. The model of conceptual change rests on the foundation of constructivism (Piaget, 1959). This model presumes that students enter into the learning environment with certain views of science content and epistemology. The mechanics of a pedagogy aligned with a conceptual change strategy are such that students are challenged to see the failings of their naïve views when placed in a scenario in which contemporary insight into the nature of science is a more intelligible and plausible solution.

The importance of constructivism and conceptual change theory form the cognitive basis for the design and implementation of the pedagogy of the sickle-cell unit toward affecting students' views of the nature of science. In this regard, an explicit and reflective approach (c.f., Akerson, Abd-El-Khalick & Lederman, 2000; Khishfe & Abd-El-Khalick, 2002) is used to have students consider the ramifications of their work with the historical material to an understanding of germane aspects of the nature of science. An explicit approach, in contrast to an implicit approach, rests on the belief that issues associated with the nature of science should be considered as planned cognitive outcomes in which students must actively construct their own understanding. These issues are further developed in the literature review.

A third source of research that forms the basis of this study is work done by science educators who draw attention to the importance of work by historians and philosophers of science on the creation, development and validation of scientific knowledge (e.g., Duschl, 1990). Recent work (e.g., Abd-El-Khalick & Lederman, 2000) has emphasized the importance of post-positivist developments in history and philosophy of science on our understanding of the nature of science (e.g., Feyerabend, 1978; Kuhn, 1970; Toulmin, 1953). These developments (e.g., emphasis on the tentative and subjective nature of science) require science educators to reconsider, contra the
trainings of the logical positivists, many of the fundamental claims about the nature of science that underlie current reform efforts.

Finally, the study also draws heavily upon techniques to assess student conceptions of the nature of science developed by Lederman and his associates (e.g., Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002). This research supports the use of open-ended surveys and follow-up interviews as valid and effective tools to characterize and measure change in students' views.

Statement of the Problem

Students have naive conceptions of the nature of science, in particular understanding how scientific knowledge is generated and validated. These conceptions often center on the belief that science is a fixed body of absolute truths (Horner & Rubba, 1978; McComas, 1996). Embedded in this perspective is the belief that theories are conjectures that are validated solely through experimentation. The more a theory "stands up" to experimental testing, the more likely that the theory represents the "absolute" truth. Furthermore, students also fail to recognize the personal role that scientists have in the construction of scientific knowledge (Abd-El-Khalick, 1998; Palmquist & Finley, 1997). Their naive view is often evident when students situate scientific knowledge as the product of objective interpretation.

Improving students' understanding of aspects of the nature of science has been a goal of science education for over a century, with recent emphasis placed in science education reform documents in the late 1980's and early 1990's (e.g., AAAS, 1990, 1993; NRC, 1996). At the same time, these reform documents call attention to the need to have students appreciate the role that history and philosophy of science play in our understanding of science. This latter point has been the emphasis of numerous theoretical and empirical studies in science education. A general claim by science
educators who advocate emphasizing the history and philosophy of science in the teaching of science (e.g., Mathews, 1994) is that such an emphasis will lead to an increased understanding of aspects of the nature of science.

Others (e.g., Abd-El-Khalick & Lederman, 2000) caution of the difficulties inherent to using the history and philosophy of science to enhance learners’ conceptions of the nature of science. Here, the general claim is that students enter the science classroom with an understanding of the nature of science that is built upon many years of prior experiences and learning. Quite often, the views of science that students have constructed are at once naïve and very robust and as such are difficult to change. Using the history and philosophy of science often requires that students “put on a different thinking cap” in order to consider the validity of scientific ways of knowing as emphasized in an historical lesson. Abd-El-Khalick & Lederman caution that “learners often dismiss historical scientific notions as wrong ways of explaining the natural world,” (p. 1061) because they have difficulty abandoning their antecedent views of science to consider the validity of historical conclusions or ways of thinking.

The philosopher of science Thomas Kuhn (1962, 1970) in discussing his incommensurability thesis points out that scientists who work under one scientific paradigm cannot by virtue of their theoretical, ontological and other commitments come to understand the epistemological positions advocated by scientists operating in another paradigm. A general analogy is often drawn between Kuhn’s thesis and the difficulty that students have in understanding the relevance of historical ways of thinking. But Kuhn himself acknowledges in his text The Essential Tension (Kuhn, 1977) that given enough personal investment, he was able to abandon his antecedent Newtonian paradigm in order to understand the conceptual merit of an Aristotelian way of thinking with regard to understanding the motion of bodies.
Given all of this, the question of interest becomes how to design and implement lessons that incorporate the history and philosophy of science so that students are placed in a role whereby they recapitulate the reasoning used by historical scientists and so that they can link the conclusions that they draw from such thinking to more informed conceptions of the nature of science. The purpose of this study is to investigate the efficacy of using a series of lessons developed from the history of research on sickle-cell anemia toward changing or enriching preservice elementary teachers' understandings of certain aspects of the nature of science.

In this regard, the study was intended to address two fundamental questions:

1. Do explicit and reflective instructional techniques improve students' nature of science views in a unit that emphasizes the history of science?

2. Are some nature of science views more apt to change than others using explicit and reflective techniques in a unit that emphasizes the history of science?

General Format of the Sickle-cell Unit

The unit was the last of a three-part sequence that forms the course, BIOS 270, Life Science for Elementary Educators II. BIOS 270 is one of six classes offered through the Mallinson Institute for Science Education at Western Michigan University for those students who major in elementary education and pursue a minor in science and mathematics. Each of the six science classes features an open-ended problem-solving environment in which students are encouraged through inquiry and discourse to construct scientific models and to understand common student alternative conceptions to learning science. Of the six classes, two are devoted to the teaching and learning of biology - BIOS 170 and BIOS 270. BIOS 170 includes three units devoted to anatomy

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2 A more detailed discussion of how the history of science is used and how the pedagogy is implemented is given in Appendix D.
and physiology, ecology, and evolution. BIOS 270 contains units on genetics, molecular and cellular biology, and a final capstone unit that is devoted to examining the disease sickle-cell anemia.

The capstone unit, which is the focus of this research project, is an encapsulation of both biology courses. In it students explore a single biological disease, sickle-cell anemia, from the perspective of multiple biological subdisciplines (e.g., molecular biology, genetics, cellular biology, physiology, population evolution, and ecology). The subdisciplinary approach is based upon the history of research on the disease. Students are invited to recapitulate the reasoning that led Anthony C. Allison and his colleagues during the 1940's and 1950's to recognize how the disease can be understood from multiple perspectives. The unit is composed of eight, two-hour classes, which require a total of four weeks to complete.

Sickle-cell anemia is an ideal candidate for this approach for two reasons. First, there are accessible "problems" in each of the subdisciplines for students to consider, and moreover these problems are well suited to being examined from an historical perspective. Second, there are strong connections among the evidence situated in the subdisciplines such that students are required to consider how the knowledge they have constructed in one context plays a role in the problems they are working on in another.

The unit begins by introducing students to a "mystery patient" who exhibits unusual symptoms. Over the course of eight classes they are challenged to develop an explanation of these symptoms by way of examining the disease from several subdisciplinary perspectives. Each class is then devoted to having students consider how a biologist from within a particular subdiscipline (e.g., ecology, molecular biology) examines problems and interprets data toward constructing an understanding of some aspect of the mystery disease.
The problems that students examine in each of the subdisciplinary classes have a basis in the history of research on sickle-cell anemia. During each class, students are provided historical data that they can use to construct their own explanations for the problems they are trying to solve in the particular class. The results of their investigations, often in the form of their own provisional theories or in the form of new evidence, are used during the course of classes both to foster student inquiry (and discourse) and to motivate the subsequent classes. In the context of each class, students “do science” in that they analyze data, make conjectures, provide (or refute) evidence and draw conclusions.

The use of history is explicit. Students are made aware that they are essentially recapitulating the historical development of understanding the mystery disease. For example, as “new” technologies or scientific research applies to the relative time period they are examining in a given class, students are made aware of the historical context in which these discoveries (or scientific insights) were made.

Throughout the lessons, there are several instances in which students are invited to consider how the work they are doing with sickle-cell problems provides them insight into more general understandings of issues regarding the nature of science. During these instances, the instructor acts as a facilitator by asking students probing questions and guiding their discussions so that the students are challenged to be reflective about nature of science issues. In this way, nature of science issues are considered as planned instructional activities. Research that examines students’ development of nature of science views (e.g., Khishfe & Abd-El-Khalick, 2002) points out the effectiveness of

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3 “New” is relative to the particular class. For example, the introduction of more reliable in-vivo testing for venous blood in the 1930’s is introduced to the class as a “new” technology such that it allows them to reconsider the inheritance models they have developed in a prior class.
having students explicitly and reflectively consider such issues in tandem with the specific science content they are learning.

Finally, students are required to keep a daily diary in which they summarize their experiences from each class. Students are instructed to be metacognitive in the diary about their understanding of the nature of science, and in this way the diary serves as another reflective tool to help students develop their own nature of science insights. They are to use the diary as a place to record their observations, to suggest further lines of inquiry, to state topics that were unresolved, and to consider how the evidence and provisional theories they have developed from prior classes play an active role in their current daily activities. At the beginning of each class, the instructor provides students with a few “seed” questions for them to answer in their diaries that require them to connect their work with the sickle-cell research to more general nature of science interpretations.

Rationale of the Unit for Improving Nature of Science Conceptions

Though the "nature of science" refers to a wide variety of epistemological issues about an informed understanding of science, this project focuses on those aspects that are generally related to how scientific knowledge is developed and validated. This emphasis is aligned with researchers in science education and in the philosophy of science (e.g., Duschl, 1990; Rutherford, 1964; Kemeny, 1959) who advocate that, "the basic purpose of science is to form theories which will explain the universe" (Kemeny, 1959, p. 156). Duschl contends that an informed understanding of science requires that students learn to appreciate the role that theories play in the construction of scientific knowledge. The following four aspects of the nature of science are the primary focus of this research largely because they are central to understanding how scientific knowledge
is developed, and they are best exemplified when examining the episodes developed from the history of sickle-cell research:

1. Theories are explanations to account for empirical data. Moreover, theories are invented by scientists and are predicated on the validity of their supportive evidence.

2. Scientific knowledge is tentative, with theories being revised or abandoned as new evidence or new insights with existing data become available.

3. Scientific knowledge is subjective (theory-laden). By virtue of their own theoretical commitments and experiences, scientists "see" data from a particular perspective.

4. The development of scientific knowledge does not require scientists to conduct controlled manipulative experiments. Rather, knowledge can be formulated by way of alternative (e.g., observation) approaches.

One reason why the sickle-cell anemia unit is ideal for pursuing these aspects of the nature of science is that the “problems” within each of the appropriate subdisciplines used to examine the disease have been clearly worked out. Furthermore, these “problems” can be easily incorporated into the lessons because they are quite accessible to students. This can be contrasted with other subjects in biology that may either be too conceptually complex or too esoteric such that their value for use in the classroom is minimal.

Also, as a part of the lesson plans, the evidence and theories that students examine or develop in one class have potential ramifications for their explorations in other classes. For example, as a result of their having considered the genetics of the disease in the third class, students make predictions about the frequency of a deleterious allele in a population of interbreeding individuals. Their hypotheses are subsequently challenged in later classes when the students are presented with anomalous data. Each of the classes is linked in some manner to one or more of the other classes in the unit.
Additionally, the problems that students examine in each of the classes are based upon the historical work of those scientists who were researching the disease. In this fashion, students are encouraged to consider the relationship between scientific knowledge and the role that scientists themselves play in the construction and development of that knowledge. Throughout the unit, there are several opportunities for students to reflect upon what is broadly referred to as the social constructive (e.g., Latour & Woolgar, 1979; Longino, 1990) aspect of science. This is particularly the case with regard to elements associated with the creation, development and change of scientific theories exemplified during the unit.

Finally, the particular pedagogy that is used for teaching the lesson plans about sickle-cell anemia is an important factor for having students reflect on these aspects of the nature of science. The instructor acts as a facilitator in the learning process by guiding students' problem solving activities, answering questions about the mystery disease, and giving the students any data related to the particular subdiscipline that the daily lesson plan is focusing upon. Moreover, when issues of the nature of science are exemplified in a given lesson, the instructor uses probing techniques to draw students' attention to those issues and facilitates a discussion about their relevance. Research in improving students' conceptions of the nature of science (further developed in the literature review) supports having students explicitly and reflectively connect their developing understanding of the conceptual material being learned in the lessons to more general understandings of the nature of science.

To a certain degree, the lessons also incorporate a conceptual change approach to have students improve their understanding of the nature of science. The general tenet of the conceptual change model (Posner et al., 1982; Strike & Posner, 1992) is to present students with a discrepant idea to their existing naïve conceptions. Furthermore, this discrepant idea must be at once intelligible, plausible, and lead to further avenues of
inquiry. Throughout the unit, the antecedent views that students harbor about the nature of science are often revealed as naïve in light of their working through the problems and making insights toward a more informed understanding. The use of problems developed from the sickle-cell research facilitates conceptual change by at once introducing discrepancies to students' conceptions and providing for intelligible, plausible, and fruitful avenues of inquiry.

Definition of Terms

Explicit (teaching of the nature of science)

An explicit approach to teaching of or about the nature of science means that in some fashion aspects of the nature of science are either directly or indirectly linked to the context-specific issues being addressed in the course of the learning. There are different types of approaches that can all be considered as explicit. The sickle-cell unit used as the intervention for this research adopts a specific method of explicit instruction. Students are encouraged to consider how their context-specific work with the data taken from the sickle-cell research provides them with insight into aspects of the nature of science. To do this, the instructor of the course gives students probing questions to consider both while they are engaged in small group work to solve the problems and while the class is engaged in whole group discussions that are facilitated by the instructor. The point of these probes is to encourage students to consider the ramifications of their conclusions with the work on the sickle-cell problems to more general informed conceptions of the nature of science. The instructor refrains from simply “telling” students about any relevant connections with the content to more informed views of the nature of science. This latter approach is often employed in a didactic (lecture) pedagogy.
Theory

This research uses a somewhat different and in a sense broader interpretation of the definition of the word, "theory" or "scientific theory," than has been articulated in other research in science education (e.g., Abd-El-Khalick, 1998) or from philosophers of science (e.g., Suppe, 1977). In these examples, theories are characterized as robust, internally consistent systems of explanations. As Abd-El-Khalick (1998) states it, "Theories serve to explain relatively huge sets of seemingly unrelated observations in more than one field of investigation. More importantly, theories play a major role in generating research problems and guiding future investigation" (p. 361).

For the purposes of this research, an acceptable conception on the part of students of the word “theory” can be characterized as a provisional scientific explanation. What we wish to impart to students is an understanding that initially couches theories as introductory explanations characterized or strengthened by the amount (and quality) of supportive evidence. The difference between the manner in which the word “theory” is at times used in this research and the manner in which it has been characterized in the aforementioned ways is one of degree. Abd-El-Khalick characterizes theories in a philosophically specific sense as more rarefied entities, analogous to the "core" theories espoused by Imre Lakatos (1970).

This research adopts a broader position on the word “theory” in the sense that students are encouraged that their own scientific explanations can in fact be considered provisional theories. The researcher does not dispute that an epistemologically more robust or correct conception of scientific theories exists, and moreover students are challenged to consider how their own provisional theories relate hierarchically to the more robust or paradigmatic conceptions of scientific theories. As such, discussions
occur during the course of the unit that address such aspects as (a) how their provisional theories differ from more substantiated scientific theories, (b) how scientific theories are developed, (c) how theories are compared against one another, (d) that there are different "levels" of scientific theories, and (e) that theories do change. These discussions are necessary if only to ensure that students do not develop or harbor a naïve view that simple explanations in science are on equal epistemological footing with more robust theories.

Naïve versus Informed Views (of the Nature of Science)

Students bring with them into the learning environment various naïve or incomplete conceptions of the world that they have constructed. Researchers in conceptual change (e.g., Wandersee et al., 1994) characterize these as "alternative" conceptions. The term "alternative" recognizes that the conception is internally valid for that student despite its being scientifically incomplete or incorrect. Table 1 lists the naïve conceptions that students commonly hold about the nature of science issues being addressed in this research and what are generally regarded as informed or contemporary views.

Open-Ended Survey

An open-ended survey is a modified questionnaire in which students are provided questions and given sufficient space to articulate answers in their own words using their own prose. This can be contrasted with forced-item, convergent surveys (e.g., multiple choice, agree/disagree, Likert-scale), in which students' answers are constrained by the choices provided on the survey. The open-ended questions are provided in Appendix B.
Table 1
Naïve and Contemporary Views of the Nature of Science (Palmquist & Finley, 1997)

<table>
<thead>
<tr>
<th>Nature of Science Issue</th>
<th>Naïve View</th>
<th>Informed or Contemporary View</th>
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| The nature of scientific theories | • Theories are based directly on observation.  
• An entire theory is falsified if subject to a single contradictory fact.  
• A theory is a hypothesis that has been proven to be correct.  
• Old theories are of no use to a scientist. | • Theories are the invention of scientists. -Scientists create knowledge (theories) based on prior knowledge, observation, and logic.  
• The occurrence of a contradictory fact does not necessarily compel the abandonment of the theory.  
• Theories are tools used to describe, explain, and predict scientific phenomena.  
• Theories are validated by their connection to other, generally accepted theories. |
| The tentative nature of science | • Scientific knowledge increases by accretion from observations.  
• Scientific knowledge progresses by an accumulation of observations.  
• Scientific knowledge is proven or disproven owing to the direct influence of observations. The goal of science is to find absolute truths.  
• Scientific knowledge is unchanging. | • The progression of scientific knowledge is not continuous.  
• Scientific knowledge is tentative.  
• The tentativeness of knowledge is related to how much people work on it. |
| The subjective nature of science | • All actions of a scientist are assumed to be open-minded and objective.  
• Scientists must avoid being influenced by anything outside of "pure" science.  
• Scientists must report data exactly as their senses perceive it. | • Scientists create knowledge (theories) based on prior knowledge, observation, and logic.  
• A scientist is influence by past research.  
• Observations are theory laden.  
• Observations are influenced by social factors. |
| Theories and Laws | • Scientific laws are found directly in nature.  
• Laws are proven theories.  
• Theories become laws given enough time and evidence to substantiate the theory. | • Laws are “created” by scientists.  
• Laws and theories are not hierarchically related. Laws are descriptions. Theories are explanations. |
The instrument used in this project is a modification of an existing open-ended survey (VNOS) that has been used in the research literature (e.g., Lederman, Abd-El-Khalick, Bell & Schwartz, 2002). In various forms, the VNOS has been in use since the early 1990's. Appendix B contains a condensed version of the modified VNOS survey used in this project.

Overview Of Empirical Methods

This research uses a pre/post intervention format and qualitative analysis of the data to develop pre-instruction and post-instruction profiles of students' nature of science conceptions. Prior to beginning the sickle-cell unit, students' views were assessed using a five-item open-ended survey (Appendix B). Used in tandem with this survey, students were randomly selected to participate in follow-up interviews so that the researcher could check the validity of the survey instrument and further probe any idiosyncratic responses that students articulated on the written survey. Following completion of the sickle-cell unit, students were again administered the same open-ended survey, and a different set of students was randomly selected to participate in a follow-up interview.

The analysis of data involved distilling students' articulated themes of the nature of science into coarse grains for comparative purposes. Through a process of coding and recoding the data, both overall and individual student profiles were developed for both the pre-instruction and post-instruction assessment instruments. From this, the researcher analyzed and characterized those instances in which students' views of nature of science aspects appreciably changed between pre- and post-instruction. The researcher also distinguished between those students whose view on a nature of science
issue changed by virtue of their experience in the sickle-cell unit as evident from clear
statements they articulated in their post-instruction instruments.

Overview of the Dissertation Chapters

Chapter 2 summarizes the literature relevant to the conceptual and empirical
issues of this project. The first section of this chapter discusses how Conceptual
Change research informs aspects of the cognitive basis for the development and
implementation of the sickle-cell lesson plans. This includes an overview of
constructivist theory and a discussion of the model of conceptual change. In second
section of this chapter, two main theses that have emerged from recent research in
understanding students’ nature of science views are presented. The first underscores the
importance of using open-ended surveys and follow-up interviews to capture or measure
students’ nature of science conceptions. The second draws attention to the importance
of designing and implementing pedagogy in which issues of the nature of science are
considered as planned instructional activities (explicit) and furthermore that students are
challenged to reflect upon the significance of their coursework to a more general
understanding of the nature of science. The final section of this chapter discusses the
relevance of recent work in the history and philosophy of science applied to the teaching
of science. This includes a discussion of the importance of post-positivist philosophical
views on contemporary nature of science perspectives. Also presented is a conceptual
argument for the need to design and implement lessons that require students to actively
engage with the historical material in the classroom and an analysis of two recent
empirical projects that measure the efficacy of the use of history and philosophy of
science to affect students views of science.

Chapter 3 details the empirical methodology used to measure
students’ views and discusses how the data is coded for analysis.
Chapter 4 presents the results of the study. This chapter is divided into four sections. The first section provides the results of students' pre-instruction views of the nature of science aspects addressed by the research instruments. The second section gives students' post-instruction views and discusses general changes in students' views. The third section examines the effect of the sickle-cell unit on individual student's conceptions of the nature of science aspects. The chapter concludes with a summary.

Chapter 5 presents a discussion of the results and an analysis of the findings, including sections that address the limitations of the research, the implications of the study, and the recommendations for future research.
CHAPTER 2

REVIEW OF THE LITERATURE

Introduction

The purpose of this research was to measure the efficacy of a particular way of using the history of science to change or enhance students' conceptions of the nature of science. This project lies at the intersection of research by cognitive psychologists on constructivism (and social constructivism) and conceptual change, by science educators on how best to measure changes in student understandings of nature of science issues, and work by historians and philosophers of science on how to introduce nature of science issues into the classroom. The following review of the literature is correspondingly divided into three sections. In section one, a review of conceptual change research draws attention to the potential efficacy of the constructivist approach used as the basis of the lesson plans of this project toward affecting students' understanding of science content and the nature of science. In section two, a review of recent research on how to affect change in students' nature of science views demonstrates two central theses for this project. First, the literature indicates that students' views (and changes therein) are better measured through the use of an open-ended survey, follow-up interviews and other qualitative instruments. Second, the literature supports the use of pedagogical methods that emphasize having students explicitly and reflectively achieve their own insights of nature of science issues in concert with the conceptual material being examined in the classroom. In section three, a review of recent literature on the use of history and philosophy of science to improve learning about nature of science issues points out that it is more effective to design and
implement integral historical cases in which students actively engage with the historical material (in contrast to using the history of science as an “add-on” to the conceptual material being studied) toward developing a more informed view of the nature of science.

Conceptual Change Research

In large measure, the pedagogical basis of the sickle-cell unit used in this project relies on an understanding of how students construct their own meaning of both science content and of the nature of science. A review of the literature concerning both constructivist theory and models of conceptual change underscores the importance of these as the cognitive foundation for the pedagogy used in the sickle-cell unit.

Constructivism

In order to properly understand the principles of Conceptual Change Research, it is first necessary to consider the foundational aspects of the theory of learning called constructivism. This theory of learning forms the basis for the validity of claims about conceptual change that is being used in this project. As such, this section will first briefly discuss constructivism and then examine how constructivist theory fits into the model of conceptual change.

The basis of constructivist theory (as advocated by Piaget, 1959) is that learning consists of a process in which students build upon their existing knowledge when they encounter new material. This draws attention to the fact that learners bring with them to the classroom a set of conceptual knowledge they have developed by virtue of their prior experiences. Learning then involves the students taking his or her existing knowledge and building upon it by way of two distinct processes. This includes either assimilating
knowledge into the existing conceptual framework or accommodating new knowledge that may be partially or wholly at odds with that framework.

These ideas have been further elaborated by psychologists of learning and cognitive scientists (e.g., Ausubel, 1960, 1968; Novak, 1977). Ausubel claims that "meaningful learning" occurs when new knowledge is assimilated or brought into a learner's existing cognitive structure. Moreover, he claims that such assimilation can occur at any range of sophistication of the existing structure. That is, assimilation is not dependent upon the number of or quality/character of the existing concepts in the conceptual framework of the learner.

Accommodation occurs when a new concept is initially incongruent with the learner's conceptual framework. To accommodate the discrepant information, the learner must reorganize his or her framework to accept the new concept as valid and meaningful. This is fundamentally distinct from assimilating a new concept into an existing framework mentioned above. For example, as a result of their prior experiences and learning, students may have developed a mental schema to represent the concept of a fish. Presenting them with a new and congruent example (e.g., a bass) may merely require that they assimilate this example into their existing structure. This contrasts with what occurs when students are presented with the fact that whales are indeed mammals and not fish. They may need to reorganize their own conceptual schema to allow for such examples such as whales, which despite sharing morphological similarities to fish, in order to be properly categorized as mammals and not as fish.

Conceptual Change

Conceptual change research (e.g., Wandersee, Mintzes,, & Novak, 1994) relies upon the constructivist theory of learning. Here, it is important to recognize that children enter learning environments having already constructed their own conceptual
frameworks for many of the things they will encounter in the classroom. Moreover, it is quite possible that these antecedently developed frameworks are incorrect or fairly naive in comparison with goal conceptions held by scientists. Conceptual change research focuses on how learners adopt alternative conceptions of the world, why those alternative conceptions are highly resistant to change, and what strategies may be effective in helping learners to adopt more valid or informed conceptions.

The often-cited approach to elicit conceptual change in learners is detailed by Posner, Strike, Hewson, & Gertzog, (1982). They claim that students engage in a process of assimilation and accommodation of new concepts when they learn. If something is in accord with their existing conceptual framework, it is merely assimilated into that framework. When students are faced with something that is at odds with their existing (and incorrect) knowledge framework, in the absence of some facilitated intervention Posner et al. claim that students may simply ignore the discrepancy or slightly alter their existing incorrect framework so that the discrepancy fits. To overcome this tendency, they advocate a methodological approach designed to facilitate accommodation. This includes first presenting the student with a discrepant concept such that a state of cognitive disequilibrium is achieved. Then, the method should ensure that the new concept is at once intelligible (that students can make sense of the new concept), is plausible (i.e. is believable), and is fruitful (i.e. it can potentially lead to other areas of investigation or inquiry).

In addition to borrowing from constructivist theory, Posner et al. claim that their conceptual change model is based on Kuhn’s (1962, 1970) ideas of paradigm shifts in science. The general claim is that much like individual scientists operating in a mode of “normal science,” students operate in a state of cognitive equilibrium in which there is little reason to change or abandon their alternative conceptions. The conceptual change model is effectively analogous to the revolutions in science whereby scientists adopt a
new way of looking at the world (paradigm shift) by virtue of their abandoning old and establishing new theoretical commitments.

The original model of Posner et al. rests on the assumption that students enter into the learning environment as rational learners with the principal motivation to expand and develop their cognitive structures. Critics have since pointed out that in fact students have other potential motivations (e.g., to get good grades) that may conflict with their involvement to engage in conceptual change. In response, Strike and Posner (1992) draw attention to the idea that such irrational aspects may be considered part of the learners "conceptual ecology." Critics (e.g., Kuiper, 1994) contend that the original model incorrectly presumes that students always have well-defined conceptual structures prior to their engaging with the learning material. In response, Strike and Posner agree that indeed students often enter into learning scenarios with less robust conceptual structures, and as such, their conceptual change model may be less effective in such cases.

Other critics (e.g., Cobern, 1996) have pointed out that the original conceptual change model advocated by Posner et al. (1982) implicitly suggests that learning of new conceptual material often requires having the students construct meaning of new science concepts using an approach in which science content is divorced from the experiential or conceptual framework that the student brings upon entering the classroom. The problem as discussed by Cobern is that "conceptual change makes little sense when the change is to science concepts that have been presented to the students in such a manner as to hold little meaning for most students" (p. 584). He further points out the importance of needing to present new conceptual material to students so that such science concepts are viewed as central to the student's thinking (force) and have potential implications or meaning (scope) connected to other conceptual (often non-scientific) material in the student's life.
Beeth & Hewson (1999) elaborate on issues similar to force and scope of newly learned science concepts by drawing attention to certain epistemological criteria that scientists use to examine and accept new conceptual ideas. They characterize these criteria as (a) consistency (that more preferable concepts should be consistent with other ideas and/or other experiences), (b) generalizability (that preferable ideas should be applicable for more than simply a single instance of a phenomenon), and (c) explanatory power (that preferable ideas provide more effective explanation of empirical events). Hewson, Beeth, and Thorley (1998) emphasize that teachers need to be aware of these criteria when having students consider conceptual material in the classroom in order to maximize the potential for conceptual change.

These pedagogical considerations point to a related concern science educators have had with the model outlined originally by Posner et al. (1982). The methodological suggestions they make (e.g., making a new concept fruitful, plausible, intelligible) are too general to provide much guidance on how to specifically and practically implement them in the classroom. Smith, Blakeslee, and Anderson (1993) highlight the important role that teachers play in the careful development and implementation of the lessons to ensure that students are able to see how new conceptual material is indeed intelligible, plausible, and fruitful.

More specifically, Beeth and Hewson (1999) discuss how the pedagogy, specifically the teacher's instructional strategy, must take into account five key elements of instruction that support and facilitate conceptual change in students' thinking. First, teachers must design curriculum with the student antecedent ideas in mind so that the lessons take into account the range of student experiences and levels of understanding. Second, the teacher must introduce what they refer to as "parallel strands" in the learning. By this they mean the instruction should involve a combination of conceptual, epistemological, and cognitive issues. Third, the teacher must make the curricular
expectations known to the students largely through modeling the type of inquiry and reflection that the teacher wishes the students to employ. Fourth, the teacher must use differing instructional strategies that support students’ exploration of their own and other ideas (e.g., individual, small group, and whole group collaborative sessions). Finally, the teacher needs to allow time for the students to engage fully in the social and conceptual practices that he or she believes are necessary for students to learn science.

The social practices of knowledge construction have also been the emphasis of recent research (e.g., Cobb, 1999; Driver, Asoko, Leach, Mortimer, & Scott, 1994). Here the research suggests that models of conceptual change should consider (in addition to the general methods discussed by Posner et al.) the importance of what is broadly referred to as the social construction of knowledge. They draw attention to the fact that students make sense of scientific concepts in the classroom by virtue of their participation in a community of learners. That is, conceptual change for an individual student is influenced at least partly by the socio-cultural environment of the classroom. Cobb’s (1999) research examines the individual construction of knowledge in a social context of the classroom. He characterizes the process of learning (conceptual change) as involving both individual and social negotiations of concepts. Thus, student construction of conceptual meaning is impacted to a degree by the interaction that the student has with his or her peers and the teacher with reference to any negotiated norms (e.g., the degree to which open discourse is encouraged).

The sickle-cell unit used in this project adopted an approach based on the insights of this research in conceptual change and has been developed to help students shift from more naïve to more informed conceptions of the nature of science. The primary role of the instructor is to facilitate explicit discussions to help students achieve their own insights about aspects of the nature of science that are related to the conceptual issues that students are exploring in the context of each of the classes. These
techniques facilitate the conceptual change process. In the course of their work in a given class, the explanations that students construct to account for the problems they address often shed light on several aspects of the nature of science. The task of the instructor is to pose questions during the students’ group work and class discussion sessions that challenge students to consider how the conclusions they have developed have implications for the nature of science that may be in conflict with their antecedent views.

In view of the foregoing, it is essential that any discrepant nature of science views be intelligible, plausible and fruitful in accord with the paradigm model outlined by Posner et al. (1982). This is why situating students’ examination of the nature of science in the context of their work with the historical problems of the sickle-cell disease facilitates the conceptual change process. Using this approach, students can readily apply the new view of the nature of science to something that is context specific, in contrast to learning aspects of the nature of science divorced from a context that students have invested time and energy to understand.

**Empirical Research to Assess a Conceptual Change Approach on NOS Views**

There have been relatively few empirical studies to measure the effect of a conceptual change approach to improving students’ knowledge of science. Jensen and Finley (1995) reported on the use of a conceptual change-based approach to improve non-major, introductory biology course students’ content knowledge of evolutionary biology. Over the course of two, two-hour lab periods, the students learned about the historical development of Darwinian evolutionary thought. Students were first presented with the Lamarckian view and then provided evidence (e.g., the results from Augustus Weisman’s experiments) that conflicted with the foundational principles of Lamarck’s theory. Students then learned the Darwinian theory of natural selection and
subsequently solved example evolutionary "problems" through applying the principles from both the Lamarckian and Darwinian views.

Jensen and Finley (195) interpret the results from a pre/post measuring of students' conceptual knowledge of evolution as indicating that the conceptual change approach using the history of the development of Darwinian evolutionary theory caused an overall increase in students' ability to answer questions about evolution in Darwinian terms. Moreover, they provide evidence that the explicit teaching of Lamarckian views did not further solidify students' naïve (Lamarckian) evolutionary frameworks. This is important because it is evidence that a conceptual change approach which has students consider their own naïve views juxtaposed with the scientifically correct ones does not necessarily increase the tenacity of their naïve views.

Palmquist and Finley (1997) examined how preservice teachers' views of the nature of science changed after their participation in two science teaching methods courses. During these courses, the nature of science was explicitly incorporated into the pedagogy, and the authors claim that conceptual change approaches were used. Students' views of the nature of science were assessed using a quasi open-ended survey and follow-up interviews. These views were obtained both before the first methods course and after the subsequent second methods course.

Palmquist and Finley (1997) claim that students' views showed positive change as a result of their participation in the methods courses. Furthermore, they point out that conceptual change approaches were partially responsible for facilitating these changes.

Palmquist and Finley (1997) indicate in their abstract that there was little direct instruction about the nature of science and as such that implicit approaches were used. This claim dramatically conflicts with the description of the courses and the pedagogy adopted by the instructors as given by Palmquist and Finley in the body of their study. Bell, Lederman, and Abd-El-Khalick (1998) point out this ambiguity and draw attention to the explicit approaches used throughout the teaching. The distinction between implicit and explicit approaches to teaching nature of science is discussed in the subsequent section.
although they unfortunately provide little in the way of specific techniques for how the conceptual change process occurred. They do indicate that the instructors of the course placed discrepant, contemporary views of the nature of science in front of the students such that it conflicted with students' prior conceptual frameworks. Moreover, they indicate that students likely connected their own explicit learning of conceptual change processes (a topic of the methods curriculum) with an understanding of how knowledge is created and developed.

The approach used in the lesson plans of this project permitted insight to be gained about the effectiveness of a conceptual change approach to having students learn about more informed understandings of the nature of science. Jensen and Finley (1995) adopted this approach to affect change in students' evolution views from a naïve Lamarckian to the contemporary Darwinian understanding. They found positive changes with such an approach and allude to its effectiveness in changing views of the nature of science. Palmquist and Finley (1997) claimed that having students learn about contemporary aspects of the nature of science that directly conflict with students' prior understanding in the context of their learning about conceptual change processes facilitates students to abandon their naïve views.

Research to Assess Nature of Science Views

Researchers in science education have been relatively consistent for the past fifty years in their call for an increased emphasis on having students learn about the nature of science (e.g., Abd-El-Khalick, Bell, & Lederman, 1998; Conant, 1951; Lederman, 1992; Rutherford, 1964; Russell, 1981; Trowbridge & Bybee, 1990). The scope of conceptual and empirical research during this time period is large and covers issues ranging from pedagogical methods to promote student nature of science understanding to empirical methods for assessing students' views on various aspects of the nature of science.
Lederman (1992) and his associates (Lederman, Wade, & Bell, 1998) provide a detailed overview of the history of pedagogical methods and empirical research done to develop and/or assess understanding of various aspects of the nature of science.

From this body of research, two issues are particularly significant for this project. First, these researchers have been divided on how to assess student understanding of the nature of science, and in particular whether qualitative or quantitative approaches are the most appropriate. A review of the merits of these two approaches immediately below demonstrates that students' views (and changes therein) are better measured through the use of qualitative instruments such as open-ended surveys and follow-up interviews. This project accordingly employed qualitative measures. Second, researchers have been divided over how best to incorporate history of science to affect change in students' understanding of nature of science, some favoring explicit and reflective pedagogies in contrast to an implicit approach (both of which will be defined below). A review of the literature demonstrates that use of pedagogical methods that emphasize having students explicitly and reflectively achieve their own insights into nature of science issues in connection with the conceptual material being examined in the classroom is the more promising approach. Both of these issues will be discussed in the subsections that follow.

Quantitative vs. Qualitative Empirical Methods

In examining the history of the empirical research, it is evident that the methods investigators have used to characterize students' (and teachers') conceptions have undergone a shift from primarily quantitative to primarily qualitative in nature. Quantitative methods include the use of instruments that are designed to accommodate statistical analysis. Thus, many of the early instruments used to assess students' (and teachers') conceptions of the nature of science were of the forced item design (e.g.,
multiple-choice questionnaires, agree/disagree questions or Likert scale surveys). A comprehensive review of these instruments is provided by Lederman, Wade, and Bell (1998). Such instruments make it convenient for researchers to code the answers so that descriptive statistics can be applied both with respect to characterizing student conceptions and toward determining if an intervention has been effective in a statistically significant sense.

In contrast, qualitative research relies on a more subjective interpretation of generated students' responses. This type of approach has been used extensively in ethnographic (anthropologic) studies, which often incorporate participant observation and/or clinical interviews (e.g., Ginsberg, 1997) to obtain information about a particular group of participants. Though qualitative research is often characterized as subjective, there are various techniques (e.g., the use of protocol analysis) that can be used to interject more objective criteria for coding the data.

Near the end of the 1980s, investigators increasingly began to use such qualitative methods or interpretive approaches (LeCompte, 1993; Strauss, 1990) to understand students' or teachers' conceptions of the nature of science. In an effort to critically evaluate potential efficacy differences between quantitative and qualitative methods, Aikenhead (1988) conducted research in which he used four different assessment instruments to measure students' conceptions. These instruments included a multiple-choice test, an analysis of a student written paragraph, a Likert scale, and a qualitative interview. His findings indicate that forced-item instruments, like multiple-choice tests and Likert scale test items, potentially bias students to selecting unintended responses. As such, Aikenhead claims that the qualitative interview is the most valid method of capturing a student's nature of science conceptions.

Recent research to understand students' conceptions of the nature of science (e.g., Abd-El-Khalick & Lederman, 2000; Abd-El-Khalick, Lederman, Bell, & Schwartz,
Also strongly emphasizes a qualitative approach. The majority of these studies incorporate a combination of some form of an open-ended survey instrument and a follow-up interview. Open-ended surveys, for example the VNOS – Views of the Nature of Science (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002) are composed of questions that are designed to permit students to share their thoughts on a variety of targeted aspects of the nature of science. Examples of these aspects include (a) the distinction between scientific laws and theories, (b) the tentative nature of science, (c) the creative nature of science, (d) the subjective and ethical dimensions of knowledge construction, (e) the role of inference in the generation of knowledge, and (f) the distinction between science as a way of knowing apart from nonscience. Surveys of this type are designed to allow students to freely express their understanding of the aspects of the nature of science while at the same time minimizing the potential for bias or leading the students to certain answers.

Lederman & O’Malley (1990) point out that the validity of open-ended surveys is improved when follow-up, semi-structured interviews are used in conjunction. Interviewers ask students to review and comment on their answers to their surveys, and in this manner, the researcher is able to determine if students interpret the question as intended. That is to say, the validity of the survey is better supported when students interpret and respond to the interview questions with the same general answers they provided on the survey instrument. Moreover, during the interview the researcher is able to probe more deeply into student responses by asking students to clarify certain aspects of their answers. The interviews thus serve a dual purpose. They help to establish the construct validity of the open-ended survey instrument, and they also allow
the researcher an opportunity to gather additional data about the students’ views by way of follow-up questioning.5

In view of the foregoing, the empirical methodology that will be used in this study will rely primarily upon qualitative approaches. This will include a combination of an open-ended VNOS survey (Appendix B) and semi-structured follow-up interviews.

Implicit vs. Explicit and Reflective Pedagogy to Enhance NOS Views

A major category of empirical research examines how students’ views of the nature of science are affected by various pedagogical interventions. Here, there are numerous methods of designing and implementing pedagogy to address students’ conceptions of the nature of science. All of these generally parse out into two types of approaches, implicit or explicit learning of the nature of science. An implicit approach is used when the instructor or the material incorporates some aspect of the nature of science, but the students’ attention is not drawn specifically to those aspects. The basic premise is that merely by virtue of engaging in the processes of science (e.g., making observations, comparing data, etc.) students will improve their understanding of the epistemology of science. Various researchers have used this approach (Barufaldi, Bethel, & Lamb, 1977; Meichtry, 1992; Riley, 1979; Scharmann, 1990), and the evidence from their studies (e.g., little change in students’ epistemological understanding of science) indicates that an implicit approach is relatively ineffective in changing students’ conceptions of the nature of science.

In contrast, an explicit approach to teaching the nature of science involves either the instructor or aspects of the lesson drawing students’ attention to those issues of the

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5 The main reason why open-ended surveys are used as the primary instrument with follow-up interviews as secondary is due to practical constraints. Ideally, it would be informative to conduct clinical interviews with each and every student that participates in
nature of science that are relevant to the content of the lesson. The role of the instructor is often one of facilitator whereby he or she poses questions to the students to get them to consider the relevance of their context specific learning to more general issues related to targeted aspects of the nature of science. Abd-El-Khalick (1998) points out that caution must be taken not to rigidly characterize explicit and implicit approaches as differing in kind. He states, “not every instructional sequence in the history (or philosophy) of science is an explicit attempt to enhance learners’ conceptions of the [nature of science], nor is every science process-skills instructional sequence or scientific inquiry activity an implicit approach to achieve that end” (p. 194). One way of characterizing the difference is that an implicit approach provides no (planned) opportunity for students to discuss (either with themselves or with the instructor) aspects of the nature of science, whereas an explicit approach somehow involves such a discussion (or invites students to reflect) on the nature of science.

Researchers who have examined or adopted the explicit approach (e.g., Abd-El-Khalick & Lederman, 2000; Abd-El-Khalick, 2001; Akerson, Abd-El-Khalick & Lederman, 2000; Akindehin, 1988; Billeh & Hasan, 1977; Carey & Stauss, 1968; Clough, 1995; Khishfe & Abd-El-Khalick, 2002; Palmquist & Finley, 1997) have evidence that indicates that explicit approaches to teaching about the nature of science are more effective than implicit approaches at producing change in students' views.

For example, a study conducted by Khishfe & Abd-El-Khalick (2002) sought to determine differences between implicit and explicit pedagogies with respect to changes in students’ understanding of science content and/or aspects of the nature of science. Two groups of sixth grade students participated in six, inquiry-oriented investigative science lessons over the course of a two and a half month period. The two groups were

the research, however, given the large number of students normally examined in research of this nature, it is largely impractical.
similar in terms of age and achievement. One group of students (termed the *implicit* group) was only subjected to the inquiry activities (e.g., for a lesson on fossils, students examined and attempted to infer the structure of a hypothetical organism by examining fossil fragments). The other group (termed *explicit*) was (in addition to the inquiry activities) encouraged to discuss the significance of their work during the activities of each lesson to more general interpretations of the nature of science. The aspects of the nature of science addressed by their research included (a) the tentative nature of science, (b) the distinction between observation and inference, (c) the empirical nature of science, and (d) the role of imagination and creativity in the development of scientific knowledge. Student reflection on these aspects were guided initially by questioning techniques employed by the instructor of the course, although the authors noted that students in later units began to discuss various germane morals concerning the nature of science on their own.

Khishfe & Abd-El-Khalick (2002) further define the character of the explicit pedagogy by suggesting that a more proper conception of this method be considered an explicit and reflective approach. The explicit component refers to the idea that aspects of the nature of science should be considered as planned, cognitive activities in which the instructor designs and implements the pedagogy to intentionally target these aspects. This should not be equated with a didactic approach in which an instructor simply tells students about such aspects of the nature of science in relation to the contextual material the students are examining. Rather, they claim that an explicit approach rests on the belief that having students consider the relevance of the nature of science with respect to their context specific learning should be viewed as a cognitive activity in which the learner must construct their own understanding. As such, the reflective component of explicit and reflective denotes the importance of designing and structuring the pedagogy so that students have some opportunity to themselves consider and reflect upon the
connection between the science content and any germane aspects of the nature of science.

Khishfe and Abd-El-Khalick (2002) have evidence from their analyses of the results of pre/post open-ended surveys and follow-up interviews that the explicit and reflective inquiry-oriented approach was more effective at changing students' nature of science views. Specifically, in the explicit group, for each aspect of the nature of science there was appreciable change (an increase in percentage) of students who antecedently held a naïve position to holding a more informed one. There was relatively little change in the views from pre- to post-instruction of those students who were a part of the implicit group. The authors point out that the effectiveness of an implicit approach rests on an untenable assumption that students who engage in processes of science (e.g., making an observation and inferring a claim) will naturally on their own make a larger connection to germane nature of science issues (e.g., that such observations are influenced by the constraints of the equipment used and/or the perceptual framework of the observer). Thus, as they additionally conclude, such nature of science views must be conceived as planned, instructional activities in which through intentional questioning strategies (e.g., probing) students will explicitly and reflectively consider these nature of science views so that on their own they construct a more informed understanding.

Furthermore, although Khishfe and Abd-El-Khalick indicated that the explicit and reflective pedagogy seemed more effective at changing overall students’ views of aspects of the nature of science, they note that relatively fewer (< 50% of the total 29) individual students from the explicit group were able to articulate more informed views for more than one of the aspects of the nature of science from their pre- and post-assessments. The authors discuss three reasons that may have contributed to individual student’s inability to articulate a change in more than one nature of science view. First, they claim that it was unrealistic to expect such large scale changes in individual
student's nature of science views when considering that the relative duration of the intervention (six classes) was short compared to the years of formal and informal instruction that these students have experienced toward constructing their antecedent views. Second, a related claim is that the individual student's nature of science views are robust and tenacious to change. Finally, the authors point out that students were able to articulate more informed understandings of the nature of science on the research instruments in relation to activities that were seemingly more intuitive to the students. This means that the content or context of the activities in which explicit-reflection occurs may impact upon the transferability of a nature of science view.

In view of the foregoing, the pedagogy used throughout the sickle-cell unit to improve students' nature of science views relies upon an explicit and reflective approach. For each class, the lesson plans identify those germane aspects of the nature of science that apply to the particular historical problems that students are working to solve. In this way, issues of the nature of science are considered as planned instructional activities for students to cognitively think about in relation to the historical material.

Furthermore, the lesson plans contain probing questions (Appendix G) for the instructor to give to the members of the student groups for them to consider while they are working on the problems developed from the sickle-cell research. These probes invite students to connect the context specific conclusions of the problems to more general insights about the relevant issues in the nature of science. In this manner, students are encouraged to be reflective about such understandings. This is further emphasized in the whole class discussions that follow the group exercises in which the instructor facilitates a discussion to have students share the insights they have constructed both with respect to the problem conclusions and with respect to the nature of science probes.
This explicit and reflective approach is also the foundation for the student daily diary entries. Students write daily entries in which they summarize the activities of the class and discuss the relevance of their work in the class to their own understanding of the teaching and learning of science. To facilitate this process the instructor provides probing “seed” questions (Appendix F) for the students to consider when constructing their diary to have them reflect upon issues related to the nature of science.

As noted earlier, Khishfe and Abd-El-Khalick (2002) claim that students’ nature of science views are resistant to change because they are a product of students’ cognitive constructions from years of prior education and life experiences. Khishfe and Abd-El-Khalick assert that the development of more informed views of the nature of science may be affected by the content or context from within students are constructing them. One concern with their particular study is that students were asked to articulate a view of an aspect of the nature of science (e.g., inferential and creative bases of science) on the research instruments (e.g., VNOS survey) in which the survey questions were taken from a context or content that was similar to that which students were doing in the course of their lessons. Thus, it is more difficult to discern if students had achieved a meaningful change in a view of the nature of science through genuine reflection and application or if they had simply memorized a more informed view of the nature of science by virtue of their activities in a lesson (and simply parroted back the view on the question of the survey from the similar context).

An informed view of the nature of science is indeed a transferable construct. Thus if the technique advocated in the present research is successful, students construct an informed view of the nature of science in one context and should be able to articulate such an understanding when asked about it in another context. For this reason, the VNOS survey used as the intervention for this research relies upon content/context of
science that is unrelated to the content or context that students are constructing their own nature of science views during the sickle-cell lessons.

It is also important to point out the arguable assumption on the part of the researcher that explicit and reflective approaches for the population of students examined in the present study (college students) will work in a manner similar to that claimed by Khishfe and Abd-El-Khalick (2002) in their research with sixth grade middle school children. For both populations of students, the basic premise is that a view of the nature of science is something that the student (be it sixth grader or college) must construct on his or her own by virtue of his or her developing a more informed view in relation to their past experiences and present learning. However, in truth it is misleading to generalize that college students engage in cognitive construction of meaning in a manner similar to that done by sixth graders. One could argue that college students' naïve conceptions of science are even more robust and resistant to change than sixth graders, because they have had simply more experiences and formal learning during which to solidify such views.

Research on The Role of History and Philosophy of Science

The following section discusses the research on the potential role of the history and philosophy of science for the teaching of science and how it is relevant for two issues of this project. The first issue concerns the major transition in how philosophers of science from the positivist to post-positivist "schools" claimed that scientific knowledge (in the form of theories) develops. Second, a review of recent literature on the use of history and philosophy of science to improve students' learning about aspects of the nature of science supports that it is more effective to design and implement lessons using the history of science in which students actively engage with
the historical material toward developing a more informed view of the nature of science. Both of these issues are further developed and supported below.

In the mid 19th century, philosophers of science became increasingly concerned with what they perceived to be the use of speculation and reference to metaphysical claims in support of the development of scientific theories. In response, there was an emphasis given to stipulating that scientific explanations be linked solely to observational entities: "Statements must be empirically verifiable, which is to say that all empiric statements occurring in a scientific theory must be capable of being reduced to statements about sensations" (Suppe, 1977, p. 10). Essential aspects of this philosophical position became generally known as the positivist movement and later extended into logical positivism. The latter shared a similar insistence on empirical grounding for scientific explanations but also incorporated the need for logical (syntactical or analytic) connectedness of the axioms used to develop the theory.

Positivists (and logical positivists) espoused what became known as the "Received View" of scientific theories summarized by Suppe (1977):

Initially science consists of empirical generalizations formulated using observational terms. Later, as the science advances, theoretical terms are introduced by definition and theoretical laws or generalizations are formulated in terms of theoretical terms. Thus science proceeds "upward" from particular facts to theoretical generalizations about phenomena, this upward process proceeding in an essentially Baconian fashion. (p. 15)

A central conclusion from the positivist philosophy is that the confirmation of scientific knowledge vis-à-vis the mechanism described above, also referred to as the "context of justification," (Reichenbach, 1938) principally involves seeking empirical evidence that supports the claim or theory in question. Another issue that the positivist philosophers identified as important is that observations used as evidence for the development and confirmation of scientific theories be (to the extent possible) distinct from a priori theoretical commitments.
Philosophers since have challenged many of the tenets associated with positivism (e.g., Feyerabend, 1978; Kuhn, 1970; Lakatos, 1977; Laudon, 1977; Popper, 1959; Toulmin, 1953). They questioned the traditional positivist tenets that described how claims are developed, tested, and evaluated in science. One such challenge centered on the inference that scientific knowledge evolves toward revealed truths in a strict inductivist sense (Schwab, 1962). As characterized by Suppe (1977):

The positivist treatment of the confirmation and disconfirmation of theories was misleading since it viewed the testing of theories as merely passing judgment on final version of theories – if it passed the test, something was added to its degree of confirmation, and if it failed the test it was falsified. Whereas in fact, the failure of a theory to pass a test usually does not lead to its rejection, but rather to its modification; moreover, these modifications are not random, but rather governed by epistemic features of the scientific enterprise. (p. 126)

From these challenges emerged a view referred to as “post-positivism” which (among other things) purports that disconfirming evidence to a theoretical position is a part of the scientific process of evaluation of theories (e.g., Popper, 1959 in falsification). Moreover, the presence of refuting evidence should not be cause to necessarily abandon the theory.

Post-positivist philosophers of the 1960’s and 1970’s (e.g., Feyerabend, 1978; Kuhn, 1962, 1970) have also challenged the positivist belief that observations be (to the extent possible) independent from theoretical commitments. One major result that has emerged from their work is the realization that observations are theory-laden, meaning that a scientist’s personal, experiential, and theoretical background fundamentally influences what he or she observes. This conclusion has been widely regarded as an attack on the notion of objectivity of science. The logical consequences of this work

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6 It is somewhat misleading to suggest that the notion of theory-laden observations was first articulated during the post-positivist era. The positivists themselves were aware of the potential for observations being affected by subjective perspectives. They sought to minimize this from occurring. Philosophers not necessarily associated with the “post-positivist” movement (e.g., Quine, 1953) also articulated views of the theory-laden influence on observations.
were widely publicized in Thomas Kuhn’s often-cited text, *The Structure of Scientific Revolutions* (1962, 1970). What emerges from the post-positivist movement is a new perspective in which the development of scientific knowledge involves subjective and creative processes. It also provides new insight into how theories change by way of considering how scientists themselves as constructors of knowledge play a role in the generation and change of scientific theories.

Perhaps most significant is that many of the tenets espoused by post-positivist philosophers paved the way for examining aspects of the philosophy of science in parallel with issues in cognitive science. For example, Kuhn’s work has been interpreted as supporting an analogy to constructivist theory and conceptual change. Much like the recognition that scientists are influenced by their prior theoretical commitments, constructivist theory also has as a foundational element the idea that learners bring with them preconceptions into the learning environment and that such elements influence how (and what) the student will learn. One of Kuhn’s central claims is that scientists adopt or are indoctrinated into “paradigms” that guide their research. A corollary of this perspective drawn out by Kuhn is that change in science proceeds by way of “revolutions” in which through various precipitating circumstances scientists become dissatisfied with their current paradigm and (ultimately) adopt another paradigm that has shown to be more fruitful. Conceptual change in science education is often depicted as

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7 It is misleading to suggest there are no ongoing debates about Kuhn’s views or for that matter about issues regarding the philosophy of science with respect to post-positivist views since Kuhn’s work (Loving & Cobern, 2000). In point of fact, there are philosophers of science (e.g., Feyerabend, 1978; Hoyningen-Huene, 1993; Hull, 1988; Lakatos, 1977) who have pointedly argued the validity of some of Kuhn’s central theses (e.g., the definition of “paradigms,” the currency of “incommensurability,” the notion of “revolutions,” and the rationality of theory choice). The purpose of this study is not to expand upon these criticisms but to acknowledge the central role that Kuhn’s work has played in science education, particularly with regard to those conceptual issues germane to this project.
analogous to paradigm shifts in that students must engage in a conceptual revolution of sorts to abandon their robustly-held, naive views of science for more informed views.

Students often harbor a variety of conceptions about the development of scientific knowledge that resemble the aforementioned central issues of the received view of theories espoused by positivists. An example is the belief that theories merely emerge from the collection of data (Duschl, 1990; McComas, 1996). The parallel to the positivist view is the assertion that a collection of observations (e.g., having seen only white swans) leads systematically to the development of the generalization or theory (e.g., that all swans are white). Duschl further characterizes this view by pointing out that students often believe that there is a hierarchical relationship between facts, theories and laws, which is to say that students believe that theories become laws when enough empirical evidence is collected to substantiate the theory.

Furthermore, when students harbor the view that scientific knowledge is largely created by objective methods, they likely fail to recognize another important and related aspect, that theories are "created" by scientists in order to explain their observations (Abd-El-Khalick, 1998). The distinction is that theories do not simply emerge from the collection of data but rather require that scientists "invent" a theory to explain the patterns in the data.

Many students also fail to recognize that theories can change (Abd-El-Khalick, 1998; Abd-El-Khalick & BouJaoude, 1997; Khishfe & Abd-El-Khalick, 2002; Lederman, 1986; Horner & Rubba, 1978). Again, they harbor a conception that theories exist within a hierarchical structure between facts and laws (Duschl, 1990). As such, the naïve view is that theories do not change but are rather proven to be true or are abandoned. This again may be attributed to an absolutist view of science in which students believe that science is concerned with the collection of facts or truths about the world analogous to the revealed truths central to the received view. Researchers (e.g.,
Homer & Rubba, 1978; Lopushinksky, 1993) claim that students hold such absolutist views of science as a result of the influence of their textbooks (which often portray the development of scientific knowledge in a cumulative and linear fashion) or their teachers (who themselves may harbor the absolutist misconception).

Moreover, for those students who claim that theories do change, their mechanisms to account for such change generally rely upon advances in technology or data collection that have allowed new information to shed light on the existing theory. There is little recognition that scientists, by virtue of their subjective backgrounds, may change a theory due to new insights they have made with extant data (Abd-El-Khalick, 1998; Lederman & Abd-El-Khalick, 2000).

DeBoer (1991) suggested that it is understandable that students hold such naïve views about the development of scientific knowledge when we examine how the practice of science has been historically represented in school science. In the early 20th century, the positivist movement strongly influenced the portrayal of the development of scientific knowledge in science education as induction-based. As DeBoer points out, the positivist view found its way into American science education during the formative periods, and as such the method of objective induction became codified in the curriculum and the textbooks (e.g., the indoctrination of "The Scientific Method"). Vestiges of the positivist philosophy (again the perpetuation of "The Scientific Method") are today still evident in many science textbooks, and these may be a significant reason why students adopt or maintain such naïve views of the generation of scientific knowledge.

The foregoing discussion establishes that students' views of the development of scientific knowledge resemble but are not identical to certain central views espoused

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8 The purpose of this section is not to give a complete overview of students' naïve views of the nature of science. Lederman (1992) provides a cogent discussion in this regard. A
by the positivist philosophy of science. Furthermore, a review of claims of the post-
positivist philosophers suggests that just as scientists are reluctant to abandon
paradigms in the face of discordant observations students may also find it difficult to
abandon their prior and unfortunately often mistaken point of view.

Using the History and Philosophy of Science in the Pedagogy

To help students overcome these various naïve conceptions of the nature of
science, science educators and historians and philosophers of science have long
advocated the inclusion of the history and philosophy of science into the learning of
science (Brush, 1989; Conant, 1951; Duschl, 1990; Mathews, 1994; Monk & Osborne,
science education researchers (e.g., Abd-El-Khalick, 1998; Collette & Chiapetta, 1989;
Duschl, 1990; Mathews, 1994; O’Brien & Korth, 1991) placing a greater emphasis on
history and philosophy of science into the learning of science will particularly help to
improve students’ naïve conceptions about the way in which scientific knowledge is
generated, develops, and changes. One reason for this is that episodes from the history
of science provide a valuable context in which students can more properly interpret or
situate these philosophical tenets about the nature of science.

Early attempts on the part of science educators to incorporate the history of
science were done to improve both students’ cognitive (epistemological) and affective
views of science. In the 1940’s Conant (1951) developed the Harvard Case Histories in
Experimental Science. These cases were used to teach science to non-majors in college
courses. The goal was to help students better appreciate science as something more than
merely conceptual content (e.g., understanding the methods of science). In the late
1950's, Klopfer (1964) developed materials for teaching science by drawing from aspects of the history of science to convey certain important ideas about the practice of science and the workings of scientists. These materials were known as the History of Science Cases (HOSC) and were self-contained booklets, each as an individual unit for instruction. Included in the units were historical narratives, quotations from scientists' original papers, student experiment suggestions and exercises, teacher's guides, and so on. The target audience for the HOSC was high school students. In the mid-1960s the National Science Foundation sponsored several large-scale curriculum reform efforts, one of which was the (Harvard) Project Physics. Project Physics was one of the first major curriculum reform efforts using the history of science to teach science at the high school level.

In the time since the introduction of Conant's Harvard Case Projects and Klopfer's HOSC, in general there have been two fundamentally different approaches used to improve students' understanding of conceptual and epistemological aspects of science. One involves using the history and philosophy of science as an "add-on" to the conceptual material being examined in the classroom. The other uses history and philosophy of science as an integral part that drives the pedagogy of the lessons.

"Add-on" Uses of the History and Philosophy of Science in Lesson Plans

An "add-on" approach to using the history and philosophy of science is done when teachers primarily incorporate episodes from the history and/or philosophy of science as tangential tools to support the conceptual material they are having students explore. Generally speaking, such teachers view the history of science as a means to bolster students' affective appreciation of science. More specifically, they believe that a
historical context or story can give students insight into science as a humanistic and meaningful endeavor (Wang & Marsh, 2002).

It is understandable why teachers often fall into the practice of using history and philosophy of science in this way. Science educators (e.g., Monk & Osborne, 1997; Roach & Wandersee, 1993) point out that because teachers are constrained by a voluminous science curriculum, they often perceive that incorporating the history of science into the lessons detracts from their ability to cover that content. Furthermore, as pointed out by Brickhouse and Bodner (1992) new teachers face significant pressures (e.g., developing classroom management skills, learning conceptual material, becoming familiar with administrative policies, etc.) which compromise their ability to see the fundamental worth of incorporating what appear to be tangential issues associated with the use of the history of science into the lessons.

In addition, there is often little emphasis given during teacher education programs to the potential merit of using the history of science to teach science. This is particularly an issue for colleges where the science education of preservice secondary school teachers falls under the responsibility of the science department. As Gallagher (1991) points out, the “advisement of prospective secondary science teachers is under control of the science faculty, who do not value the history of philosophy of science as a significant part of a young scientist’s or science teacher’s education” (p. 128). Thus, it is not surprising given these circumstances that when the history of science is at all used in the classroom, it is viewed as an ancillary item to the teaching science content.

**Integral Uses of the History and Philosophy of Science in the Lesson Plans**

An integral use of the history and philosophy of science to advance the teaching of science is exemplified by lessons that use aspects of the history and philosophy of science to drive the pedagogy being implemented in the classroom (e.g., Allchin, 2000;
Lin, 1998; Irwin, 2000; Solomon, Duveen, Scot, & McCarthy, 1992). In contrast to an “add-on” approach, the instructor recognizes that episodes or problems from the history of science are more central to developing students’ conceptual and epistemological understanding. The sickle-cell unit used as the intervention for this dissertation incorporates the historical episodes in an integral manner.

Science educators (e.g., Monk & Osborne, 1997; Roach & Wandersee, 1993) point out that because teachers are constrained by the school curriculum, they often perceive that incorporating the history of science into the lessons detracts from covering that content. As such, they suggest using historical vignettes because these can be more easily integrated into the lessons and do not require an overly large time commitment.

In contrast, others such as Allchin (2003, 1993) advocate a more active use of the history of science to teach nature of science issues. Regarding his claims of how history should be incorporated, Allchin pointed out that historical cases can be particularly useful toward immersing students in the conceptual framework of the scientists that were working to solve the problems exemplified in the case and in this manner, students are encouraged to recapitulate the type of reasoning employed by the historical figures.

The sickle-cell unit used as the intervention for this study is based upon Allchin’s (1993) claims regarding the effectiveness of having students actively recapitulate historical reasoning. Over the course of eight, two and a half hour long classes, students examine the disease from number of perspectives of biology and the problems that led scientists to recognize they were related to one another. The advantage of this protracted approach is that students are given sufficient time to immerse themselves in the historical “story.” Part of this involves ongoing considerations of the nature of science (e.g., how their provisional theories are constructed and validated) that are linked to evidence that is situated in an historical context. The unit provides many...
opportunities over the course of several classes for students to essentially “reconstruct” their views of the nature of science.

The success of this use of the history of science versus the use of historical vignettes is the degree to which students are themselves interacting (e.g., collecting, analyzing, inferring, posing) with the historical evidence in developing their own understanding of content and epistemology. Students model the work and reasoning employed by past scientists, and in this way they recapitulate various methodological processes toward developing their own explanations to account for whatever historical problems or scenarios are provided in the lessons.

Actively engaging with the historical material in this way is distinctly different from more passive approaches that have students “read about” episodes or problems from the history of science. As is often the approach taken with using historical vignettes, the story essentially sets the context of some historical scientific problem and essentially “tells” students how the scientists examined and evaluated data toward constructing their own explanations. The approach that is often used in the classroom (e.g., Monk & Osborne, 1997; Roach & Wandersee, 1993) is to then engage students after they have read the story to consider the relevance (qua the historian of science) of the historical conclusions or ways of thinking exhibited by the scientists in concert to the students’ own beliefs about science.

A criticism that is often raised to using the history (and philosophy) of science to teach students science in this way (Abd-El-Khalick & Lederman, 2000; Jenkins, 1996) is that students judge the validity of historical conclusions or ways of thinking from their own contemporary (and often naïve) perspective. That is to say, it is difficult for students to “put on the required historical thinking cap” (Abd-El-Khalick & Lederman, 2000, p. 1061) to make sense of the larger nature of science morals exemplified by the historical context. The tension arises when students are asked to
read about some episode in the history of science and within the span of a discussion or activity are required to embrace (or criticize) the contextual validity of the conclusions reached by those scientists. In this case is understandable that students may simply read these short stories with a "Whig interpretation of history" (Brush, 1974; Butterfield, 1931, 1957; Mayr, 1982) meaning that they evaluate a historical scientist's conclusions or ways of thinking with reference to contemporary perspectives rather "instead of evaluating a scientist in terms of the intellectual milieu in which he was active," (Mayr, p. 12). Abd-El-Khalick & Lederman characterize this as, "their [prospective science teachers] frameworks of science have developed over years of high school and college science...thus learners often dismiss historical scientific notions as wrong ways of explaining the natural world," (2000, p. 1061).

Teachers should instead strive to maximize the degree to which students are investing in the historical material so that they unbeknownst to them recapitulate the thinking processes employed by the historical scientists. In short, when students are "told" about historical conclusions or historical ways of thinking, (in contrast to students themselves solving the historical problem by way of examining the evidence and constructing an explanation), it overlooks the importance of having students themselves invest in the historical episode so that they might achieve ownership and validation of the conclusions that result. Furthermore, when teachers have students "read about" such historical conclusions and juxtapose them with their antecedently constructed views about science, they run the risk that students will immediately devalue the historical view as misguided or foolish.

This is potentially the case in Monk and Osborne's (1997) approach whereby they advocate teachers placing the historical way of thinking in parallel with students' proposed explanations for a scientific problem. This is accomplished by having students initially propose their own explanations to account for some scientific problem (that is
antecedently identified by the teacher as having a relevant and accessible historical account). The teacher then gives the student(s) a vignette that describes how an historical figure sought to explain the same phenomenon that the students are examining. Students are then challenged to consider multiple views (their own and the historical) at the same time in an effort to select which view is “correct.” One of their objectives (which is laudable) is that students will further their ability to discern between competing views toward selecting the one that they feel is most explanatory (best supportive evidence). Furthermore, they contend that some students antecedently hold views that are in accord with historical scientist’s explanations, and as such the experience fosters in students an affective appreciation that they can at least “think like a scientist.”

Monk and Osborne’s approach is troubling for two reasons. First, there is the general concern with “read about” or passive approaches in which students are not encouraged to actively engage with the historical material other than to evaluate the legitimacy of the conclusions reached by the historical figures. This holds even if the teacher has students evaluate the legitimacy of the historical figure’s “ways of thinking” in addition to the historical figure’s specific conclusions. This is because such approaches do not situate the students as the central figure constructing their own understanding but rather have them act as an evaluator of someone else’s constructed view.

Second, Monk and Osborne contend that their approach rests in part on a constructivist philosophy of learning. A central claim of constructivism is that students build upon their own existing conceptual frameworks as they develop a more informed view of science (content and epistemology). Having students “read about” the

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9 A more protracted discussion of constructivist philosophy (theory) is provided in the first section of this chapter.
historical conclusion exemplified in the vignette is problematic because students are not necessarily encouraged to actively recapitulate how the scientist or scientists highlighted in the case came to their understanding.

Under the constructivist philosophy (or theory) of learning, we presume that students bring to their own learning various conceptions of science that are based on their own experiences and prior learning. When we invite students to “read about” an historical story (or conclusion reached therein) we run the risk that these students will juxtapose such stories against their own (current) conceptual framework and as such may tend to rationally reconstruct the conclusions in the story from their own antecedently constructed cognitive framework.

Allchin (2000) claims that it is important for teachers to minimize the likelihood that students rationally reconstruct history when examining episodes from the history of science. This occurs when teachers or students reconstruct historical episodes by examining them from contemporary standards rather than viewing the claims, experiments, data, etc. of the historical scientists from the perspective of the times and scientific norms in which they operated. Such reconstructions undermine the use of history, because they create or reinforce the perception in students’ minds that historical figures were incompetent. This point again emphasizes the potential concern with the use of the history of science in which students are asked to “read about” historical stories or problems (e.g., Monk & Osborne, 1997; Solomon et al., 1992; Roach & Wandersee, 1993). Such rational reconstructions are more likely to occur when the investment that students make with the historical episode is primarily by way of reading about the science.

In view of the foregoing, the sickle-cell unit described in the series of lesson plans in this study emphasizes that students interact with the history of science primarily by way of “doing science” in a context similar to that which scientists in the past

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worked. By this it is meant that students recapitulate the reasoning of the historical scientists through examining problems (and lines of evidence) that are developed from the history of research on the sickle-cell phenomenon. This method is distinctly different from simply having students "read about" the conclusions (and rationale) that the various historical scientists adopted. Rather, students are challenged by way of this approach to engage themselves in certain processes of science (e.g., examining, evaluating, explaining, persuading), and through this approach they construct an understanding of both content and epistemology in accord with the methodological approaches taken by the historical figures.

The advantage of this approach is that it helps to minimize the likelihood that students will view historical conclusions or ways of thinking as misguided. One reason for this is that the approach alleviates the potential for students to immediately juxtapose their own constructed views against historical conclusions (that they have not developed themselves). This is because students themselves are constructing conclusions to problems that are likely similar to those that were reached by the historical scientists. In sum, student understanding or appreciation of historical ways of thinking is best thought of as requiring an active process whereby the students recapitulate the history of science.

Empirical Research to Assess the Effect of Using the History of Science

Empirical research (e.g., Abd-El-Khalick & Lederman, 2000; Abd-El-Khalick, 1998; Irwin, 2000; Klopfer & Cooley, 1963; Lin, 1998; Rowlands, Duveen, & Scot, 1992; Solomon et al., 1992; Welch & Walberg, 1972) designed to assess the efficacy of using the history of science to improve students' conceptions of the nature of science has yielded mixed results. Evidence from these studies indicates that the use of history of science can improve certain conceptions of the nature of science, while other aspects
remain resistant to change. Of the numerous empirical studies that examine the use of the history of science to affect students' views of the nature of science, a majority examines the effect of shorter interventions (e.g., vignettes). There are relatively few noteworthy empirical studies that examine the longer and more integral use of the history of science. The remainder of this section will critically review two selected examples (Abd-El-Khalick, 1998; Solomon et al., 1992) from this latter research and provide a comparative context for the pedagogical and empirical methods used in the present study.

Example 1: Solomon et al., (1992)

In 1992, Solomon et al. conducted an empirical study of middle-school students' (n = 94, ages 11 - 14) progress on learning science as a result of materials developed from episodes in the history of science. Specifically, the researchers sought to measure how students' views of aspects of the nature of science and students' understanding of science content were affected by historically-situated materials.

The principle motivation for the study was in response to increased attention given by the National Curriculum of England and Wales to having students learn aspects of the nature of science in addition to science content. Furthermore, the members of the National Curriculum specifically emphasized that students should examine how scientific ideas have changed through time, particularly with reference to the affect of the "social, moral, spiritual and cultural contexts in which they are developed" (p. 409). This latter emphasis was broadly encapsulated by stressing the increased need for the history of science in the lessons.

The research was conducted in three separate school locations using a total of five different classrooms. For each class, the instructor selected 6 out of 13 available historical cases from which to design his or her teaching units. The cases, which were
developed by Solomon (1991), largely adopted a similar method to teach the history of science and the nature of science. Though each of the five teachers selected a different subset of the 13 available cases, the overall general "pedagogy" for each of the classes was similar. The researchers claimed that the five separate classes could be considered a relatively homogeneous group with respect to the student composition and the lessons provided.

The researchers assumed an "action researcher" role. This means that they worked alongside the instructor of the course during the teaching of the historical materials to assist with the delivery of the materials (e.g., facilitate students' laboratory exercises, etc.). At the same time, the researchers conducted experimental research in which they collected data by way of observation and measurement (through the use of surveys and interviews) of students' progress on the concepts of science and the nature of science. The researchers claim that the multifaceted design of their research (intervention study, action research, experimental research) introduced "inevitable constraints" (p. 413) although they maintained that they could effectively compartmentalize these seemingly conflicting roles (e.g., helping the students with content issues during the lessons versus being impartial and objective during observations of students' progress). Given the nature of their research, it is this researcher's opinion that such complete compartmentalization was not entirely possible.

There were two main sources of data used for the empirical portion of the study. Students were administered a pre and post questionnaire to capture their views about targeted aspects of the nature of science. The contents of the questionnaire were developed from generalized (categorized) student responses to a pilot survey administered well before the historical units began. From the general responses to the pilot survey, the researchers constructed a targeted pre and post questionnaire. Unfortunately, the researchers provide little detail on how the initial pilot survey was
validated and what criteria were used to categorize students' responses toward constructing the consolidated final questionnaire.

The final questionnaire used a forced-item (multiple choice) format. Students were asked pointed questions about aspects of the nature of science and were required to select from one of several choices for each of the questions. In their paper, Solomon et al. (1992) report that only four of the questions from the original questionnaire administered as the pre- and post-instrument were useful for empirical purposes. Unfortunately, the researchers provide no detail about the total number (and character) of questions in the original questionnaire. The aspects of the nature of science covered by the questions that the researchers claim as informative include (a) the reasons scientists conduct experiments, (b) whether scientists know what to expect to happen before they do an experiment, (c) the definition of a scientific theory, and (d) the subjectivity of science (theory-laden nature of science).

The second source of data involved interviews during which students were asked to further explicate the responses they provided on their questionnaires. The authors provide no indication whether they interviewed the same child for his/her responses to both the pre and post questionnaire. Furthermore, it is unclear whether the authors probed students for any changes they may have exhibited concerning aspects of the nature of science as evidenced from responses given in their post questionnaire.

The historical cases were developed by the principal author (Solomon, 1991). The cases were designed to be administered over several days. During this time, students would read various aspects of an historical event and then engage in short activities (e.g., make a poster, sequence a set of statements, perform an experiment, or role play) to better understand aspects of the historical event or problem. The purpose for the activities was to "encourage pupils to reexamine the text in order to extract as much information as they could" (p. 412).
In their results, Solomon et al. report that students' views on the aspects of the nature of science related to the design and nature of experiments (items 1 & 2 from above) and the definition of a scientific theory (item 3) were significantly altered from a naive to a more contemporary view. As evidence, they cite the change in the overall character of the responses that students gave to the questionnaire and the follow-up interviews. Furthermore, they conclude "our units for teaching the history of science within the normal school curriculum made a valuable contribution to the pupils' understanding of the nature of science" (p. 418).

One concern with the researchers' chosen empirical method is with the questionnaire they constructed and employed to gather data. Various researchers in science education (Aikenhead, 1988; Lederman, 1992; Lederman & O'Malley, 1990) point out that forced-item surveys (e.g., multiple-choice questions) have the potential to artificially bias students toward selected unintended responses. Furthermore, as emphasized by Lederman (1992), the questions and available answers for each item of the survey had been developed from the experiential framework of the researchers. As such, the questions themselves and the available (multiple choice) answers may not have captured or measured the students' actual conceptions.

Another concern is that the authors provide no detail of the protocol they used for conducting interviews with the students (other than describing that both pre- and post-interviews took place). It is unclear whether or not students were interviewed for both their pre- and post-questionnaire responses or if the researchers elected to simply interview students for either one or the other. Furthermore, it is unclear if the researchers additionally chose to interview students during the teaching unit.

Perhaps the most fundamental concern is that the authors simply did not provide enough detail about the pedagogy of the adopted historical unit(s) such that the reader is able to see how the pedagogy explicitly or implicitly connects learning of the nature of
science with the history of science. In the example given in the article (Mountains on the Moon Case), the authors discuss how over the course of several days students read various extracts from the history of science that document how the telescope was discovered and then used by Galileo. Over the course of eight sections, students “learn how lenses were first used by medieval monks for reading...then through the Dutch discovery of the telescope to Galileo’s improvement of its magnification...to how Galileo saw shadows on the moon growing longer night after night, interpreted them as evidence for mountains, and calculated the height of these” (p. 412). Subsequently, students are then told of the “older theory of a smooth moon shining with its own light is related to a contemporary belief in heavenly perfection” (p. 412).

Following these initial readings, students are challenged to reexamine the text by way of creating posters of their interpretations of the textual material and by way of conducting various experiments (e.g., measuring the length of shadows on a simulated moon as a function of the height of objects). It is also not clearly stated whether (or not) instructors of the course facilitate discussions about the nature of science or whether students were expected to implicitly gain a better understanding.

Interestingly, the researchers discuss how many of their students had conceptual difficulty in seeing the value of historical thinking as evidenced by students stating the “difficulty they had in emphasizing with the thinking of scientists whose theories they knew to have been superseded” (p. 417). In point of fact, the researchers seemed antecedently aware of the potential for such difficulties because they earlier in the paper discussed Kuhn’s (1962, 1970) incommensurability thesis as “the enormous hurdles in the way of those who try to understand earlier modes of explanation, whether they are adults or children” (p. 411). This is noteworthy if only because the particular method for using the history of science may have contributed to students’ inability of seeing the
conceptual merit of historical thinking. In this method, students seem largely to "read about science" prior to their actually "doing" science.

The sickle-cell case used as the intervention in this project avoids what appear to be shortcomings of the pedagogical approach implied by Solomon et al. Rather than have students read about historical conclusions and then reenact or critically examine those conclusions, the sickle-cell case places students in the role of the scientist "doing science." That is to say, students are given evidence to consider toward constructing an explanation for a problem that is presented to them each class. Through this process, students are often later challenged to revisit their earlier conclusions in light of new evidence or new insights they have subsequently constructed. Because the students are the constructors of knowledge, they are less likely to simply dismiss their own earlier views as misguided or foolish and rather come to a better appreciation for the tentative nature of science.


In 1998, Fouad Abd-El-Khalick examined how three different history of science courses (a science survey course, a course in scientific controversy, and a course in evolution) affected college students' conceptions of aspects of the nature of science. These aspects included the tentative, empirical, subjective, social and cultural nature of science. The research additionally captured students' views on the role of experiments vs. observations in the generation of scientific knowledge, the distinction between theories and laws, and the role of imagination, creativity, and inference in science.

The participants of the study derived largely from two groups. The first group consisted of all undergraduate and graduate students (n = 169) enrolled in three history of science courses, and the second group consisted of 15 preservice secondary science teachers who were enrolled in a Master of Arts in Teaching (MAT) program at the same
university. Prior to their enrollment in one of the history of science courses, the MAT students had completed a science methods course during which a contemporary view of aspects of the nature of science received explicit instruction.

This study addressed three questions. The first was whether or not (and in what ways) history of science courses influenced college students’ conceptions of the nature of science. The second question examined whether or not students who enter the history of science courses with a conceptual framework of the nature of science that is aligned with a contemporary conception (i.e. the MAT students) were likely to achieve improved or enriched views of the nature of science as a result of their participation in the history of science courses. The final question concerned identifying what aspects of the history of science courses (e.g., content, pedagogy, class dynamics) were most influential in changing or impacting students’ views.

The research used a pre/post test design. Students’ views of the nature of science were captured using the VNOS (Views of the Nature of Science), an open-ended questionnaire in which students were free to express their answers to various structured questions about the targeted aspects of the nature of science. Students were administered an identical VNOS questionnaire at both at the beginning of the course and again at the end of the course.

A random percentage (approximately 15-20% of the total pool) of students were additionally selected as candidates for follow-up interviews about the responses they gave to either their pre or post VNOS questionnaire. The purpose for these interviews was to establish the construct validity of the VNOS instrument and to allow the researcher an opportunity to further probe students’ responses to the questionnaire. The latter served as additional data for qualitative characterization of students' views.

The researcher also developed in-depth profiles for each of the history of science courses by way of several mechanisms. First, the researcher interviewed the
instructors of each of the courses in an effort to characterize the individual instructor's views of the nature of science as they related to the development and implementation of that instructor's pedagogy. Second, the researcher sat in on the classes for each of the three history of science courses, and through a combination of the course syllabi, instructor profiles, field notes and audiotapes he was able to develop comprehensive profiles of the manner in which the historical content and the pedagogy were designed to address the nature of science.

The Scientific Controversy course used cases developed from 18th to 20th century examples. The course contained relatively few students (n = 18 students) and used small group discussions to examine controversial scientific discoveries with an emphasis on the psychological, social, and rational characteristics of science. The instructor of the course relied upon an implicit approach for addressing these aspects of the nature of science. It was implicit in the sense that the instructor did not facilitate any discussions to have students connect their understandings developed of the content of the course to more general and germane aspects of the nature of science.

The History of Science course (Survey course) was mid-sized (n = 45 students) and utilized a lecture format to highlight major events in the history of science from the period of ancient civilization to the post-Roman era. The instructor of the course stated that a goal was to make students aware of the social and cultural embeddedness of science. This instructor also utilized an implicit approach in connecting lessons from the history of science with the nature of science.

The Evolution course was relatively large (n = 116 students) and relied upon a lecture format. The topic of the course was an examination of evolutionary theory using a two-part approach. Students first learned of the development of the theory by way of examining Darwin's conceptual contribution. Then, the course examined the development of the theory of evolution/natural selection from approximately the late
1800's to the mid 1950's. The instructor indicated that a major goal of the course was to have students consider aspects of the nature of science related primarily to the creation, development, and change in scientific knowledge. To this end, the instructor did engage in several explicit discussions about the nature of science during the lecture sessions.

After analyzing the pre questionnaire and interview responses, the researcher found that students exhibited a variety of naive conceptions about the targeted aspects of the nature of science prior to instruction in one of the history of science courses. In contrast, the preservice MAT teachers who had been given explicit instruction on aspects of the nature of science in a prior Methods course exhibited more contemporary views prior to instruction in a history of science course. After analyzing the post data, the researcher found little overall change in students' views after their having participated in the history of science courses.\(^\text{10}\) Preservice teachers' conceptions of the nature of science exhibited more change (or enrichment) in their views than the other science students. In summary, Abd-El-Khalick concluded that there was little empirical support from this study to support the claim that coursework in the history of science would improve students' conceptions of the nature of science unless certain nature of science aspects were explicitly addressed.

In the discussion of his results, Abd-El-Khalick points out several issues that he contends likely contributed to the relative ineffectiveness of the history of science courses. The first issue is that the history of science was generally presented to students in a didactic (lecture) fashion,\(^\text{11}\) and moreover the instructors of the two courses relied primarily upon an implicit approach to having students consider aspects of the nature of science.

\(^{10}\) Abd-El-Khalick did find that some students' views of the nature of science changed with regard to only one aspect (or at most two). None of the participants in the study achieved significant improvement (change) in multiple aspects of the nature of science as was measured by the VNOS and follow-up interviews.

\(^{11}\) This is largely with reference to the evolution and survey courses. The controversy course used a group discussion approach.
The second issue involves the assumption that students' general conceptions of the nature of science had been robustly developed prior to their enrolling in the history of science course and as such it was unrealistic to expect one course in the history of science to change those prior views. This issue speaks to the tenacity of alternative or naive conceptions. Finally, Abd-El-Khalick points out that in two of the history of science courses (the Survey course and the Controversy course), improving students' understanding of the nature of science was not the overriding goal of the courses. In the next few paragraphs, each of these issues raised by Abd-El-Khalick will be further discussed, and the relevance of his claims with respect to the design and implementation of the method used for the sickle-cell case in this dissertation will be addressed.

Abd-El-Khalick contends that the history of science was presented in a pre-packaged form to the students who participated in the three history of science courses. Essentially, students were presented with historical narratives via a lecture format. The problem with this, suggests Abd-El-Khalick, is that students were unlikely on their own to "put on a different thinking cap" in order to make sense of or critically examine the context of the historical episodes. As such, students viewed the aspects of the historical narratives from their own contemporary understanding and likely dismissed considering the historical view as relevant to understanding aspects of the nature of science. Contributing to this issue was that there was little explicit attention facilitated by the instructors of the course toward having students connect the historical episodes with understanding the nature of science.

The evolution instructor did engage students in several conversations about the nature of science, although Abd-El-Khalick characterizes the overall degree of explicit facilitation of the nature of science as low in all three courses. This is particularly the case with regard to the survey course and the evolution course. The evolution course instructor did engage students periodically (although characterized as minimal by Abd-El-Khalick) about the nature of science. The empirical

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14 The evolution course instructor did engage students periodically (although characterized as minimal by Abd-El-Khalick) about the nature of science. The empirical
One of the strengths of the history of research on sickle-cell anemia that is used as the unit of instruction for this dissertation is that it requires students to immerse themselves in the historical aspects by way of having them engage in problem-solving activities in which they recapitulate the work of scientists working on the sickle-cell phenomenon. Furthermore, the instructor of the course acts largely as a facilitator to students' problem-solving activities by posing questions that require students to consider on their own how their work with the sickle-cell problems connects to an understanding of larger nature of science perspectives. The instructor also facilitates whole-class discussions in which the student groups are given an opportunity to comment on their interpretations of the data and the nature of science probes. Thus, this dissertation examines what would appear to be a potentially beneficial combination of pedagogical methods alluded to by Abd-El-Khalick. First, the history of science is not simply pre-packed and presented to students in a didactic way. Students immerse themselves in the historical context by way of group problem solving and discourse. Second, the instructor actively facilitates explicit discussions that help students connect the relevance of the conclusions achieved in their group work with the historical material to more informed conclusions about germane aspects of the nature of science.

The second issue raised by Abd-El-Khalick to explain why students' views remained largely unchanged concerns the idea that students have their own informal and formal experiences within and without of the formal school science constructed robust and tenacious views about the nature of science. Conceptual Change Research (e.g., Wandersee, Mintzes, & Novak, 1994) underscores that students' do not easily change.

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results of Abd-El-Khalick's research indicate that there was more change or enrichment in the views of students who had enrolled in the evolution course. This gives some support to the claim that explicit attention is more effective at improving or changing students' views.
the alternative conceptions they have constructed, and as such instructors must design instructional pedagogy with this in mind.

Two aspects of the sickle-cell unit are important to consider in light of this issue. First, the unit is situated as the third unit in a three-part sequence. During the first two units, aspects of the nature of science are addressed as students interact with various historically situated teaching materials. In this way, a claim can be made that students are sensitized to discussions about the nature of science prior to their beginning the sickle-cell unit. This idea is to a degree similar to Abd-El-Khalick's claim that students need to be exposed to discussions about the nature of science prior to their enrollment in history of science courses, as was the case with the MAT students in his study.

The second aspect is that throughout the sickle-cell unit, the pedagogy incorporates an approach that is similar to the traditional conceptual change model (Strike & Posner, 1992; Posner et al., 1982). The classes are designed to have students confront their naive conceptions by way of considering how the provisional theories they've constructed as a result of their problem solving and discourse shed light on a more contemporary understanding of the nature of science. The role of the instructor is to facilitate students' thinking on these issues.

An underlying claim of the conceptual change research (addressed in the first section of this chapter) is that students' naive conceptions are quite robust and resistant to change. This is one reason why traditional instruction (e.g., lecture) often fails to help students abandon their naive views in favor of more contemporary ones. Traditional learning generally requires that that the students passively engage with the material, and as such it is less likely that students will actively (own their own) engage with the material to reconstruct their own cognitive frameworks in a way that has them replace the naive view with the more informed one.
In contrast to the historical classes described in Abd-El-Khalick's research, the sickle-cell unit incorporates what would appear to be two beneficial characteristics. First, students are actively involved with conceptualizing the historical material (in contrast to a didactic approach). This is accomplished via using the problem-solving/discourse method. Second, the unit uses several explicit and reflective mechanisms (e.g., instructor facilitation and probing questions during their group work) to have students connect their learning with aspects of the nature of science. Taken together, these two fundamental characteristics are used to help students overcome their reticence to abandon naive views of the nature of science in favor of more contemporary ones.

Conclusion

Relevance to the Cognitive Issues of the Pedagogy

The development and implementation of the sickle-cell unit used as the intervention for this study relies upon the constructivist theory (Piaget, 1959) of learning as the basis for considering how students learn both science content and epistemology. It recognizes that students enter into learning with a prior understanding about science that they have constructed by virtue of earlier experiences and learning. Moreover, the unit underscores that a major responsibility for learning must come from the efforts of students as they actively engage with the material and develop a new or enriched understanding.

Furthermore, the unit incorporates a form of the conceptual change (Posner et al., 1982; Strike & Posner, 1992) strategy to have students essentially “reconstruct” their antecedent views of science in favor of more contemporary or informed views. Throughout the lessons, students consider evidence bearing on problems taken from the history of research on sickle-cell anemia. The explanations that students construct to
account for the various problems often conflict with their prior views (or previously constructed explanations). Students evaluate the adequacy of the new perspective they develop in subsequent classes during which they examine still other problems (that build off the understanding they are developing). In this way, students not only learn about a particular example, but also gain insights into the processes and nature of science.

Several researchers in science education (e.g., Abd-El-Khalick, Bell, & Lederman, 1998; Abd-El-Khalick & Lederman, 2000b) underscore that a view of the nature of science is something that students cognitively construct. This stands in contrast to those who believe that a view of the nature of science is an affective construct. The distinction is that those who advocate that a nature of science view is a cognitive construct claim that lessons should ensure that the nature of science is explicitly considered in concert with the conceptual material being examined in the classroom.

The pedagogy of the sickle-cell lessons uses an explicit and reflective approach to bring the nature of science into the lessons. The relative effectiveness of this approach (in contrast to implicit approaches) is supported by the research literature (e.g., Abd-El-Khalick et al., 1998; Akerson, Abd-El-Khalick, & Lederman, 2000; Khishfe & Abd-El-Khalick, 2002). The approach taken in the unit is careful to ensure that students' learning of aspects of the nature of science occurs by virtue of their reflective insights gained from their investment with the group problems and the probing questions (see Appendix F). This type of approach can be contrasted against other pedagogical techniques (e.g., didactic) used as the basis for improving students' conceptions of the nature of science.
Relevance to Empirical Research of the Study

Consistent with the increasing use of qualitative, interpretive methods to measure students' conceptions of the nature of science (e.g., Abd-El-Khalick & Lederman, 2000; Abd-El-Khalick, Lederman, Bell, & Schwartz, 2001; Akerson, Abd-El-Khalick & Lederman, 2000; Lederman & O'Malley, 1990; Lederman, 1999; Palmquist & Finley, 1997), this study incorporates a combination of an open-ended survey (VNOS – Views of the Nature of Science) and follow-up, semi-structured interviews. The advantage of the use of open-ended surveys is that they allow respondents to express their own opinions about the nature of science rather than be forced to rely on predetermined responses. As such, the survey minimizes the potential for bias. The use of follow-up interviews in tandem with the pre- and post-instruction surveys is suggested by Lederman and O’Malley (1990) to allow the researcher an opportunity to ensure that the survey was validly capturing students’ intended views and to allow the researcher an opportunity to further probe students’ answers or have them clarify idiosyncratic responses.

Relevance to the Use of History/Philosophy of Science in the Pedagogy

A review of the literature concerning the history and philosophy of science provides insight into the origins and nature of students’ naïve views that they possess regarding aspects of the nature of science. Such views are often analogous with those espoused by philosophers of science associated with the post positivist movement. Broadly stated, students hold the conception that science is associated with finding truths, that observations are divorced from theoretical commitments, that the development of knowledge by scientists occurs by induction of generalizations from the systematic and objective collection of data, etc.
The lesson plans for the sickle-cell unit incorporate the history of science as a backbone to the pedagogy. In this way, students are encouraged to actively engage with the history of science by recapitulating similar reasoning employed by historical scientists who were working to develop an understanding of the sickle-cell phenomenon. This is accomplished in a problem-solving environment in which students examine data in an attempt to construct their own explanations. This approach can be contrasted with more passive methods (e.g., as is often the case with historical vignettes) in which instructors have students largely “read about” the conclusions reached by historical figures.

When students engage with the material in an active fashion by solving problems taken from the history of science and recapitulating (unbeknownst to them) the reasoning employed by historical scientists, they take ownership of the conclusions they reach and thereby come to see the validity of their own explanations. This method may help lesson the tendency for students to immediately dismiss historical conclusions (or ways of thinking) as misguided or foolish. In this manner, the lessons are designed to allow students to “put on the historical thinking cap” (Abd-El-Khalick & Lederman, 2000) and as such permit students to more readily see the validity of their conclusions to understanding issues associated with the nature of science.
CHAPTER 3

RESEARCH METHODOLOGY

Method for Empirical Research

The empirical approach taken in this dissertation is best characterized as interpretive research (e.g., Strauss & Corbin, 1990). The data sources include the results from open-ended surveys and transcripts of follow-up interview sessions with a subset of those students who completed the survey. As such, the research conclusions rely largely on qualitative analyses of these data sources. This type of analysis is emblematic of naturalistic research. The general method is an evaluative investigation. This means that one objective of the research is to measure the effect of a method of incorporating the history of science on students' learned conceptions of the nature of science. In this manner, the research is summative in nature.

More specifically, the research used a pre- and post-assessment open-ended survey to measure students' conceptions of certain aspects of the nature of science. A percentage of the pre- and post-respondents were selected to participate in a semi-structured interview. The purpose of these interviews were to at once establish the validity of the survey and to allow the researcher an opportunity to probe more deeply into the answers students provided to their survey responses. This approach has been used extensively in research on student conceptions of the nature of science (e.g., Abd-El-Khalick & Lederman, 2000; Abd-El-Khalick, 2001; Akerson, Abd-El-

Research Population

The research was done at Western Michigan University. The participants were preservice teachers, most of who are elementary education majors and who will ultimately teach at the elementary and middle-school levels. This population of students is required to complete several courses in science education to satisfy their elementary education degree. At present, the sickle-cell unit is the last of a three-part unit that forms the course, BIOS 270, Life Science for Elementary Educators. BIOS 270 is one of six classes offered by The Mallinson Institute for Science Education for elementary education major students.

Though the course is not compulsory, the majority of students who enroll satisfy a minor requirement in science and mathematics as a part of their elementary education experience. Although there are no prerequisites for taking the course, it is not uncommon for students to have taken other science education classes prior to beginning BIOS 270.

The research took place during the fall semester of 2002 and the winter semester of 2003. In each semester, there were two sections of the course offered with a total of approximately 24 students per section. The total potential pool of
participants was composed of 94 students. The actual number of students who completed the study was 81.\textsuperscript{15}

Ninety percent (n = 73) of the population was female. Sixty percent of the population was between 18 to 21 years old; another 37% between 22 to 24 years old. The majority of the students (95%) had no prior teaching experience. The remaining 5% had completed or were taking concurrently a preservice internship at the time of the study. The entire population of students came from the Midwest, with the majority (> 95%) coming from within state.

**Research Instruments**

**Open-ended survey**

A condensed version of the survey (pre and post are identical) is contained in appendix B. The difference between the full and the condensed version is that in the full version, each question appears on a separate sheet of paper to allow students sufficient room to write their responses. In total, the full version requires five pages.

The design of the survey and the method for its validation have been described in prior research on students’ conceptions of the nature of science.

\textsuperscript{15}The actual number of students in the study was less than the potential pool. Several reasons account for the difference. One student (1% of potential pool) elected not to participate in the study at the outset for personal reasons. Seven students (7%) either did not complete the pre-survey instrument or did not complete the post-survey instrument. Finally, five students (5%) who agreed at the outset to participate in the study and who completed the pre- and post-survey instruments did not regularly attend class during the sickle-cell unit of the course. After accounting for these circumstances, the total number of students who participated in the study was 81.
The advantages of using an open-ended survey versus a closed or forced-item (e.g., multiple choice) format to measure students’ perceptions is addressed in the research literature (Aikenhead, 1988; Lederman, Wade, & Bell, 1998; Lederman, 1992; Lederman & O’Malley, 1990). The survey contains five separate questions, each question addressing a particular aspect of the nature of science. Each of these aspects has received specific attention in recent reform documents in science education (AAAS, 1990, 1993; NRC, 1996). Below, each of the survey questions is further explicated, including an indication of how the question was created and specific passages from the reform documents (where appropriate) that establish the relevancy of the question. A more detailed description of philosophical significance of each question is provided in the subsequent chapter of this dissertation in which the results of the research are given.

In question #1, students are asked to provide their understanding of the design and role of scientific theories in the construction of scientific knowledge. This question was designed by the researcher in an attempt to elucidate students’ views on the relationship that evidence has in the construction of theories, the idea that theories are something that scientists invent (i.e. they are not truths to be found or discovered), and the importance of the explanatory role that theories have in science. These aspects receive support in reform documents:

“Scientists do not pay much attention to claims about how something they know about works unless the claims are backed up with evidence that can be confirmed and with a logical argument.” (AAAS, p. 11)

“Scientific investigations usually involve the collection of relevant evidence, the use of logical reasoning, and the application of
imagination in devising hypotheses and explanations to make sense of the collected evidence.” (AAAS, p. 12)

Having students understand the central role of the development and status of scientific theories is further emphasized by science education researchers (e.g., Duschl, 1990).

Question #2 was slightly adapted from Abd-El-Khalick et al. (2001) VNOS (Views of the Nature of Science) instrument. Here, the emphasis is on understanding students’ views of the tentative nature of science by way allowing them to explain their understanding of the nature or status of theory change. Having students appreciate that scientific knowledge is not absolute or proven is highlighted in the AAAS documents (pp. 7 - 8). The naive view often held by students is that they believe scientific knowledge as something that is fixed in the sense that theoretical understanding in science is either wholly accepted or wholly abandoned (Duschl, 1990; Cotham & Smith, 1981; Horner & Rubba, 1978). Often this is evidenced by students expressing the belief that theories are fixed or proven rather than considering them at best something that can only be explanatory and refutable. Moreover, for those students who recognize that theories do change, they usually characterize change solely in terms of advances in knowledge brought about from advances in technology. There is little recognition that scientists may achieve new insights with existing data.

Question #3 invites students to share their understanding of the distinction between scientific theories and scientific laws. The common naive view is that students place theories and laws in a hierarchical and developmental framework
Here, students may claim that theories evolve into laws should enough evidence be gathered to sufficiently “prove” the theory. This stands in contrast to recognizing the ontological difference between theories as explanations and laws as descriptions (Rhodes & Schaible, 1989). This question was taken directly from the VNOS survey employed by Abd-El-Khalick, Bell, & Lederman (1998).

Question #4 asks students to consider if the creation of scientific knowledge is predicated on the need for conducting controlled, manipulative experiments. A more informed view would reflect that knowledge in science can be created from a variety of methods other than from experimentation, for example through the use of observational inquiry. This question was taken from the VNOS survey used by Abd-El-Khalick (2001).

Question #5 asks students to consider what is broadly construed as the subjective (theory-laden) nature of science. This question was taken from the VNOS survey used by Abd-El-Khalick (2001). The emphasis in the question is to discern whether or not students recognize that scientists, by virtue of their own theoretical and experiential frameworks, have subjective interpretations of data. Moreover, a “correct” answer could reflect how scientists achieve certain insights as a result of their own subjective backgrounds. This stands in contrast to the naïve view in which students claim that there must be something inherent in the data itself (or lack thereof) that prevents scientists from achieving consensus.

Furthermore, this question relates to an understanding of the relationship between theory and observation. The more naïve view espouses that there is no
affecting relationship between theory and observation (analogous to what advocates of the positivist philosophy of science termed the theory-value distinction) such that what a scientist observes is not clouded by any theoretical commitment. A more informed philosophical view (e.g., Kuhn, 1962, 1970) holds that there is a relationship between theory and observation in the sense that what a scientist observes is unavoidably framed in part by the antecedent theoretical commitment held by that scientist.

For each of the questions, students were asked to explain or defend their answers. The principal reason for stressing this is to increase the validity of potential inferences drawn from student responses. In the absence of understanding the reasons for student answers, there is no principled way to discern if students have merely memorized a view of the nature of science or not. Memorization should not be classified as a meaningful or enriched understanding. An example case is when a student indicates in the pre-survey that a theory is an “educated guess” and in the post-survey claims that a theory is an “explanation.” In the absence of providing reasons for their understanding (or change therein), the researcher has no way of legitimately claiming whether or not the student has achieved a true conceptual change about their understanding of the word theory or has simply given a memorized view.
Semi-structured Interviews

Research indicates that the validity of using an open-ended survey is enhanced when it is used in tandem with a semi-structured interview (Lederman & O'Malley, 1990). The purpose of the interview is to allow the researcher to ensure that students' responses on the survey are accurate as intended (i.e. the students understand the questions). That is to say, the validity of the survey is better supported when students interpret and respond to the interview questions with the same general answers they provided on the survey instrument. Additionally, the interview allows the researcher to probe more deeply into various aspects of the students' answers. This way, the researcher can identify what meanings students ascribe to certain words that they use in their survey answers. The post-interview also allows the researcher an opportunity to ask students if (and how) their views have changed from the pre-survey to the post-survey, and the researcher can ask students pointedly what factors may have been responsible for those changes.

The person who conducted the actual interviews with the students was different than the instructor/researcher of the study. The reason that a different person was chosen to do the interviews was to comply with requirements outlined by the Human Subjects Internal Review Board (HSIRB) at the university where the study took place. In short, the HSIRB requires that research on human subjects be done in such a way that there is the minimum possibility that students feel potentially coerced into participating in the study. For this reason, the researcher (who was also the instructor of record for the course) did not know which students participated in the
actual study but rather received copies of surveys and interview transcripts with
coded names.

Given this stipulation, the researcher worked with a fellow doctoral student in
science education who had similar interests in researching students' nature of science
conceptions. Approximately six months prior to the study, the researcher shared
several conceptual and empirical studies (e.g., Abd-El-Khalick & Lederman, 2000;
Palmquist & Finley, 1997) so that the collaborating student could become familiar
with the scope of nature of science issues and empirical methods specifically
addressed in the research done in this study. Moreover, the selected literature allowed
the collaborator to become acquainted with the purpose and methodological structure
of the interviews themselves. To augment the collaborator's understanding of
interview technique, the researcher suggested several pieces of literature (e.g.,
Ginsberg, 1997) for the collaborator to read.

Finally, the researcher provided the collaborator several copies of actual
student written responses to both pre- and post-instruction pilot surveys. In this way,
the collaborator could see how students specifically responded to the survey
instruments and could better anticipate the antecedent views the students held prior to
entering an actual interview. Furthermore, the researcher and collaborator engaged in
several mock interviews in which the researcher played the role of one of the sample
pilot students and allowed the collaborator to conduct a clinical interview about the
hypothetical views.
During the actual interviews conducted in the study, the collaborator asked each student to read each of the survey questions, to read their responses, and to paraphrase each of their responses. The collaborator ensured that the student understood the questions and then asked each student about any particular idiosyncratic wording or phrasing that the student may have used in a particular answer. Moreover, when appropriate, the collaborator asked students to respond to various probing questions to get them to further explicate their general nature of science views for a particular aspect addressed by the survey.

**Specific Procedures**

A pilot survey was developed and administered to students prior to the construction of the final survey used in this dissertation. The purpose of the pilot survey was to check for the validity of the questions authored by the researcher. Here, it was essential to determine if students interpreted the question in the manner meant by the researcher. Of the five questions in the pilot survey, two were authored by the researcher (questions #1 and #4 in Appendix B). The results of the pilot survey showed ambiguity between what the researcher hoped students would interpret on the

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16 All research conducted at the university is in accordance with the guidelines established by the Human Subjects Internal Review Board (HSIRB). The full HSIRB application, including consent form and interview script are located in Appendix C.  
17 The pilot was administered to students who participated in prior sections of the course and were not a part of the final study.  
18 Four of the five questions in the pilot survey were only slightly modified from the VNOS instrument used as the model. As such, the researcher was less concerned about the validity of these four questions given that prior researchers confirmed the validity of these questions (e.g., Abd-El-Khalick, 1998).
two new questions and what they indeed did interpret as revealed from their answers
to the survey and by their responses to the questions posed in a semi-structured
interview. As a result, the new questions contained in the pilot survey were modified
into the forms contained in the final version of the survey used in the study
(Appendix B).

The final survey represents a modified version of the VNOS instrument that
has been used in recent research to assess students’ conceptions of the nature of
science (Abd-El-Khalick 2001; Akerson, Abd-El-Khalick, & Lederman, 2000;
Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002; Lederman & O’Malley, 1990;
Lederman, Wade, & Bell, 1998). The final survey represents both the pre- and post-
instruction instrument.

At the beginning of the course, the researcher told the students that aspects of
the course would form the bases for empirical research in improving science
education. Students were instructed that part of the research would require that they
complete a survey about their views of various aspects of science. The potential
participants were also informed that there was a possibility of their having to do a
follow-up interview about the responses they would give to the survey instrument.
For those students who agreed with the research requests19, they were given an
informed consent document to sign.

19 Only a few students elected not to participate in the study. Given the relative
homogeneity across all of the students in the course with respect to the number of
science education courses previously taken, the age of the students, and the lack of
teaching experience, the researcher does not believe that there were systematic
differences between students who did not elect to participate in the study.
Two classes prior to the beginning of the sickle-cell unit (the final eight classes of the course) the collaborator administered the pre-instruction survey to the students who had agreed at the outset of the course to participate in the research. Students were instructed to read each question of the survey carefully, to answer each portion of the question, and to write their answers in the space provided on the individual pages of the survey, with the understanding that they could elaborate on the back of any page if necessary. For those students who did not agree to participate in the research, they were asked to work quietly at their desk while the other students completed the survey. On average, the survey required approximately 40 minutes to complete.

Following completion of the survey, the researcher randomly divided the participants into two groups, termed the pre-group and the post-group. From the pre-group, students were randomly selected to participate in a semi-structured follow-up interview about their responses to the pre-survey. In total, 23% (n = 19) of the overall population participated in the pre-instruction interview. From the post-group, students were randomly selected to participate in a follow-up interview to what would be their responses to the post-survey administered at the end of the unit. In total, 16% (n = 13) of the overall population participated in the post-instruction interviews. The reason that a different group of students was interviewed for the post-survey versus the pre-survey was to minimize the potential for a "testing effect" in which the pre-survey interview could be viewed as a quasi-intervention thus potentially influencing a student's views. Therefore, all post-survey participants had not been interviewed.
beforehand. This method was taken directly from current research on understanding student views of the nature of science (Abd-El-Khalick 2001, 1998; Akerson, Abd-El-Khalick & Lederman, 2000).

For each pretest interview, a research collaborator\textsuperscript{20} established a convenient time for the respondent and the collaborator to convene. The location of the interviews was consistent and occurred in a private room located nearby the class where the instruction took place. All pretest interviews took place before instruction began for the sickle-cell unit.

The interview format replicated that done by prior researchers (e.g., Abd-El-Khalick, 1998; Lederman & O’Malley, 1990). For the pretest interview, the collaborator had students examine and read over their answers they provided to the pretest survey. Then, for each question students were asked whether or not the question was clear to them and were asked to paraphrase their answers they provided. After this, the collaborator asked follow up questions that related to specific issues or terms that were raised in the students’ answers. Here, the collaborator probed more deeply into what students meant by certain phrases or words that they used. The content and structure of many of the follow-up probes were taken directly from Abd-El-Khalick’s (1998) interview format. Table 2 provides a summary of the major follow-up probes used in the interview.

\textsuperscript{20} As explained earlier in this chapter, a collaborator in the research conducted the follow-up interviews. Due to HSIRB regulations, the researcher (who was also the instructor of the course) was not permitted to conduct interviews with the students.
Table 2

Semi-structured Interview Probes

<table>
<thead>
<tr>
<th>Survey Question</th>
<th>General Issue /Belief Raised by Student</th>
<th>Probing Question(s)</th>
</tr>
</thead>
</table>
| 1               | Student claims theories are “proven”   | • How would you “prove” a theory?  
                        |                                       | • How much evidence or experiments does it take to “prove” a scientific claim?  
|                 | If student indicates a theory as “a guess” | • What do you mean by a “guess?”  
|                 | Theories are/have been tested           | • What do you mean by “tested?”  
                        |                                       | • Can you have a theory without testing? Why or why not?  
| 3               | (no specific issue)                     | • In terms of status and significance as products of science, would you rank scientific theories and laws? And if you choose to rank them, how would you rank them?  
| 4               | Science knowledge requires controlled experiments | • Let’s consider a science like astronomy or anatomy. Can we (or do we) do manipulative experiments in astronomy or anatomy? If yes: Please explain and provide an example? If no: But we still consider astronomy or anatomy as science. What are your ideas about that?  
| 5               | “Not enough supportive data”            | • It is very reasonable to say that the data is scarce and that the available evidence supports both hypotheses equally well. However, scientists in the different groups are very adamant about their own position and they publish very pointed papers in this regard. Why is that?  
                        |                                       | • Why would some scientists consider the idea of a meteor falling from the sky to be unacceptable or strange?  
|                 |                                       | • When scientists conduct scientific investigations, which comes first, theory or observation?  

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Following completion of the sickle-cell unit, the researcher again administered the post-instruction survey to all willing participants. After collecting their completed post-surveys, the collaborator contacted those individuals who were identified beforehand to participate in the post-interview. The post-interview format was very similar to that done with the pre-test respondents with one notable exception. The collaborator asked the post-interview participants to compare their responses from their pre- and the post-survey answers. From this, the collaborator asked the students to identify if their views about a certain question had changed and asked them to identify both how they had changed and why they had changed.

The data collection complied with the rules according to the Human Subjects Internal Review Board (HSIRB) of the university. As such, all documents and transcripts were coded. The researcher will maintain the corresponding list that identifies students names with their given codes. All data will be kept in a secure location. A full copy of the HSIRB application is contained in Appendix C.

Treatment of the Data

Survey Responses and Interview Transcripts

This data was analyzed by using aspects from differing protocols outlined in similar research into student conceptions of the nature of science (Abd-El-Khalick 2001; Abd-El-Khalick, Bell, & Lederman, 1998; Akerson, Abd-El-Khalick, & Lederman, 2000; Palmquist & Finley, 1998). The first task was to read through the pre- and post-surveys to establish initial categories of responses. This first round
analysis generated broad inferences to how students interpreted and responded to each question. It is important to underscore that these emergent responses were those ascribed by the students by virtue of their responses on the surveys (as inferred by the researcher). This is distinctly different from the researcher having predetermined categories and effectively pigeonholing student’s answers into those antecedently characterized views. The same process was then done to the interview transcripts.

Following the initial characterization of students’ responses to both the survey and interview data, the general inferences created from these process were compared and contrasted to discern if the survey was a valid representation of the students’ intended responses as matched to the interview responses. A high degree of validity was evidenced when the general inference drawn by the researcher to a specific question on the written survey largely matched the inference drawn to the same question in the interview.

The second stage of analysis involved taking the students’ pre and post-survey responses and generating more detailed summaries for each of their responses to each individual question. Following this initial treatment, the specific summaries were grouped into larger-grained themes that emerged as a result of interpreting students’ responses to each question. Student’s responses to various questions were then checked against one another to ensure that the student was being consistent with his or her answers. For example, it is possible that a student properly indicated that a theory is a tentative explanation for question #1 only to follow up that answer with a claim that theories are unchanging in question #2.
The second stage of analysis was also completed for those students who participated in the follow-up interviews. Though the primary reason for the interviews was to ensure the validity of the surveys, additional data was generated during the interview process when the researcher asked probing questions. The student responses to these probes were used to augment the answers they provided on their surveys. Furthermore, during the post-interview, for those instances in which a student’s view had evidently changed from the pre-survey, the researcher pointedly asked the students to comment on their reasons for the change. These reasons were noted during the second stage of analysis and matched to the coded student’s views for later interpretation.

Two separate methods were done to examine whether the researcher was reliably coding the data. First, 10% of the surveys completed for the pre/post-pool were randomly selected and given to a faculty member who has a specific expertise in the history and philosophy of science. Moreover, this faculty member has an informed understanding of the issues germane to both naïve and informed (or contemporary) conceptions for each nature of science questions addressed by the survey. The faculty member was given the general coding scheme for each question of the survey and asked to independently analyze the randomly selected subset of surveys. In this way, the faculty member was asked to code each student’s responses by reading through the student’s articulated views and categorizing them accordingly. From this independent analysis, the degree to which the coding of the researcher
corresponded with that done by the faculty member (noted as inter-rater reliability) was 80%.

Concerning the second method, approximately one month after the initial rounds of data analyses, the researcher performed a blind re-coding of 20% randomly selected surveys from the pre-instruction pool. The purpose for this blind analysis was to see if the researcher was consistent in coding these selected samples into themes that were similar to those that emerged from the initial rounds of coding. The results of this indicated that the researcher was very consistent (>95%) in using the same interpretive framework throughout the code / re-code procedure.

The data regarding both students’ pre and post-instruction views is presented in two ways. The first resulted from a process of categorization and modification to distill the data into overall profiles. This data is presented in Chapter 4 in tabular form for each aspect of the nature of science. This method of data characterization allows the researcher to see if (and how) overall thematic responses to each aspect of the nature of science shift as a result of the intervention (the sickle-cell unit).

The second way the data was handled was by treating each student as an individual case. Here, the purpose was to see if (and how) each student articulated support of his or her view given in response to the questions about the nature of science on the survey. The importance of this is to identify if students were being reflective about their views by way of providing examples that go beyond what was given in the text of the questions for each item on the survey. This issue is particularly important in order to establish in the post-instruction survey that the
sickle-cell unit was (at least) partially responsible for changing or enriching a student’s view. That is, the researcher looked to see if the student was able to provide a reflective example from his or her work with the sickle-cell unit in addition to articulating a more informed view of the nature of science for a particular question.

The final stage of analysis for the pre and post-survey and interview data was to compare students’ pre- and post-views to determine if their views about the given nature of science aspects had changed. Abd-El-Khalick (2001, 1998) uses a method of characterizing change as either true “change” or “enrichment.” The former occurs when a student genuinely displays a change from a naïve to a more informed understanding of the nature of science. Enrichment is useful to account for those students who begin the class with a more informed understanding by virtue of their responses to the pre-instruction survey. Enrichment is said to occur when the student provides evidence from the post-instruction survey that links his or her (still) informed view with some portion of the learning he or she experienced while in the class.

About the Researcher

At the time of the study, the researcher was a doctoral candidate in The Mallinson Institute for Science Education at Western Michigan University, Kalamazoo, Michigan. He has earned a B.S. in molecular and cellular biology and a M.A.T. in the teaching of biology from two different educational institutions. Prior to beginning his doctoral work, the researcher spent several years working in private
industry in the research and development of pharmaceutical and health-care devices. He also briefly taught high-school biology and earth (physical) science.

The researcher’s interest in using the history of science to affect students’ understanding of aspects of the nature of science emerged during his coursework while as a doctoral student. To this end, the researcher worked in coordination with another faculty member at the Mallinson Institute for Science Education to design a course in biology, BIOS 270, which uses the history of science frequently to help students learn both science content and epistemology.

The researcher was responsible for developing the third unit of the course, which is the unit of analysis for this project. To do this, the researcher spent nearly one year reading through the primary research literature that frames the historical development of the sickle-cell phenomenon. He also interviewed one of the prominent figures whose work was instrumental in developing a critical piece of the historical story (Anthony C. Allison, MD, PhD). From this body of historical work, the researcher began to develop a series of lessons in which students would examine the chronological development of the sickle-cell disease. Furthermore, the researcher intended that the lessons treat the history of science in an artifactual manner, which is to say that individual episodes taken from the history of research would be used as the bases for “problems” that students would examine toward constructing an understanding.

From this corpus of research, it was clear that several aspects of the nature of science would be accessible and germane to the work that students would do while in
the context of their daily classes. The researcher selected those aspects of the nature of science that were deemed most likely to be discussed during the unit as the focus of his empirical work for this project.

The Researcher’s Views of The Nature of Science

Science represents a unique approach to explaining the natural world. At its core, science is an empirical discipline, meaning that knowledge in science is ultimately grounded in sensory perceptions. This usually involves scientists gathering data through some form of observation and/or experiment and using the resultant data in support or in refute of a held position.

Broadly characterized, the purpose of science is to develop explanations to account for and predict patterns that emerge from observations. Often people refer to this process as model building; the idea being that science involves constructing, testing, and refining explanatory models that account for a given problem or scenario. Under the “model” conception, an exemplar scientific model should not only provide an appropriate explanatory framework for the problem in question but should also allow scientists to make predictions about correlated events to the parameters of the model.

A scientific theory is a well-supported explanation to account for a problem of interest in science. Moreover, like models, theories not only serve an explanatory function but also allow scientists to make predictions (or retrodictions). For example, Darwin’s theory of natural selection provides a unifying mechanism that accounts for
the incremental change (or transformation) of one species into another. This theory also allows scientists to make predictions about phenotypic characteristics of transitional forms not yet discovered. In fact, Darwin himself used the retrodictive power of his theory to propose the existence of the transitional organism that should exist between the reptile and avian lineages. This retrodiction was found to hold true when scientists discovered the fossilized remains of archaeopteryx.

More robust theories in science (e.g., plate tectonics, atomic theory) often draw their evidential support from multiple disciplines of science, and they also frequently result in opening (or generating) new avenues of research. Evidence in support of the theory of natural selection came from such disciplines as geology (the conceptual and factual basis of the theory of uniformitarianism), horticulture, geography, and comparative anatomy. Furthermore, the proposal of the theory of natural selection paved the way for new problems in biology (e.g., debates concerning the inheritance of continuous vs. discontinuous variations).

Distinct from a scientific theory, a scientific law is a well-supported description of a universal and consistent pattern in nature (e.g., Newton’s Laws of Motion), and in this way, laws often describe relationships between variables. Though they are distinct, laws and theories are not unrelated. Theories can provide an explanatory element for the patterns that the law purports. The heliocentric model of the solar system provides an explanatory framework for the observed motions described in part by Newton’s Laws.
This is not to imply that theories and laws are hierarchically related, as is often a widely held misconception. That is, theories do not “become” laws after the collection of significant data or after the passage of time. Rather, theories and laws are separate entities, both serving an important function in the development of scientific knowledge. Both theories and laws are validated by the amount of supportive evidence that has been collected to substantiate them. That is, one measure of the validity of scientific knowledge (i.e. theory/law) is the amount of confirming evidence that supports or reaffirms its basic tenets.

The naïve view often associated with the last claim is the belief that science involves the creation of absolute truths. Evidence of this belief is usually given in statements in which people indicate that scientific laws and or theories are “absolute,” fixed, or “proven” entities. Because so much evidence has been collected in favor of the tenets of the law (or theory) the general misconception is the inference that the law or theory will be forever true in all situations.

A more philosophically informed understanding has that scientific knowledge is tentative, or subject to potential change (modification). Though the strength of a law or theory is due in part to the amount (and quality) of supportive evidence, there should be no reason to discount the possibility (however remote) that a piece of data will be collected in the future which might jeopardize the logical structure of the tenets of the law or theory. This underscores the fallacy in the belief that scientific knowledge proceeds by way of purely inductive approaches.
It is also naïve to conceive of theory change solely in terms of scientists collecting new data (which casts doubt on existing theory). The common conception in this regard is that advances in technology precipitate new data that when incorporated into the existing theory necessitates a change in (or altogether abandonment of) the theory. It is naïve to presume that theory change only occurs because of new data. Rather, change in theory may also occur in the case when scientists gain new insights with existing sets of data.

It is also important to recognize that the discovery of anomalous data does not necessarily cause the immediate abandonment of a commitment to a theoretical position. Anomalies may be treated in a variety of ways. If they cast doubt on one of the minor positions of the theory, scientists may simply ignore them. If on the other hand, the anomaly threatens some of the major tenets of the theory, then scientists are confronted with the need to substantially change (or possibly abandon) the entire theory. The above underscores that the strength of a theory is (in addition to the amount and quality of supportive evidence) also partly a function of the relative lack of refuting evidence or avoidance of conceptual problems to that theory.

As much as the strength (or validity) of scientific knowledge is determined by the quantity and character of the data that scientists collect, it is equally important to recognize the human dimension of science. That is, science is a product of human cognition. Because of this, issues such as creativity, subjectivity, consensus, and ethics (among others) are critical components to the development and evaluation of scientific knowledge.
In this light, a scientific theory is something that scientists "invent" to explain the patterns or problems that they encounter. It is not something that merely emerges from the data. Often it requires scientists to make creative leaps or adductions from the data that they possess in order to conceptualize the theory. For example, Darwin was successful in developing the theory of natural selection partly because he was adept in connecting related pieces of evidence (e.g., analogies to artificial selection by bird fanciers, the economic population conclusions of Malthus, and Lyell's theory of gradual geological change).

It also underscores why not all scientists come to similar explanations when they are presented with similar (if not exact) pieces of data to consider. This is often referred to as the subjective (or theory-laden) nature of science, meaning that the theoretical positions that scientists adopt are partly influenced by the way in which scientists "see" or interpret the data. The counter and philosophically more naïve view claims that scientists are objective, to the extent that they are able to conduct observations free from a-priori theoretical commitments. Scientists come from disparate backgrounds. They are influenced by their previous educational and work-related experiences, their religious and political perspectives, their standing within the community of practicing scientists and within the socio-economic milieu in which they practice. All of these things understandably shape their interpretation of data that they examine.

Partly as a result of these disparate positions (and the ensuing theoretical positions that result from them), the evaluation of scientific knowledge involves a
process of consensus. This means that scientists present their work for peer review and criticism through such venues as meetings and journals. This reflects that the development of knowledge in science is contingent on a socially-constructed framework in which more valid theoretical positions are given more credibility or are encouraged for further analysis.

However, it is important to realize that the acceptance (or rejection) of scientific claims by the mechanisms described above is understandably influenced by the social and political norms in which scientists (or consensus bodies) operate. What this implies is that differing worldviews of science emerge, with potentially incongruent (although likely similar) explanations coming as a result of the aforementioned influences. This is often evidenced in, for example, such statements as “western view” of science, though this is not to suggest that science involves relativism in that disparate theoretical positions are given (necessarily) equal merit.

That scientific knowledge results as a product of human creation, development, and interpretation underscores that scientific knowledge is partially reflective of the this cultural or social milieu in which it is practiced. The contrasting position is that scientific knowledge (e.g., theoretical commitments) represents a distinct reality divorced from an interpretive framework. However, the former should not imply that science involves uncritical relativism. Part and parcel of what negates a relativist view of science is that despite the existence of often different interpretive frameworks, science does involve consensus toward acceptable theories vis-à-vis the mechanisms described above.
CHAPTER 4

RESULTS

Introduction

The present chapter presents a qualitative analysis of participating students’ views as revealed in written surveys and interview transcripts. An open-ended survey (Appendix B) used as the primary instrument to capture students’ views addressed the following aspects of the nature of science (a) the nature of scientific theories, (b) the tentative nature of science, (c) the difference between scientific theories and laws, (d) the validity of observational methods in science, and (e) the subjective (theory-laden) nature of science. Each of these aspects was addressed individually as a separate question (or series of questions) on the survey and also in follow-up interviews.

The chapter is divided into four main sections. The first section, “Participants’ Pre-instruction Views of the Nature of Science,” analyzes students’ views of the five selected aspects of the nature of science that are the object of this research prior to the intervention. The second section, “Participants’ Post-instruction Views of the Nature of Science,” summarizes students’ post-instruction views and analyzes the efficacy of the intervention with reference to all five of these issues. The third section, “Effect of the Unit on Individual Student’s Views,” evaluates why

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21 Throughout the chapter, for brevity the phrase “subjective (theory-laden) nature of science” is shortened to “subjective nature of science.”
certain aspects of the unit were or were not effective at changing the individual’s views. A fourth section, “Summary,” concludes the chapter.

Participants’ Pre-instruction Views of the Nature of Science

Nature of Scientific Theory

The first question on the survey\textsuperscript{22} asked students to define what is meant by a “scientific theory,” to discuss where theories “come from,” and to give an example of a theory in science:

Often in science, we hear words like “theories” used to describe scientific knowledge. What is a theory? How are theories developed? Can you give an example of a scientific theory?

Science educators suggest that on a basic level, a scientific theory should be conceived as an explanation to account for some phenomenon or problem of interest. Moreover, the explanation should be supported by evidence, derived from either empirical and/or inferential methods (Driver, Leach, Millar, & Scott, 1996; Duschl, 1990). In his characterization of scientific theories, Abd-El-Khalick (1998) draws from the philosophical work of Suppe (1977) when he describes theories as robust, internally-consistent systems of explanations. As Abd-El-Khalick states it, "Theories serve to explain relatively huge sets of seemingly unrelated observations in more than one field of investigation. More importantly, theories play a major role in generating research problems and guiding future investigation" (1998, p. 361).

\textsuperscript{22} In several locations in this section of the chapter, the survey questions are given as a reference to the reader. Note that the form of the question differs from the actual survey instrument as contained in Appendix B.
Also suggested by science educators (e.g., Abd-El-Khalick, 1998; McComas, 1996) as important that students understand is the idea that theories are human constructions to account for problems and observations in science. As such, theories do not merely emerge in an inductivist sense from the examination of data but are rather created by scientists from their interpretations of the data. Thus, theories are something that scientists “invent” to explain the data. Theories also serve additional roles or functions. They allow for predictions to be made and often pose the existence of unseen or intangible events and entities.

Duschl (1990) draws from the work of the philosopher of science, Imre Lakatos (1970) the idea that there is a hierarchy of theories whereby the more robust or “core” scientific theories deserve such a status by virtue of the amount of supportive evidence that they contain, the amount of time that they have withstood repeated efforts to invalidate them, the degree to which the theory encapsulates or is inclusive of other related entities or problems associated with the theory, and so on. In contrast, more provisional or “fringe” theories provide explanations to more narrow problems and are provisional by virtue of their immaturity. An example of a “core” theory, as characterized by Duschl (1990), would be akin to the theory of evolution or the theory of plate tectonics.

Answers to the surveys and interviews revealed four general themes23 that students ascribed to creation and status of theories (Table 3). As listed in the table,

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23 Throughout this chapter, the emerged views students articulated about the nature of science are presented as themes. These themes are given numbers in tabular form only for the purpose of acting as identifiers. The reader should not assume that the
these themes are broadly arranged from the more naive to the more informed view of the nature of theories. For this question of the survey, the degree to which the independent analysis of the students’ responses to the interview matched those given on the students’ pre-survey was 79%.24

Table 3

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Number and Percentage of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A prediction or “educated guess”</td>
<td>n = 4 5%</td>
</tr>
<tr>
<td>2</td>
<td>A fact, idea, or concept expressed with reference to empirical backing or support</td>
<td>n = 32 40%</td>
</tr>
<tr>
<td>3</td>
<td>An explanation to account for some scientific phenomenon or question (w/ reference to empirical backing)</td>
<td>n = 42 52%</td>
</tr>
<tr>
<td>4</td>
<td>Could not be determined</td>
<td>n = 3 4%</td>
</tr>
</tbody>
</table>

Thirty-two students (40%) held the view that theories are the same as facts, ideas or concepts. The views largely articulated by these students put theories on par with revealed truths:

A theory is a proven25 fact that has [sic] researched to be true. Theories are created by individuals who have researched a certain topic and have created...

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24 Four of the nineteen participants (21% percent of the population studied) expressed a more informed view of a theory during the interview session. In these cases, the “codes” were readjusted to reflect this more sophisticated understanding.

25 During the follow-up interview, the collaborator asked students to clarify what they meant by the term “prove” or “proof.” Consistent with similar research (e.g.,...
data on these topics. After creating the data, experiments are done if need be and they prove their topic to be true, which is then called a theory. (F02-8, pre-survey)

A theory is a discovery that has been made and has support to back it up. A theory is something that has be proven to be true after much research and observation has been done. (F02-14, pre-survey)

Nowhere in the answers that these students gave to item #1 of the survey was an indication (either explicit or implicit) that theories serve an explanatory function.

Rather, as exhibited in the first example, these students held the view that theories are revealed truths or conclusions, and they often couched these truths by claiming that they emerge from the collection of experimental data.

The majority of the respondents (n = 42, 52%) indicated that they thought of theories as ideas or explanations offered to account for some problem or issue in science:

A theory is a person, or group of person’s explanation about why something happens, why something is the way it is, how something came about, etc. Theories are based on extensive research, but are not explanations that have been proven factual. (F02B-03, pre-survey)

A theory is a practice or suggestion used to explain situations in science. These situations cannot be proven or disproven [sic] completely but stand because the information on them is valid for the time being. (W03-04, pre-survey)

For this subgroup of students who held a more informed understanding of theories as explanations (theme 3 from Table 3), there were several views concerning how they perceived theories to be created. These are summarized in Table 4.

Lederman & Abd-El-Khalick, 2000), students frequently use these terms to refer to evidence or data rather than the implied “absolute” meaning.
Table 4
Subgroup Views of How Theories are Created

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Number and Percentage of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Theories are developed following the collection of empirical data</td>
<td>n = 21, 50% (of subgroup)</td>
</tr>
<tr>
<td>2</td>
<td>Theories are developed or emerge as a part of an explicit “scientific method.”</td>
<td>n = 11, 26%</td>
</tr>
<tr>
<td>3</td>
<td>Theories are developed from data derived from experiments and/or other methods (e.g., observation)</td>
<td>n = 2, 5%</td>
</tr>
<tr>
<td>4</td>
<td>Empirical methods and creative interpretation</td>
<td>n = 2, 5%</td>
</tr>
<tr>
<td>5</td>
<td>Could not be determined</td>
<td>n = 4, 10%</td>
</tr>
</tbody>
</table>

The majority (n = 21, 50% of subgroup, 26% of overall) of the students who were able to articulate the explanatory role of theories also indicated the general importance of evidence derived from doing some sort of empirical method:

Theories are created from a bunch of research and tests that scientists have done over the years. All the information is then formed to create a theory. (F02-04, pre-survey)

Theories are created through research. First, someone comes up with a hypothesis, then the hypothesis is tested, sometimes over and over. After the hypothesis is proven, then it becomes the theory. (F02B-04, pre-survey)

Theories are created by developing a research question, and then [by] getting experimental data to prove your question or hypothesis. After you have concluded your research, and presented your findings, if it is widely accepted it becomes a theory. (F02B-17, pre-survey)

A theory starts out as a hypothesis and is tested and retested. Someone proposes a hypothesis, and studies and research are done to test this hypothesis. If it seems to hold true after time it may become a theory. (W03B-03, pre-survey)
The distinction is that these students either explicitly or implicitly conveyed what they perceive as a general empirical method of doing science in which theories emerge after the collection of data vis-à-vis conducting experiments or other approaches.

Another subgroup of students (n = 11, 26% of subgroup, 14% of overall) either explicitly or very implicitly articulated a view in which theories emerge from or are the product of a prescribed "scientific method":

A theory starts first as a hypothesis, which is an educated guess. Next the hypothesis needs to be proven, so experiments are conducted. When the experiments are complete the data produced [sic] in the analysis. The data can be presented in many different forms, such as graphs. From the data, a theory can be produced, either supporting the hypothesis or not. (F02B-05, pre-survey)

Theories are developed from a basic scientific question in which the answer is tested several times through experiments and tests. It is based and developed on this scientific practicum. (W03B-09, pre-survey)

I guess you could have a theory like a hypothesis could be kind of like a theory to why something happens, and then in order, it's kind of like a process scientists go through. You come up with a theory, and then you test it, or a hypothesis, so your hypothesis could kind of be your theory of why something happens, and then you could test it. [W03-12, pre-interview]

Two students (5% of subgroup, 2% of overall) were able to articulate that theories could be formulated from distinct approaches (e.g., controlled experimentation vs. observational inquiry) that serve as legitimate means for collecting empirical data:

Theories are created in many ways. You could have a theory about something without doing experimentation to gather evidence, it could just be an observation. Or theories could involve a lot of research by the individual(s)
creating the theory that provides data and evidence to support the theory. (F02-21, pre-survey)

You can observe anything and formulate ideas from it or explanations. Experiments could also help theories develop, and interactions with others, with other information could help theories develop. [Note the student subsequently articulates a correct definition of an experiment in contrast to an observation when pressed by the interviewer], [W03-17, pre-interview]

Two students within the subgroup (5%, 2% of total) held what seemed to be the most informed understanding of the creation of scientific theories:

A theory is an explanation someone has on how something works. Theories are created from experiments done after you have made a hypothesis. They are also created from a person’s ideas and thoughts on the subject. (F02B-08, pre-survey)

Caution must be taken not to overestimate the nature of these latter students’ views, however, there is evidence in their answers that they understand the role that subjectivity plays in the development of a scientific theory in addition to understanding how evidence comes into play.

It should be emphasized that no student articulated a very informed view of scientific theories in the manner defined by researchers in science education (e.g., Abd-El-Khalick, 1998) or the philosophy of science (Suppe, 1977). That is, there was no evidence given from the surveys or follow-up interviews about such characteristics as internal consistency, predictive functions, ability to open new research programs, etc. These characteristics are central to understanding what makes robust or “core” theories particularly distinct from more provisional ones and certainly more distinct from the naïve vernacular use of the term.
With regard to the overall group, there is evidence that many students held the
general misconception that theories are fixed and unchanging entities or that science
involves a search for absolute truths. That is to say, some of the students held the
view that theories are “proven” rather than understanding that theories are tentative or
subject to change. This particular aspect of the nature of science is addressed in the
second question of the survey, and student views on this issue are explicated in the
subsequent section. Still, it is important not to overlook that a significant percentage
(48%) of students revealed in their answers to this initial question their views on the
tentative nature of science when they articulated their views on the creation and
nature of scientific theories:

In order for it to be a theory, it would have to be proven every time, unless
there was an error in which it wouldn’t be proven. It would have to work
every single time. (F02-11, pre-interview)

Well, because usually a hypothesis is something you just, well, I guess the
way I have always thought of it as, is something you would come up with that
you’d want to prove and then when you prove it, it would become a theory.
Then, as soon as you say that it cannot be proven wrong, then it can became a
law. (F02B-04, pre-interview)

A theory is something that a scientists thinks and develops to explain a
phenomenon in science or in our world. A theory has been tested but has not
been called a law, which means it has been proven every time. (W03-12, pre-
survey)

A theory is something that is tested and worked on until proven. (W03B-15,
pre-survey)

The first quote illustrates an absolute view of scientific theories in which the student
believes them to be either wholly-accepted or wholly-abandoned. In the second quote,
the student also conceives that theories are absolute entities, however, the conception
is slightly more subtle. This student holds a hierarchical view in which theories eventually become laws when enough supported evidence is collected to “prove” the theory without contrary circumstances. The third example illustrates yet another subtlety. Here the student implies the hierarchy between theories and laws however also conveys that theories are tentative while laws are absolute (this student explicitly indicated that theories are tentative in the subsequent question of the survey). Table 5 summarizes the explicit or implied view students held about the tentative nature of science by virtue of their answers to the first question on the survey.

Table 5

<table>
<thead>
<tr>
<th>Inferred View of the Tentative NOS</th>
<th>Pre-view number/percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theories are “proven” or “fixed”</td>
<td>n = 18</td>
</tr>
<tr>
<td></td>
<td>22%</td>
</tr>
<tr>
<td>Theories are not “proven” or cannot be “proven”</td>
<td>n = 21</td>
</tr>
<tr>
<td>No answer on inference</td>
<td>n = 42</td>
</tr>
<tr>
<td></td>
<td>52%</td>
</tr>
</tbody>
</table>

Finally, at the end of this first question of the survey, students were asked to give an example of a theory. A significant percentage of respondents (n = 16, 20%) left this section of the survey blank. Thirty-eight students (47%) give invalid examples of a scientific theory:

Pathagoreum’s [Theorum] Theory. (F02-06, pre-survey)

By participating and being involved in this class, I am more likely to do better when I am assessed. (F02B-25, pre-survey)
The moon revolves around the earth is a theory. (W03-22, pre-survey)

Invalid examples were wide-ranging. Students often failed to recognize the difference between a hypothesis in science and a theory. Students also cited well-known “problems” in science as examples of a scientific theory (e.g., the “theory” that the world is flat). Several students also cited well-known scientific theories (e.g., the theory of evolution), but it was clear from their responses that they were not familiar why they were theories:

[The theory of evolution] lets me explain why people have several wisdom teeth, while others have, you know, a few. I have heard that the people who have two or three are more evolved then the other ones that might have four. (F02-22, pre-interview)

Twenty-seven students (33%) gave valid examples of a scientific theory, ranging from more robust to more provisional examples:

The theory of plate tectonics suggests that the earth is made up of plates that were once all joined. (W03B-11, pre-survey)

We create theories often in BIOS 180 [another science class]. We do an experiment and then come up with an explanation to show why what happened did. We then do more experiments to either strengthen or disprove the theory. We make a claim (theory) and then support that with evidence. (F02-21, pre-survey)

Finally, it should be noted that students’ responses during the interview sessions revealed that many hold a conception of the creation and development of scientific theories in light of what they believe to be the universal scientific method followed by all scientists:

You actually have to do the experiment or conduct it in order to prove that it would be a theory, to prove that it was right. That is how they are created through that way. It’s just like a process. (F02-11, pre-interview)
The hypothesis is like your if/then research question... your theory is just basically how you would prove that to be true, or not really completely true, but like your model... Theories are first created by observations, then by developing a research question, and then getting experimental data to prove your question or hypothesis. After you have concluded your research and presented your findings, if it is widely accepted then it becomes a theory. (F02B-17, pre-interview)

This notion of a “process” or “method” that scientists employ to develop scientific knowledge may underlie many of their more naïve beliefs about scientific theories. That is, a number of the students held the belief that theories merely “emerge” from the collection of data after a scientist conducts “experiments.” This rather narrow inductivist view may have its roots in the more general belief that scientists indeed do follow a prescribed scientific method.

The Tentative Nature of Science

The second question on the survey asked students to comment whether or not they believe that once constructed, scientific theories are subject to change (modification):

After scientists have developed a theory (e.g., atomic theory. theory of evolution), does the theory ever change? If you believe that scientific theories do not change, explain why theories do not change and defend your answer with examples. If you believe that scientific theories do change, explain why (and how) you think theories change and give an example from your experience or learning in which a theory has changed.

The purpose of this question was to elucidate students’ views on the tentative nature of science. This aspect of the nature of science emphasizes that students understand that scientific knowledge (in part in the form of theories) should not be considered as
absolute or proven knowledge but rather as knowledge which is potentially subject to change (Abd-El-Khalick & BouJaoude, 1997; McComas, 1996).

Broadly construed, science is an empirical discipline, which is to say that the acquisition and development of scientific knowledge involves scientists collecting and interpreting data (vis-à-vis experimentation, observation, inference, etc.). A common misconception of science that is often associated with the philosophical tenets of inductivism is that the systematic collection of scientific observations leads naturally and progressively to the development of fixed generalizations. The problem with inductive conclusions, as pointed out by the philosopher David Hume (Hume, [1768] 1999) is that it is impossible to account for every single observation that would confirm the generalization, which is to say that the next piece of data one collects may possibly refute the general claim. As such, though claims scientists make to explain the natural world may be based upon inductive methods, it is important to recognize that these claims are always subject to potential refutation and are therefore tentative.

It is also important to recognize that theories do exhibit a hierarchical relationship. Some theories in science are considered more robust or “core” than others because they have withstood the “test of time” by “surviving” numerous attempts at being refuted. Still, it is important to understand that despite their

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26 As argued by the post-positivist philosophers of science (e.g., Kuhn, 1962, 1970), theoretical commitment often precedes or influences a scientist’s observational framework.

27 There are many reasons why certain theories should be considered more robust than others, and a long history of withstanding attempts to refute the theory is one of them.
privileged status of being robust or “core” (Lakatos, 1970) even these theories are subject to potential change should new evidence or insight with existing data cast doubt on the extant theory.

Answers to the surveys and interviews in this research revealed four general themes that students ascribed to the tentative nature of science (Table 6). As listed in the table, these themes are arranged from the more naïve view to the more informed view students associated with the tentative nature of science. For this question, the degree to which students’ responses given during their follow-up interviews matched the responses they articulated in their pre-surveys was 89%.

A relatively small number of students (n = 10, 12%) held the view that scientific theories are fixed entities. The general view espoused by students under this category is that once created, scientific theories then become permanent fixtures in scientific knowledge:

I do not think theories change. I think they are proven or disproven [sic] because if they are changed they are essentially a different theory. If someone disproved the theory of evolution, they would not just “change” the theory, new theories would be created. (F02B-23, pre-survey)

I don’t believe theories change. A theory is something researched and proven to be. In order to become a theory you must evaluate every situation around the area. You can’t have a theory if you haven’t done all the research. Therefore, if it is a theory it will never change. The theory of evolution is an example. No one can prove it wrong. (F02-08, pre-survey)

Others include, for example, the ability of the theory to connect multiple domains or problems, to explain larger sets of empirical problems (or data), to avoid fundamental conceptual problems, etc., (Duschl, 1992).
Table 6

Students' Pre-Instruction Themes of the Tentative Nature of Science

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Number and Percentage of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Theories do not change. Once created, they are absolute or fixed entities.</td>
<td>n = 10 12%</td>
</tr>
<tr>
<td>2</td>
<td>Theories can change with the discovery of new data.</td>
<td>n = 40 49%</td>
</tr>
<tr>
<td>3</td>
<td>Theories can change. They change by virtue of advances in technology that lead to new data.</td>
<td>n = 22 27%</td>
</tr>
<tr>
<td>4</td>
<td>Theories can change by virtue of new insights that scientists achieve with existing data.</td>
<td>n = 3 4%</td>
</tr>
<tr>
<td>5</td>
<td>Theories can change when there are either (or both) changes in technology (new evidence) or new insights achieved by scientists with existing data.</td>
<td>n = 3 4%</td>
</tr>
<tr>
<td>6</td>
<td>Theories can change, but the student gives no support.</td>
<td>n = 2 2%</td>
</tr>
<tr>
<td>7</td>
<td>No answer (or inarticulate)</td>
<td>n = 1 3%</td>
</tr>
</tbody>
</table>

The theory of evolution is fixed. We are always evolving and reproducing – so how could this theory change? (W03B-23, pre-survey)

The status of theory as revealed by the second student's answer is that such a designation can only occur after exhaustive and overwhelming evidence has been collected to provide seemingly irrefutable support. Moreover, the answer also reveals the common misconception held by many students that theories emerge primarily from the collection of data.

A majority of students (n = 70, 86%) held the view that theories are subject to change. However, a large portion of this population (n = 40, 49% of overall) merely
articulated that the reason that theories change is because new evidence (data or "proof") becomes available which then allows scientists to modify the existing theory. A second subgroup of students (n = 22, 27% of overall) held the view changes in technology (new advances) are largely responsible for creating or revealing new discoveries or data:

Theories change because as time goes on, technology improves and scientists may discover things that can change some factors of their theories. (F02-02, pre-survey)

I think they [theories] can. Over time it would change being that the society of the world keeps changing. Things are going to change, so a theory that might once be logical now might not be so logical like say in the future. I would say that through technology and things like that we keep advancing our society. (F0211, pre-interview)

Theories may change as new studies and evidence are produced. As technology and knowledge increases, scientists may find new ways to explain things. These would change their theory. (W03-21, pre-survey)

A minority of students (n = 6, 8%) held the more informed view that theories do change by virtue of new insights scientists have with existing data (with or without changes or advances in technology to bring about new data sources – themes 4 & 5 from Table 6):

I think theories change because new evidence can be found and linked to the theory. Also, another scientist might come up with an idea that no one else has thought of before. Another reason theories can change is new technology that allows research to be done more efficiently. (F02B-24, pre-survey)

Everyone believes different things. Our background lends to our will to accept ideas or to not accept them. If a person wants to challenge a theory, they will look for reasons and proof of why they are wrong or why they are right. Theories can evolve. (F02B-21, pre-survey)
I believe that a theory can change with new technology and research techniques. It also may change as the times change and scientist’s attitudes or beliefs change with them. (W03B-11, pre-survey)

Maybe if they [scientists] were looking at somebody else’s experiments or information that they see an error or maybe they don’t understand how a certain parts works, so they want to rework the experiment. Or maybe just from their own culture or religious background they don’t believe it to have happened the way it is explained. (W03-04, pre-interview)

Students were also asked to provide an example to support their belief that theories either do or do not change. The purpose of this question was not necessarily to discern whether or not students could use an example appropriately to support their view. Rather, the purpose was to learn if students were able to correctly identify a theory in science and to identify possible origins of students’ views about this aspect of the nature of science. This latter emphasis later becomes important to link if students’ changed views on this aspect of the nature of science were attributable to something they experienced in the sickle-cell unit.

Twenty students (25%) used an appropriate or valid example (or examples) of a scientific theory to support their expressed view:

A theory that has changed would be the theory that maggots just appeared on meat [spontaneous generation]. It was disproved when the covered meat didn’t get any flies on it. (F02B-02, pre-survey)

In my class we watched a video that explained many different theories of the origin of life. Those theories had changed over the years because they were finding out more new facts about it. It went all the way from “The Big Bang” theory to the theory that life was created in the oceans. Theories can always be changed and revised based on new knowledge. (F02B-15, pre-survey)

When we thought the earth was the center of the universe and the sun revolved around it. Now we know that the earth revolves around the sun, therefore the theory has changed. (W03B-01, pre-survey)
The greater majority of students either provided no example at all (n = 19, 23%) or gave what would be considered an invalid example of a theory (n = 41, 51%):

- If you throw a ball in the air, it will return to the earth. (F02B-13, pre-survey)
- A long, long time ago people thought the world was flat, until someone sailed around the world to discover it to be round. (F02-02, pre-survey)
- The theory of “what comes up must come down” – if someone was able to prove that something that always goes up doesn’t every come down then the theory is not a theory. (W03-15, pre-survey)

Finally, it is important to note that students’ views of the tentative nature of science (theories) were not necessarily consistent between the first and second questions of the survey. Fourteen students (17% of overall) exhibited what should be characterized as mixed views of the tentative nature of science. These students gave evidence in question one of the survey that theories are fixed and proven entities yet claimed in the second question that theories are subject to change. Furthermore, a large number of students articulated in the answers that they gave to the second question that theories are tentative (86% of the overall), only to follow up with a claim in their answer that “laws” are the major fixed or absolute entity in science. The specific distinction between theories and laws is examined in the next question.

### Scientific Theories versus Laws

The third question on the survey asked students to comment whether or not they believe there to be a distinction between scientific theories and scientific laws:

Is there a difference between a scientific theory and a scientific law? Illustrate your answer with an example.
The question also asked students to provide an example for each. Broadly stated by science educators, theories are constructed explanations that account for entities or problems in science. In contrast, laws are descriptions that account for patterns in science (Rhodes & Schaible, 1989).

Students often incorrectly hold theories and laws in a hierarchical and developmental framework (Duschl, 1990). The former means that students believe laws to be superior to or more important (or robust) than theories. They also often believe that theories evolve into laws should enough evidence be gathered to sufficiently “prove” the theory.

This latter point reveals another view that is often held by students. They frequently believe that laws are fixed or absolute (proven entities). This is true even for those students who believe that theories are subject to change (Abd-El-Khalick & Lederman, 2000). That is to say, students may recognize that theories are tentative, but they fail to understand that scientific laws are also tentative.

As is the case with understanding how theories are developed (and potentially change), scientific laws are based largely on empirical findings. As such, there is a possibility, however remote, that a future observation will be collected or a future insight made with existing data that refutes the law. What this means is that like theories, scientific laws are also tentative.

Answers to the surveys and interviews in this research revealed five general themes that students ascribed to the distinction between theories and laws (Table 7). Note, for the coding of this question, several students articulated more than one theme.
Table 7
Students’ Pre-Instruction Themes of the Theory/Law Distinction

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Number and Percentage of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laws are absolute or certain. Theories are not. Laws do not change while theories do.</td>
<td>n = 60 74%</td>
</tr>
<tr>
<td>2</td>
<td>Laws are more “valid” than theories. Laws are based on “visible” evidence. Theories are often based on speculation, inference, or guesses.</td>
<td>n = 10 12%</td>
</tr>
<tr>
<td>3</td>
<td>Theories become laws when “proven” or tested over and over.</td>
<td>n = 14 17%</td>
</tr>
<tr>
<td>4</td>
<td>Both laws and theories are subject to potential change.</td>
<td>n = 2 2%</td>
</tr>
<tr>
<td>5</td>
<td>Recognize a difference but are unable to articulate.</td>
<td>n = 6 7%</td>
</tr>
<tr>
<td>6</td>
<td>No Answer</td>
<td>n = 3 4%</td>
</tr>
</tbody>
</table>

in their responses to the surveys and interviews. For this question, the degree to which students’ responses given during their follow-up interviews matched the responses they articulated in their pre-surveys was 90%.

A majority of students (n = 60, 74%) held the view that laws are somehow absolute or proven entities in science while theories are not:

A scientific law is something that is always going to work. It never changes. A scientific theory is just, there is room for a change and more improvement. There is evidence to back it, but it can still change. Boyle’s Law in chemistry…it is never going to change. It’s always going to give you the correct answer when applied to the right problem. (F02-11, pre-interview)

Yes, a theory is something that is still questioned, it is not absolutely proven, and a law is something that is known as fact. An example of a law is Newton’s law of gravity. This law shows it is a fact that there is a definite pull of gravity on the earth’s surface. This law is demonstrated clearly time and
time again and has not been proven wrong. Therefore, it is a fact that will never change. (W03-10, pre-survey)

A scientific law is something that is based on actual scientific evidence and that is true in every single instance, such as the law of gravity. A scientific theory is an “idea” of how something happens or why it occurs. It can change. (W03B-07, pre-survey)

It is what I have always learned that laws are just like more set in stone than theories would be, but that’s just how I’ve always learned like in high school in my background is that. (W03-14, pre-interview)

A subgroup (n = 8, 10% of overall) of these students indicated in their answer that in addition to believing that laws are fixed or absolute that theories indeed “become” laws when sufficient evidence is gathered:

Yes [there is a difference between a theory and a law], a theory can be changed, and a law cannot be changed. A theory becomes a law when it has been tested numerous times with results coming out the same every time. (F02-22, pre-survey)

A theory has yet to be proven. A scientific law is an answer to something that has been proven 100% with no doubt. It was first a theory but became a law when it was fully proven true. (F02-02, pre-survey)

A scientific theory is a theory that has not been proven true yet. A scientific law is a theory that has been proven true. (W03-22, pre-survey)

I think that a law has been proven definite, that it never changes, where a theory has not been proven yet. What I think is that a law is a theory that has been proven through time. (W03-8, pre-interview)

This latter aspect that theories “evolve” into or become laws when sufficient evidence is collected was expressed by a total of 14 (17% of overall) students who responded to the pre-survey.

A moderate number of students (n = 10, 12%) conveyed the belief that laws are different than theories because of the nature or quality of supportive evidence.
Their claim is that laws are more “powerful” or substantial than theories because they are based on more substantial or visible evidence, whereas theories are less substantial because they often are based on inference or speculation. This latter belief is partially driven by the misconception that theories are simply “opinions” or “guesses” in the vernacular sense of the word:

A scientific law is much more powerful than a theory. A law is something that must be followed, where a theory can be questioned or changed. (F02-18, pre-survey)

A scientific theory is an idea of belief where a scientific law has and can be proven. For example, the theory of evolution is explained differently by different people. This is due to what a person believes. Where the law of gravity is 100% true – you know it and there is no other explanation for it. (W03-06, pre-survey)

A scientific theory is a belief or possible explanation; a scientific law is the actual explanation or true meaning of something. (W03B-04, pre-survey)

Only two students were able to articulate an understanding that both theories and laws are subject to potential change. However, though the students revealed a more informed understanding that laws and theories are tentative, they were not able to articulate a substantive difference between theories and laws other than a vague reference to “concreteness”:

I think that a scientific theory would be considered less concrete than a scientific law. I think of a scientific law more like the law of gravity or some other physics law. I don’t think that there should necessarily be a difference, though. A scientific law may have held up until now, but tomorrow something could be discovered that could make the law seem less absolute. If a theory can change from new information, a law could too. (F02-21, pre-survey)

A scientific theory could be stated that it has not been fully tested yet. It could just be that it hasn’t been proven wrong yet. A scientific law has been completely tested and examined and is believed to be completely right. This doesn’t mean however, in the future that technology will get more advanced
and what was believed to be a law now could be proven wrong. (W03B-14, pre-survey)

No student was able to accurately discuss the general distinction between theories (as explanations) and laws (as descriptions).

Students were additionally asked to provide an example of a law and theory to support their position. Thirty percent (n = 24) of the total population gave incorrect or invalid examples of either a theory or a law:

I guess a scientific law could be that the body is made up of cells. There is no disputing that so it must be a law. (F02-04, pre-survey)

The scientific theory of mankind centuries ago was that the earth is flat. The scientific law has proven that the earth is in fact a revolving sphere. (F02B-03, pre-survey)

For example, there used to be a theory that the earth was flat. That changed as new discoveries were made. Now we know the shape of the earth and it can be considered a law because it has been proven to be true. (W03-21, pre-survey)

Forty percent (n = 33) of the total gave no example at all to support their position.

Thirty percent (n = 24) of the total was able to articulate an example for either a scientific law or a scientific theory (or both) in support of their particular view:

A scientific law is [the law of] gravity. A scientific example of a theory is the origin of life. (F02B-15, pre-survey)

Spontaneous generation was a theory that we now know isn’t true. The scientist believed it was then because he proved that bugs appeared on the meat and others believed him. It is a law that when something goes up, it will always come down under normal atmospheric conditions. (F02B-21, pre-survey)

Finally, for some of the students (11 out of 19) who participated in the follow-up interview, they were asked an additional probing question for this topic:
"Would you rank scientific theories and scientific laws? And if so, how would you rank them?"

Seven out of the 11 students who were asked this question in the interview chose to rank laws as superior to theories. Five of these 7 students defended this ranking by indicating that laws should be superior since they were "proven" (unchanging entities):

Scientific law has, all people accept them as fact. A scientific theory is still being created and still being made. It seems like the law has been already ranked, because if they weren't ranked, then it wouldn't be considered a scientific law. They're the basic foundations of science. (F02B-17, pre-interview)

The other two expressed the belief that theories should be considered subordinate to laws because they are based largely upon speculation or inference and as such do not deserve the status of a law:

Because there can be many different theories for one thing. There can be like we learned the other day about, autogeny and SET theories of how cells developed from way back many millions of years ago to how they became complex cells that they are today. There are two different theories, and we really can't tell like how exactly they got the way they did. (F02-17, pre-interview)

This latter emphasis underscores the misconception that students often hold in which they conceive of laws as absolute truths, with no possibility of being changed. Four of the eleven students who were asked this question during the follow-up interview claimed that they would not rank theories and laws:

I don't think I would because even though a theory is possible to change, it is what is understood now, and that is how we see things now, so it is just as important as a law, because it can lead you in certain directions to or even in different directions you could look at something and notice it's not going this way. So, I am going to look at it in a different way. Which could possibly lead
you to a law or to a different theory, so it is just as valid as a tool for understanding science. (W03-4, pre-interview)

**Development of Scientific Knowledge – The Validity of Observational Methods**

The fourth question on the survey was intended to understand students’ views on the validity of scientific knowledge derived from means other than from conducting experiments:

Scientists often conduct experiments to gather data. In general, an experiment is a controlled intervention that involves manipulating something of interest by holding certain things constant and varying others. Does the development of scientific knowledge require scientists to do experiments? If yes, explain why, and give an example to defend your position. If no, explain why, and give an example to defend your position.

On the survey, the question was introduced with a short statement that gave a definition of a scientific experiment. The reason for explicitly defining an experiment in this way was to center students’ thinking upon “experiment” in a more narrow sense than they often hold. Research (Abd-El-Khalick, 1998) indicates that a significant percentage of students conflate “experiment” with “hands-on” activities and fail to recognize a more proper conception of the word. Thus, it was important to more narrowly define an experiment in order to establish a baseline for students to interpret the central question.

Science is empirically based, which is to say that the development of scientific knowledge occurs through the use of a variety of empirical methods. Conducting an experiment is one of the ways in which scientists strive to gain scientific knowledge. In contrast, scientific knowledge can also be acquired by conducting observations. In
fact, some disciplines in science (e.g., astronomy) are based entirely upon data collected through observation (Chiappetta & Koballa, 2002). Science educators have found that students often believe that knowledge in science is developed only following manipulative experiments (Lederman, 1992). It may be that such a conception has a root in the perpetuation of students being instructed that science proceeds by way of a “scientific method.”

The total population of students for this question on the survey was 42, instead of the 81 figure used for the other survey questions. The reason for the discrepancy is that the researcher modified the survey question between the fall and winter sections of the course. Prior to the two winter sections (with N = 42), the survey question did not give a definition of a scientific experiment as a prefacing statement to the actual question. The absence of this statement revealed that students in the fall sections inappropriately held naïve views of an experiment (e.g., conflate experiment with any “hands-on” activity or conflate experiment with observation).

The survey question invited students to share whether or not they feel that the development of scientific knowledge requires experiments. Students were additionally asked to provide an example to support their position. Answers to the surveys and interviews in this research revealed four general themes that students ascribed to the means of developing knowledge in science (Table 8). For this question, the degree to which students’ responses given during their follow-up interviews matched the responses they articulated in their pre-surveys was 100%.
Table 8

Students’ Pre-Instruction Themes of the Validity of Observational Methods

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Number and Percentage of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Students incorrectly equated experiments with observations or “hands-on” activities</td>
<td>n = 14, 33%</td>
</tr>
<tr>
<td>2</td>
<td>Experiments are necessary to “prove” or “validate” scientific knowledge or to “test” theories.</td>
<td>n = 22, 52%</td>
</tr>
<tr>
<td>3</td>
<td>Experiments are not required, but experiments are “better” or “needed” to validate knowledge (this infers a hierarchy).</td>
<td>n = 3, 7%</td>
</tr>
<tr>
<td>4</td>
<td>Observational evidence is valid for acquiring knowledge in science.</td>
<td>n = 2, 5%</td>
</tr>
<tr>
<td>5</td>
<td>No reason given</td>
<td>n = 1, 2%</td>
</tr>
</tbody>
</table>

Despite the introductory definition that preceded the question on the survey, a significant number of the respondents (n = 14, 33%) incorrectly conflated conducting an experiment with making observations. This was evident in the answers they articulated on the survey:

Yes [“experiments” are necessary]. Anyone can make a statement about something and believe it to be true, but in science you need to prove why it is true. This is why experiments are essential, to see why things occur and how. Experiments allow scientists to really observe things and make conjectures about why they happen. (W03B-14 pre-survey)

Development of scientific knowledge requires scientists to do experiments. In order to prove your theory is the most accurate you would need proof to back it up. An example might include how a flower grows, you need to observe levels of soil, oxygen, water, and sunlight. (W03-09, pre-survey)

Because scientists need to accumulate data and research to back up their belief or theory. To prove the theory that the continents started all connected in Pangea, scientists went to certain continents to find similar fossils, mountain range alignments from continents and other such things to prove that they

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were together. Without this, they could have no back up information. (W03B-01, pre-survey)

That a large percentage of students broadly and incorrectly held this definition of an experiment is consistent with other researchers (e.g., Abd-El-Khalick, 1998) who have examined students’ nature of science views. Many students believe that an experiment is simply any “hands-on” activity in which data is acquired. Thus, it is not too surprising given this view of an “experiment” that students in this subgroup rather strongly indicated that “experiments” are necessary for the development of scientific knowledge. At the very least, one can infer that these students understand that science is an empirical discipline, and moreover that the development of scientific knowledge requires an evidential base.

The next largest group of students (n = 22, 52%) held the view that experiments are necessary for the development of scientific knowledge:

I believe that there is no other way for scientists to know about something for sure without conducting experiments. By experimenting [on] a hypothesis, scientists are able to come up with factual results and test them even more when the variables are changed. (W03B-04, pre-survey)

I think so. If you want to prove something you have to have evidence. The best way of doing this would be doing an experiment. For example, if we wanted to see how a drug would affect someone’s heart we would give a pill to one person and not to the other and then look at their heart and compare them. (W03-06, pre-survey)

Three students (7%) held the slightly more informed view that the development of scientific knowledge does not necessarily require experimentation. However, these students also indicated that experiments are necessary to validate scientific knowledge:
Yes, experiments are necessary because it will solidify your guesses. Although, other things are important, such as observations. (W03-21, presurvey).

I don’t think experiments are required for all scientific knowledge. However, when trying to understand how/why something happens and to know what would happen if alterations occurred, experiments have to be held to examine and completely understand the results – which in turn link back to the initial subject. (W03B-21, pre-survey)

[Science does not necessarily require] experiments because you can’t really experiment with something like the theory of evolution. Something chemical or something like, such as DNA you can experiment with, but there is [sic] some things you just are not able to experiment with. I still think you can gather data, but you just might not be able to necessarily experiment with it. I think you can have a theory without doing the experimentation, but the experimentation can validate your theory. (W03-19, pre-interview)

There is an implication in these students’ answer that other means (e.g., observation) are permissible ways of collecting data. Furthermore, the students give evidence that knowledge acquired or developed through experimentation is superior or more valid to knowledge derived from making observations.

Two students (5%) were able to articulate a fairly contemporary view:

No, it [conducting experimentation] is not required. Making observations can create scientific knowledge. For instance, when hiking in a field and woods collecting insects, I used to notice butterflies seemed to be more abundant near a plant called milkweed (I think). This observation created knowledge that butterflies enjoy this plant for food and this occurrence was pretty constant. (W03-17, pre-survey)

Caution must be taken not to incorrectly extrapolate from these students’ answers, however, there is evidence that the students understand that knowledge in science can be derived or based upon observation and inference. Anecdotally, the second example is particularly encouraging. Not only does the student recognize the validity of observational methods for collecting evidence toward making a provisional theory,
but also the student understands that in part the validity of the explanation itself is predicated on consistency of the observations.

Students were also asked to provide an example to support their view. An example could be valid whether or not the student held a relatively naïve or a relatively more informed view on the subject. In other words, it is entirely possible for a student to conceive that knowledge development requires an experiment and then illustrate this claim with a legitimate example.

For the purposes of analysis, only the subgroup of students (n = 26) who did not incorrectly conflate experiment and observation were examined with regard to the examples they provided. Only 7 students (27% of subgroup, 17% of overall) were able to give a valid example to support their view. The remainder gave no example at all (n = 19, 73%, 45% of overall.

Several of the students who responded in their survey that experiments are necessary to further scientific knowledge (or to validate scientific knowledge) were asked an additional series of probing questions during their follow-up interview:

“Let’s consider a science like astronomy or anatomy. Can we (or do we) do manipulative experiments in astronomy or anatomy? If yes: Please explain and provide an example? If no: But we still consider astronomy or anatomy as science. What are your ideas about that?”

The purpose of these questions was to see if students recognized that certain sciences by their very nature do not avail themselves to manipulation in the sense of experimentation. When asked these questions, the majority of students fell back to a position in which they conflated an experiment with an observation:
Well, I don’t know [very] much about astronomy, but in anatomy you can [do experiments]. You can look at a corpse and learn how the body is set up. You are more or less experimenting with the idea of what it is. (F02-11, pre-interview)

Well, in astronomy you could use telescopes or angles of the light from the stars or planets, and you could use those to put on paper...you could see where the light goes over time and how it changes. (W03-4, pre-interview)

Or, the students adopted the position in which they believed that it was possible to recreate or simulate conditions from astronomy such that scientists could do manipulative experiments:

No, I think that [astronomy] is definitely a science. I think that we have seen where we can recreate in laboratories and experimental buildings some of the same things that are happening. So maybe not going out and [manipulating/controlling] but to recreate the same conditions. (F02-11, pre-interview)

They [scientists] don’t actually go up and grab a star and study it, but as far as maybe studying the gases that are present in astronomy, I would think they could manipulate and control those. (W03B-4, pre-interview)

Students were not able to recognize that data derived solely from observational inquiry could serve as legitimate sources of scientific knowledge. Students held to the belief that some form of experimentation is necessary to “prove” or validate any evidential findings.

The Subjective Nature of Science

The fifth question on the survey was designed to capture students’ understanding of the subjective nature of science:

It is believed that about 65 million years ago the dinosaurs became extinct. Of the reasons formulated by scientists to explain the extinction, two enjoy wide support. The first, formulated by one group of scientists, suggests that a huge
meteorite hit the earth 65 million years ago and led to a series of events that
causedithe extinction. The second explanation, formulated by another group of
scientists, suggests that massive and violent volcanic eruption were
responsible for the extinction. How are these different conclusions possible if
all of these scientists have access to and use the same set of data to derive
their conclusions? Defend your answer.

The question briefly provided students with a description of a rather well known
scientific problem - the challenge of explaining how dinosaurs became extinct.
Students read how different explanations have been developed by scientists to
account for the problem, and they were asked to discuss how such differing
explanations are possible given that all of the scientists are working with (or have
access to) the exact same data.

That science is subjective means that scientists “see” or interpret data from the
perspective of their own experiences and learned understanding. The philosopher of
science, Thomas Kuhn (1962, 1970), points out that observations in science are not
independent from theoretical perspectives or commitments, which is to say that
scientists cannot by virtue of their own experiences be totally objective in analyzing
or interpreting data. Rather, scientists are influenced by such factors as their
philosophical background, their social and political experiences, their personal drives,
and so on (Abd-El-Khalick, 1998). Moreover, a scientist must often rely upon
creativity and imagination in concert with his or her personal commitments in order
to interpret data.

In contrast, a common misconception held by students is that scientists are
very objective in their work (McComas, 1996). This is particularly the case for the
interpretation of data. Students often fail to see how personal commitments or
paradigms influence this aspect of science and rather believe that such influences undermine or are against how they perceive science should operate.

The survey question invited students to interpret how such seemingly disparate explanations are possible given that the scientists had access to the same data. Students were additionally asked to provide an example based on their experiences in science in which a similar scenario occurred. Answers to the surveys and interviews in this research revealed five general themes that students ascribed to the subjective nature of science (Table 9). Note, for the coding of this question, several students articulated more than one theme in their responses to the surveys and interviews. For this question, the degree to which students' responses given during their follow-up interviews matched the responses they articulated in their pre-surveys was 95%.

Two general categories of answers emerged from the analysis of students' responses. This finding is consistent with similar research done by Abd-El-Khalick (1998) in his analysis of undergraduate students' responses to the same question. The first category is that students attributed the controversy to a lack or scarcity of available evidence. Within this category were three themes.

Sixteen students (20% of total) held the first theme that scientists cannot go back and “see” what happened in the past:

No one knows exactly what happened to make the dinosaurs extinct. They are looking at the same data but through trial and error they come up with their own explanations. (F02-14, pre-survey)
Table 9

Students’ Pre-Instruction Themes of the Subjective Nature of Science

<table>
<thead>
<tr>
<th>Category</th>
<th>Theme</th>
<th>Description</th>
<th>Number and Percentage of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students believe there must be a scarcity of available data.</td>
<td>1</td>
<td>Scientists cannot go back and “see” what happened in the past. Students do not consider inference as valid so scientists have to guess.</td>
<td>n = 16 20%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Not enough conclusive evidence to “prove” one or the other theories. No recognition of other factors that may play a role.</td>
<td>n = 21 26%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Scientists are forced to use creativity to “fill in the gaps” rather than realize that creativity and imagination are central to a scientist’s work.</td>
<td>n = 5 6%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Scientists interpret data differently (but no explanation why).</td>
<td>n = 40 49%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Scientists interpret data from the perspective of their own subjective frameworks that are a product of their background and experiences.</td>
<td>n = 4 5%</td>
</tr>
<tr>
<td>The controversy is attributed to factors other than or in addition to the lack of evidence or data.</td>
<td>Inarticulate answer</td>
<td>n = 14 17%</td>
<td></td>
</tr>
<tr>
<td>No answer</td>
<td></td>
<td>n = 0</td>
<td></td>
</tr>
</tbody>
</table>

I believe that there is no way that we could find out what really happened. All we have are theories. (F02-22, pre-survey)

Neither [of the] scientists knows what it was exactly like at this point in time, and neither know exactly what the environment was like or the environmental conditions. (F02-02, pre-survey)
They [scientists] may have found evidence that is millions of years old. This evidence is not necessarily reliable because of its age. Since the evidence may not be reliable, scientists could see the data differently. (W03-19, pre-survey)

Because we weren’t around then to see. We have no recorded data, just fossils. (W03-03, pre-survey)

On a fundamental level, these students lack an understanding of the role or validity that inference plays in the development of scientific explanations. This belief is likely correlated with the assertion that scientific theories are either “guesses” with no reference to the need for evidence (expressed by F02-22 in question 1 of the pre-survey) or are absolute and proven entities (expressed by F02-14) and as such require “testing” to substantiate the validity of the theory.

Twenty-one students (26%) held the second theme in this category that there is not enough conclusive evidence to “prove” one or the other of the theories. Students fail to recognize the underdetermination of scientific theories by evidence, i.e., theories make claims about the world that go beyond evidence available to support them. For these students, they fail to recognize that other factors then the data itself (e.g., creativity, social background, personal commitments, etc.) play important roles in the development of scientific theories:

These different conclusions are possible because there is no information currently available that proves one or the other without a doubt or disproves one. As the data exists right now it can be used to come to both conclusions. (F02-21, pre-survey)

Because there could be enough evidence to support either one of these theories but not enough evidence to discount one of them. (F02-04, pre-survey)
Well, you don't have all of the evidence. Things like this happen and one conclusion is not better than the other unless you have the evidence to disprove one or both. (W03-20, pre-survey)

Five students (6%) expressed the belief that creativity is a part of science. However, they conveyed the idea that such creativity is a necessary “evil” so that scientists can “fill in the gaps” because of insufficiency with the existing data set:

These two conclusions are possible because there are missing pieces to the puzzle and scientists have filled them in with ideas (different ideas). Therefore they have received [reached] different conclusions. (F02-03, pre-survey)

The data does not tell how dinosaurs became extinct, so scientists come up with their own beliefs on what exactly caused the extinction of the dinosaurs. (F02B-22, pre-survey)

Because there are pieces of the puzzle missing! It happened so long ago that a lot of the evidence is missing. Based on what data they do have, it still does not give sure answers, so scientists have to fill in the blanks. That may be why there is two different conclusions, probably more! (W03B-16, pre-survey)

In the second category that emerged from the analysis of data, students articulated a more informed view of the subjective nature of science. They did this by indicating in some fashion that factors other then the scarcity of available data could be responsible for scientists adopting differing theories to account for the extinction of the dinosaurs. Within this general category, two themes were reflected in students’ answers.

The first theme was articulated by 49% (n = 40) of the population of students. Here students expressed a general claim that other factors were possibly responsible for scientists interpreting data differently. However, students did not elaborate further to offer an explanation why this is so:
The data can be manipulated and experimented within two or more completely different ways. In [our class] the idea of the black tube; everyone saw what it looked like and listed its characteristics, but not every group came up with the same mode of how it was created on the inside. (F02-11, pre-survey)

This is possible because each scientist has their own way of looking at the data to develop a theory. (F02B-17, pre-survey)

Individuals are unique in mind, opinions, etc. The scientists have the data in front of them, yes. However, everyone has unique opinions, ways of thinking, different ways of looking at a set of data. Different conclusions, then, can be construed. (W03B-10, pre-survey)

These different conclusions are possible because people interpret data differently. The one group of scientists looked at the data and simply went in a different direction with it than the other group. The data supports both of their theories, but the opinions of the two groups differ. (W03-10, pre-survey)

Five percent (n = 4) of the population held a rather informed view of the subjective nature of science. Here, the students articulated that factors other than the scarcity of data were responsible for scientists adopting differing views. Moreover, the students were able to provide an explanation to account why this is so:

Not every person is going to think the same way. Each person brings their own background knowledge and beliefs which is why two different theories emerged. (F02-13, pre-survey)

Scientists use their own interpretations and opinions to formulate theories. Although they have similar data, they may have different beliefs as to what caused information in their set of data. (F02B-03, pre-survey)

They [scientists] use data to support their personal theory. Also, the data does not necessarily explain itself, so the scientist may perceive the data differently, depending on their beliefs. (F02B-05, pre-survey)

Well, everybody is their own person. Scientists disagree all the time on things, and they do have their beliefs. They have their beliefs that they like to go after, and other scientists have their beliefs they like to go after... let's say one scientist knows a lot about the subject they are going after, and another scientist knows a lot more on that subject. Maybe the one with less knowledge
will think, well, there is no way that this could be true, because they start thinking and putting things together, but the other scientist with all the knowledge would say, well, yes this does make sense. (F02-24, pre-interview)

It is possible for scientists to see things differently due to prior knowledge and understanding. Scientists take the information given to them and create explanations. These explanations encompass more than the information given to them. It includes the way they view the world and their understanding of science. (W03-04, pre-survey)

Students were additionally asked to provide an example from their own experience with science to substantiate their view expressed to the dinosaur question. Thirty-seven percent (n = 30) students provided a valid example. The majority of these cited the differing theories to account for the origin of life. Others cited the differing views under evolutionary theory to account for the relationship between extant and ancestral organisms.

Twenty-two percent (n = 18) of the population provided invalid examples to support their position. Such examples ranged from an inappropriate comparison of evolution vs. creationism to account for species change to simply citing conflicting pieces of evidence (e.g., that some people are dark skinned while others are light skinned as fueling a controversy in genetics). Forty-one percent (n = 33) of the population gave no example or provided an unintelligible response.

Finally, several of the students (14 out of 19) that participated in the follow-up interview were asked a series of probing questions designed to better elucidate their views on the subjective nature of science. Of the probes used, one of them was noteworthy in terms of the unified nature of students' responses:

"Which comes first, theory or observation?"
Thirteen of the students who answered this probe indicated that observation precedes theory. This is true even for those students who articulated in their survey/interview responses a more informed view of the subjective nature of science. Despite claiming in some fashion that scientists’ backgrounds influence how they interpret data, the students adopted a position that had observation come before the development of theory:

I think that observations are generally made first so that a theory can be developed. (F02B-03, pre-interview)

I would say observation, because if I am observing something, and I start asking questions to myself why does this happen, then I have to formulate what I know, and it becomes a theory at that point...without observing something, it's not going to set your mind into a thought pattern of what is going on here and what it is that you are looking for. (F02B-10, pre-interview)

First you come up with an idea, which would be a hypothesis. Hypothesis would come first. That what you think will happen is the question you have in mind, and you are going to observe and do experiments to test that hypothesis to either prove or disprove that the hypothesis is correct, and from those observations and from your original hypothesis then you can form a theory. I would say that observations come first. (W03-12, pre-interview)

Aside from the one student (who also articulated a view that subjective factors play a role in how the scientists perceive or interpret data), there was no indication from the answers provided to this probe that students understood that theoretical commitments potentially impact how or what a scientist “observes” in his or her data.

Participants’ Post-Instruction Views of the Nature of Science

At the end of the sickle-cell anemia unit, the students were asked to complete the open-ended survey again. In addition, 16% (n = 13) of the respondents to the post-
survey were randomly selected to participate in a semi-structured follow-up interview. The purpose of the interview was to ensure the validity of the completed survey and to allow the interviewer an opportunity to further probe students' responses given in the survey. In this way, the interview served as an additional data source to elaborate on any idiosyncrasies held by the students.

It is important to note that a different group of randomly selected students was chosen for the post-interview than was selected for the pre-interview. The reason that a different group was chosen was to minimize a potential "testing effect" in which it could be argued that merely by participating in the pre-interview an additional "intervention" occurred. Thus, it was important to use a different group of respondents for the post-interview so that their answers could not have been affected by a prior interview session.

In addition to asking respondents about their answers given on the post-survey, the interviewer had the students examine their answers that they gave to the pre-survey. When it was clear that a student's view had changed from the answers they provided on the pre-survey versus the post-survey, the interviewer pressed students to articulate why their view had changed.

With regard to the analysis of the post-instruction data, the emergent themes that students articulated for each question in the post-survey and post-interview were similar in nature to those that they gave on the pre-survey and pre-interview. Because this was the case, the summary of students' post-instruction views is presented in this section largely in tabular form. More detail is however provided about the examples
that students articulated, given that many of the students situated their understanding with reference to the sickle-cell unit.

In this regard, the examples that students provided to support their views are categorized according to one of four themes. As with the pre-survey responses, several students articulated either a valid (general) or invalid example to support their view. In the post-survey, two additional themes emerged. The first includes those instances in which a student referred to something that he or she did during the course of the sickle-cell unit, however, the example that the student provided was too vague or nonsensical. The second accounts for those students who were able to support their view of the nature of science with a more specific and valid example taken from some aspect of their work in the sickle-cell unit.

It is important to stress that a vague or passing reference to the sickle-cell unit (e.g., "in the sickle cell class we talked about theories") is not considered as evidence of meaningful reflection to establish the efficacy of the sickle-cell unit toward changing or enriching students’ views. Only when a student provided a valid example using some aspect or episode from the sickle-cell unit to substantiate their claim given on the survey is a meaningful link considered to have been made. This issue becomes particularly important when examining the effect of the sickle-cell unit on individual student’s views of the nature of science. This is discussed in the subsequent section.
Post-Instruction Views of the Nature of Scientific Theory

Students' pre- and post-instruction views of the nature of scientific theories as characterized by the pre/post-survey and pre/post-interview data are contained in Tables 10, 11, 12, and 13. The themes expressed in Table 10 are broadly arranged from the relatively more naïve to the relatively more informed view of the nature of scientific theories.

The most notable shift in students' beliefs occurred within the subgroup of students who articulated the more informed view of theories as explanatory elements in science (Table 11). Here, students greater characterized a theory as an explanation supported by data derived by either (or both) experimental and/or observational approaches. The significance of this is that students seemed to appreciate the role that data collected by making observations plays in the development of scientific knowledge (in the form of theories). Also noteworthy is the reduction in the number

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Pre-view</th>
<th>Post-view</th>
<th>Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A prediction or “educated guess”</td>
<td>n = 4 5%</td>
<td>n = 1 1%</td>
<td>-3</td>
</tr>
<tr>
<td>2</td>
<td>A fact, idea, or concept expressed with reference to empirical backing or support</td>
<td>n = 32 40%</td>
<td>n = 23 28%</td>
<td>-8</td>
</tr>
<tr>
<td>3</td>
<td>An explanation to account for some scientific phenomenon or question (w/ reference to empirical backing)</td>
<td>n = 42 50%</td>
<td>n = 57 70%</td>
<td>+15</td>
</tr>
<tr>
<td>4</td>
<td>Could not be determined</td>
<td>n = 3 4%</td>
<td>n = 0 0%</td>
<td>-3</td>
</tr>
</tbody>
</table>
Table 11
Changes in Subgroup Views of Creation of Theories

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Pre-view N = 42</th>
<th>Post-view N = 57</th>
<th>Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Theories are developed following the collection of empirical data</td>
<td>n = 21</td>
<td>n = 24</td>
<td>+5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50% (of subgroup)</td>
<td>42% (of subgroup)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Theories are developed or emerge as a part of an explicit “scientific method.”</td>
<td>n = 11</td>
<td>n = 0</td>
<td>-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Theories are developed from data derived from experiments and/or other methods (e.g., observation)</td>
<td>n = 2</td>
<td>n = 27</td>
<td>+25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%</td>
<td>47%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Empirical methods and creative interpretation</td>
<td>n = 2</td>
<td>n = 3</td>
<td>+1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Could not be determined</td>
<td>n = 4</td>
<td>n = 3</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10%</td>
<td>5%</td>
<td></td>
</tr>
</tbody>
</table>

of students who articulated that they believe scientists follow a prescribed “scientific method.”

It should be emphasized that though there was movement in student views toward a more informed understanding, in truth no student was able to articulate a very informed conception of a theory as described earlier in this chapter. The results from Table 11 are encouraging, however, because they suggest that students are articulating a more refined conception of a theory, even if the grains of movement are relatively fine.

Furthermore, as evident in Table 12, there were fewer students who characterized theories (either explicitly or with a substantial inference) as “proven” or “absolute” entities in science. Caution must be taken here not to infer too much from
Table 12

Claimed or Inferred Pre- and Post-views of the Tentative Nature of Science

<table>
<thead>
<tr>
<th>Inferred View of the Tentative NOS</th>
<th>Pre-view number/ percentage</th>
<th>Post-view number/ percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theories are “proven” or “fixed”</td>
<td>n = 18 22%</td>
<td>n = 6 7%</td>
</tr>
<tr>
<td>Theories are not “proven” or cannot be “proven”</td>
<td>n = 21 26%</td>
<td>n = 18 22%</td>
</tr>
<tr>
<td>No answer on inference</td>
<td>n = 42 52%</td>
<td>n = 57 57%</td>
</tr>
</tbody>
</table>

this result as there was an increase in the number of “no answer or inference” in this regard. This means that it is quite possible that those students who held the view that theories are “proven” or “absolute” from the pre-instruction instruments may indeed have retained that view following the sickle-cell unit, although they simply did not give enough evidence in the post-instruments to indicate so.

Table 13 indicates that a relatively large number of students (n = 18, 22%) were able in their post-instruction view to cite an appropriate example from the sickle-cell unit to support their view of the meaning of a scientific theory:

After the third unit [sickle cell] I realized that theories aren’t always proven like we came up with many theories and then the next class we proved them wrong, and so I guess I came in with the expectation that theories could prove everything no matter what and so after that unit I realized that wasn’t the case…one of the first classes we said that the allele for the mystery disease was dominant and by the next class we realized it wasn’t dominant, it was recessive. (F02-14, post-interview)

When looking at the mystery patient and studying Dr. Allison’s data. Actually seeing what he had shown through observing children and testing tribesmen. (F02-08, post-survey)
Table 13

Changes in Students' Examples to Support a Scientific Theory

<table>
<thead>
<tr>
<th>Example Cited</th>
<th>Pre-view percentage</th>
<th>Post-view percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invalid</td>
<td>47% n = 38</td>
<td>6% n = 5</td>
</tr>
<tr>
<td>Valid (unrelated to sickle cell case)</td>
<td>33% n = 27</td>
<td>51% n = 41</td>
</tr>
<tr>
<td>Vague sickle cell reference</td>
<td>0% n = 13</td>
<td>16% n = 13</td>
</tr>
<tr>
<td>Valid sickle cell example</td>
<td>0% n = 18</td>
<td>22% n = 18</td>
</tr>
<tr>
<td>None given</td>
<td>20% n = 16</td>
<td>4% n = 3</td>
</tr>
</tbody>
</table>

In this unit, [our] theory was that the parasites from malaria are not attracted to the hemoglobin in the red blood cells of patients suffering from the mystery disease. Something is wrong with their hemoglobin. (F02-22, post-survey)

We were presented with a mystery patient and were given symptoms, blood samples, family medical history, pedigree charts and maps of the patient's home country displaying various information. We had to use this information to create a theory on what we thought the disease was and where it might have come from. (F02B-03, post-survey)

Post-instruction Views of The Tentative Nature of Science

Students' pre- and post-instruction views of the tentative nature of science as characterized by the pre/post-survey and pre/post-interview data are contained in Tables 14 and 15.

As evident in Table 14, following completion of the sickle-cell unit, more students held the view that theories can change. Furthermore, there was a slight
Table 14

Changes in Students' Views of the Tentative Nature of Science

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Pre-view</th>
<th>Post-view</th>
<th>Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Theories do not change. Once created, they are absolute or fixed entities.</td>
<td>n = 10</td>
<td>n = 2</td>
<td>-8</td>
</tr>
<tr>
<td>2</td>
<td>Theories can change with the discovery of new data.</td>
<td>n = 40</td>
<td>n = 45</td>
<td>+5</td>
</tr>
<tr>
<td>3</td>
<td>Theories can change. They change by virtue of advances in technology which lead to new data.</td>
<td>n = 22</td>
<td>n = 27</td>
<td>+5</td>
</tr>
<tr>
<td>4</td>
<td>Theories can change by virtue of new insights that scientists achieve with existing data.</td>
<td>n = 3</td>
<td>n = 0</td>
<td>-3</td>
</tr>
<tr>
<td>5</td>
<td>Theories can change when there are either (or both) changes in technology (new evidence) or new insights achieved by scientists with existing data.</td>
<td>n = 3</td>
<td>n = 7</td>
<td>+4</td>
</tr>
<tr>
<td>6</td>
<td>Theories can change, but the student gives no support.</td>
<td>n = 2</td>
<td>n = 0</td>
<td>-2</td>
</tr>
<tr>
<td>7</td>
<td>No answer (or inarticulate)</td>
<td>n = 1</td>
<td>n = 0</td>
<td>-1</td>
</tr>
</tbody>
</table>

increase in the number of students who indicated that theories change for reasons other than data that is precipitated from technological advances (e.g., from new insights with existing data):

Because there could be set data and everyone could look at it and depending on your thought or ideas you could look at it differently. You could read and only look for certain stuff you want to see… I do think some theories change as time goes on because of data. Changes in the data or data is added…technology is changing so much everyday. It plays a big part because with technology changing it sheds more light on aspects that may have not been able to [have] been looked at before. (F02B-05, post-interview)

I believe that theories do change because new information is always coming about. This new information may be used in order to further pursue an existing theory. Theories also change because people look at the same data and may interpret it differently. (W03B-09, post-survey)

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The distinction here is that students recognized that in addition to the possibility of new data giving rise to a change in theory (brought about by potential advances in technology) they articulated that theory change may be due to differing insights with the existing data. This issue is particularly relevant to understanding that science involves creative aspects (interpretation) with extant data and is related to understanding that the development or interpretation of scientific data is partially a subjective endeavor.

As shown in Table 15, a significant percentage (48%, n = 39) of students in their post-instructional responses cited a valid example from the sickle-cell unit to support their view that theories change:

Theories change. Theories are improved upon once more data is collected, which in turn allows new theories to be created. The original theory remains because it was once thought to be true, but because it is decided that it is no longer true, it has “changed.” Using the example of the mystery patient, we initially believed that the disease was homozygous dominant, information we derived from a pedigree chart that used in-vitro blood testing. When science was improved upon and in-vivo testing was found to be more accurate, the pedigree charts changed, and thus our theory “changed” to the disease being passed recessively. (F02B-03, post-survey)

In the beginning stages, we looked at the blood samples of the mystery disease in BIOS 270. These samples were taken in the form of an Emmel test, where they take blood on the slide and cover it in wax and let it set for 48 hours. We know now that the process deoxygenated the blood. Then, they [scientists] didn’t know, because that is the way they knew [how to test]. So, as technology changed, they learned that it was a “bad” way to do it. (F02-07, post-interview)

Like when we looked at the map of Uganda and observed where the frequencies were highest. Then, was there anything physically or topographically on the map that might affect why the frequencies were so high? We noted that higher numbers were near water and low in the mountains, so we figured that it had to do with mutations in the water. But in
the next class we added on to that by realizing that malaria was higher in these areas and our disease was protected against malaria. (F02B-23, post-interview)

One example where a theory changed is when we were doing an investigation of sickle-cell anemia. With in-vitro testing it appeared that sickle-cell anemia was a dominant allele. With in-vivo testing (of blood) done 20 years later, it seems to be a recessive allele. (W03-21, post-survey)

Table 15

Changes in Students' Examples to Support the Tentative Nature of Science

<table>
<thead>
<tr>
<th>Example Cited</th>
<th>Pre-view percentage</th>
<th>Post-view percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invalid</td>
<td>51% n = 41</td>
<td>12% n = 10</td>
</tr>
<tr>
<td>Valid (unrelated to sickle cell case)</td>
<td>25% n = 20</td>
<td>12% n = 10</td>
</tr>
<tr>
<td>Vague sickle cell reference</td>
<td>0% n = 18</td>
<td>22% n = 18</td>
</tr>
<tr>
<td>Valid sickle cell example</td>
<td>0% n = 39</td>
<td>48% n = 39</td>
</tr>
<tr>
<td>None given</td>
<td>23% n = 19</td>
<td>5% n = 4</td>
</tr>
</tbody>
</table>

Post-instruction Views of the Distinction Between Theories and Laws

Students' pre- and post-instruction views of the distinction between theories and laws as characterized by the pre/post-survey and pre/post-interview data are contained in Tables 16 and 17.

As evident in table 16, there was very modest change in overall students' views on this aspect of the nature of science. As shown in Table 17, no students were able to articulate a specific example from the sickle-cell case to support their claim made about a distinction between theories and laws.
### Table 16

Changes in Students’ Views of the Theory/Law Distinction

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Pre-view</th>
<th>Post-view</th>
<th>Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laws are absolute or certain. Theories are not. Laws do not change while theories do.</td>
<td>n = 60 74%</td>
<td>n = 57 70%</td>
<td>-3</td>
</tr>
<tr>
<td>2</td>
<td>Laws are more “valid” than theories. Laws are based on “visible” evidence. Theories are often based on speculation, inference, or guesses.</td>
<td>n = 10 12%</td>
<td>n = 2 2%</td>
<td>-8</td>
</tr>
<tr>
<td>3</td>
<td>Theories become laws when “proven” or tested over and over.</td>
<td>n = 14 17%</td>
<td>n = 12 15%</td>
<td>-2</td>
</tr>
<tr>
<td>4</td>
<td>Laws describe patterns. Theories are explanations.</td>
<td>n = 0 0%</td>
<td>n = 4 5%</td>
<td>+4</td>
</tr>
<tr>
<td>5</td>
<td>Both laws and theories are subject to potential change.</td>
<td>n = 2 2%</td>
<td>n = 5 6%</td>
<td>+3</td>
</tr>
<tr>
<td>6</td>
<td>Recognize a difference but are unable to articulate.</td>
<td>n = 6 7%</td>
<td>n = 8 10%</td>
<td>+2</td>
</tr>
<tr>
<td>7</td>
<td>No Answer</td>
<td>n = 3 4%</td>
<td>n = 0</td>
<td>-3</td>
</tr>
</tbody>
</table>

### Table 17

Changes in Students’ Examples to Support the Theory/Law Distinction

<table>
<thead>
<tr>
<th>Example Cited</th>
<th>Pre-view percentage</th>
<th>Post-view percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invalid</td>
<td>33% n = 24</td>
<td>9% n = 7</td>
</tr>
<tr>
<td>Valid (unrelated to sickle cell case)</td>
<td>33% n = 24</td>
<td>33% n = 27</td>
</tr>
<tr>
<td>Vague sickle cell reference</td>
<td>0% n = 4</td>
<td>5% n = 4</td>
</tr>
<tr>
<td>Valid sickle cell example</td>
<td>0% n = 4</td>
<td>0% n = 4</td>
</tr>
<tr>
<td>None given</td>
<td>41% n = 33</td>
<td>52% n = 42</td>
</tr>
</tbody>
</table>
This finding is not surprising when considering that the topic of laws in science was only briefly discussed in the sickle-cell unit. During the second class on genetics, students were asked to compare how their provisional theories relate more generally to more robust or "core" theories found in science (e.g., theory of evolution). Following this, the instructor also asked students to articulate a difference between theories in science and laws in science. It was evident throughout all of the sections of the class that students were not able to properly define a law in science such that they could even articulate modest distinctions or comparisons to their views of a scientific theory. For this reason, the instructor resorted to didactically "telling" students the definition of a law (although the instructor was careful to refrain from indicating to students whether or not laws are subject to potential change).

Therefore, despite the instructor explicitly and didactically telling students about laws in science, they were still unable to articulate more informed views of the distinction between theories and laws on the post-instruction instruments. This again is not overly surprising when we consider that there were simply no opportunities for students to engage in reflection of the material (problems) of the unit to a more general understanding of theories versus laws.

This underscores the importance of having nature of science aspects that are capable of being linked reflectively with the contextual material students examine. Philosophers of science (e.g., Beatty, 1980) draw attention to the claim that biology has no laws similar in kind to those that encapsulate other scientific disciplines (e.g., physics). Support for this position rests on the claim that biology is replete with
counterexamples that undermine or detract from the ability to make claims about the generalizability of the descriptions that laws purport.

**Post-instruction Views of The Validity of Observational Methods**

Students’ pre- and post-instruction views of the validity of observational methods as characterized by the pre/post-survey and pre/post-interview data are contained in Tables 18 and 19.

As shown in Table 18, there was a decrease in the number of students who inappropriately conflated an experiment with a “hands-on” activity. One inference is

Table 18

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Pre-view</th>
<th>Post-view</th>
<th>Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Students incorrectly equated experiments with observations (or “hands on” activities).</td>
<td>n = 14 33%</td>
<td>n = 9 27%</td>
<td>-5</td>
</tr>
<tr>
<td>2</td>
<td>Experiments are necessary to “prove” or “validate” scientific knowledge or to “test” theories.</td>
<td>n = 22 52%</td>
<td>n = 8 17%</td>
<td>-14</td>
</tr>
<tr>
<td>3</td>
<td>Experiments are not required, but experiments are “better” or “needed” to validate knowledge (this infers a hierarchy).</td>
<td>n = 3 7%</td>
<td>n = 3 11%</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Observational evidence is valid for acquiring knowledge in science.</td>
<td>n = 2 5%</td>
<td>n = 21 43%</td>
<td>+19</td>
</tr>
<tr>
<td>5</td>
<td>No reason given</td>
<td>n = 1 2%</td>
<td>n = 1 1%</td>
<td>0</td>
</tr>
</tbody>
</table>

that by virtue of their participation in the unit, several students were able to articulate or recognize a distinction between experimental methods and other forms of data.
collection. Additionally, more students held the view following instruction in the sickle-cell unit that observational methods, in contrast to experimental methods, are valid means for collecting data for the purpose of developing knowledge in science. There was also a relatively large decrease in the number of students who held the view that experiments are necessary to validate or "prove" scientific theories.

For those students (themes 2, 3, & 4 in Table 18; subgroup n = 33) who, in their post-instruction view by virtue of their answer distinguished an experiment from other methods of data collection (i.e. they did not conflate experiments with for example observations or "hands-on" activities), there was also an increase in the number of students who were able to cite a specific example from the sickle-cell anemia case to support their view regarding the claim that observational methods (e.g., observations) are valid methods for collecting data and developing scientific knowledge (Table 19):

Our third unit of BIOS 270 was an example that it is not necessary to perform experiments. It was clear how much sense the heterozygote advantage made in the situation and no experiments were performed. We only made observations. (W03-14, post-survey)

Post-instruction Views of The Subjective Nature of Science

Students' pre- and post-instruction views of the subjective nature of science as characterized by the pre/post-survey and pre/post-interview data are contained in Tables 20 and 21.

As evident in Table 20, there was a substantial increase in the number of students who were able to articulate following the sickle-cell unit that disparate
Table 19

Changes in Students’ Examples to Support the Validity of observational Methods

<table>
<thead>
<tr>
<th>Example Cited</th>
<th>Pre-view percentage</th>
<th>Post-view percentage</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invalid</td>
<td>0%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Valid (unrelated to sickle cell case)</td>
<td>17%  n = 7</td>
<td>24%  n = 8</td>
<td></td>
</tr>
<tr>
<td>Vague sickle cell reference</td>
<td>0%</td>
<td>33%  n = 11</td>
<td></td>
</tr>
<tr>
<td>Valid sickle cell example</td>
<td>0%</td>
<td>21%  n = 7</td>
<td></td>
</tr>
<tr>
<td>None given</td>
<td>45%  n = 19</td>
<td>21%  n = 7</td>
<td></td>
</tr>
</tbody>
</table>

Table 20

Changes in Students’ Views of the Subjective Nature of Science

<table>
<thead>
<tr>
<th>Theme</th>
<th>Description</th>
<th>Pre-view</th>
<th>Post-view</th>
<th>Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Scientists cannot go back and “see” what happened in the past. Students do not consider inference as valid so scientists have to guess.</td>
<td>n = 16</td>
<td>n = 9</td>
<td>-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20%</td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Not enough conclusive evidence to “prove” one or the other theories. No recognition of other factors that may play a role.</td>
<td>n = 21</td>
<td>n = 8</td>
<td>-13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26%</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Scientists are forced to use creativity to “fill in the gaps” rather than realize that creativity and imagination are central to a scientist’s work.</td>
<td>n = 5</td>
<td>n = 2</td>
<td>-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6%</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Scientists interpret data differently (but no explanation why).</td>
<td>n = 40</td>
<td>n = 37</td>
<td>-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>49%</td>
<td>46%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Scientists interpret data from the perspective of their own subjective frameworks that are a product of their background and experiences.</td>
<td>n = 4</td>
<td>n = 22</td>
<td>+18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%</td>
<td>18%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inarticulate answer</td>
<td>n = 14</td>
<td>n = 7</td>
<td>-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17%</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No answer</td>
<td>n = 0</td>
<td>n = 0</td>
<td>0</td>
</tr>
</tbody>
</table>
theoretical positions can be attributed to the general category that scientists interpret data differently. Moreover, within this category, there was an increase in the number of students who claimed in the post-instruments that such differences in interpretation were due to subjective factors (e.g., personal experience and position) that influence a scientist’s “way of thinking” – theme 5:

Scientists come from different educational backgrounds and different upbringings and these characteristics affect what they may find valuable about the data. They will have different interpretations due to different styles of reasoning, thinking, and organizing. (W03-10, post-survey)

These different conclusions are possible because all scientists come with “baggage.” They all have different scientific backgrounds, different ideas, different ways of thinking about things. (F02-21, post-survey)

There was also a decrease in the number of students who held the view that the controversy is due largely to a scarcity of evidence, with the specific view that there must be a lack of evidence one way or another to “prove” one or another of the competing theories.

There was also an increase in the number of students who were able to cite a specific example from the sickle-cell anemia case to support their view regarding the claim that subjective factors play a role in the interpretation of scientific data (Table 21):

During the mystery patient investigation, other groups formed other theories about the disease based on their discussions...our group’s [theory] was different from theirs based on how we interpreted the evidence. (F02-07, post-survey)

The different conclusions are possible because all scientists come with “baggage.” They all have different scientific backgrounds, different ideas, different ways of thinking about things. In this [sickle-cell unit] when working
with mystery disease theories, different [groups of students] would come up with different ideas based on the exact same data. (F02-21, post-survey)

It gets into people’s background of how they choose to explain something like different types of scientists might explain the different explanations with the same information [data]. When we looked at the map of different allele frequencies of the mystery disease some people [thought] it has to be caused by a mosquito because everyone is by the water and mosquitoes are by the water. Other people would say, “What about this tribe? They are not even by water!” (FO2B-23, post-interview)

Their personal beliefs (i.e. religion, morals, etc) are not the same. They come from different areas, lifestyles and knowledge prior to concluding about this topic. People look through their own perspectives, and they are not the same. With the “mystery disease” (sickle-cell anemia) in Uganda, [our] ideas for how this phenomenon came about ranged from mutagens in the water, cell mutations, mosquitoes transmitting, and even “blackness.” And all of us had the same data presented to us. (W03B-07, post-survey)

Table 21

Changes in Students’ Examples to Support the Subjective Nature Of Science

<table>
<thead>
<tr>
<th>Example Cited</th>
<th>Pre-view percentage</th>
<th>Post-view percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invalid</td>
<td>22% n = 18</td>
<td>7% n = 6</td>
</tr>
<tr>
<td>Valid (unrelated to sickle cell case)</td>
<td>37% n = 30</td>
<td>22% n = 18</td>
</tr>
<tr>
<td>Vague sickle cell reference</td>
<td>0% n = 19</td>
<td>23% n = 19</td>
</tr>
<tr>
<td>Valid sickle cell example</td>
<td>0% n = 26</td>
<td>32% n = 26</td>
</tr>
<tr>
<td>None given</td>
<td>41% n = 33</td>
<td>15% n = 12</td>
</tr>
</tbody>
</table>
Finally, as was the approach taken in the pre-survey follow-up interview, several of the students that participated in the post-survey follow-up interview were asked a series of probing questions designed to better elucidate their views on the subjective nature of science. Of the probes used, one of them was noteworthy in terms of the majority of students’ responses:

"Which comes first, theory or observation?"

Of the six students who were asked this question during their follow-up interview, five of them articulated the view that observation must come prior to theory. These students also claimed in their responses to the survey question that scientists interpret data differently to account for the dinosaur controversy. It is important to note that these students were not able to articulate why such scientists interpret data differently.

One of the six students who was asked this follow-up probe expressed the view that theory could or does at times precede observation:

Well, it depends on how you work. You might have a theory in your mind and look for data to support that theory. Or, you may have an observation that was interesting to you, and you try to develop a theory to account for it. It could go either way. (F02-21, post-survey)

It is noteworthy to mention that this particular student articulated a relatively more informed view of the subjective nature of science by virtue of her answer to the post-survey and follow-up interview. This student additionally was able to provide a valid example to support her view taken from the work she did while in the sickle-cell anemia unit.
Effect of the Unit on Individual Student’s Views

A more detailed way to examine change was to identify and analyze individual students for which appreciable change occurred from their pre-instruction to post-instruction view. This was done by looking at each response students provided and determining if their view on a given aspect of the nature of science shifted (from a relatively more naïve to a relatively more informed perspective).

Moreover, it was important to examine if individual students had, in contrast to a “change” in his or her view, an “enrichment” in his or her understanding of some aspect of the nature of science. Enrichment is said to occur when a student who already possesses a relatively more informed perspective of the nature of science further substantiates this view by giving a valid example on the survey or in the interview (Abd-El-Khalick, 1998; Abd-El-Khalick & Lederman, 2000).

Thus, for the purposes of this research, four specific categories are used to identify change or enrichment on an individual student level (Table 22).

Table 22

Characterizing Individual Change or Enrichment in NOS View

<table>
<thead>
<tr>
<th></th>
<th>Pre-unit NOS view</th>
<th>Post-unit NOS view</th>
<th>Pre-unit example</th>
<th>Post-unit example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change</td>
<td>Naïve</td>
<td>Informed</td>
<td>Invalid or valid</td>
<td>Valid</td>
</tr>
<tr>
<td>Linked change</td>
<td>Naïve</td>
<td>Informed</td>
<td>Invalid or valid</td>
<td>Valid sickle cell</td>
</tr>
<tr>
<td>Enrichment</td>
<td>Informed</td>
<td>Informed</td>
<td>Invalid or none</td>
<td>Valid</td>
</tr>
<tr>
<td>Linked enrichment</td>
<td>Informed</td>
<td>Informed</td>
<td>Invalid or none</td>
<td>Valid sickle cell</td>
</tr>
</tbody>
</table>
“Change” indicates that the student’s view on an issue in the nature of science shifted from a relatively more naïve to a relatively more informed view and the student provided a valid (general) example to support his or her view. “Linked Change” means that the valid example the student cited was directly connected to some aspect of the sickle-cell unit. “Enrichment” indicates that the student retained a relatively more informed view as evident in the post-instruments and was also able to articulate a valid (general) example to support that view. “Linked Enrichment” denotes that the example cited to support the nature of science view was connected to the sickle-cell unit.

The reason that it is important to examine individual change (or enrichment) in student’s views in addition to analyzing change in the general population is because the latter simply does not provide conclusive evidence to warrant a valid claim about the efficacy (or lack thereof) of the sickle-cell intervention to establish meaningful change (or enrichment) in nature of science views. It is important for researchers to analyze the reasons (or examples) that individual students provide in defense of their pre- and post-instruction responses in order to establish whether or not the unit was successful.

In this regard, it should be emphasized that the researcher was careful to be conservative about the degree to which a student was genuinely affected by the sickle-cell unit. For this reason, only those students who articulated a rather explicit example from the sickle-cell case to support their nature of science views were
regarded as a "linked" change in view. As revealed in the following section, there were at times significant numbers of students who gave rather general references to their experiences in the sickle-cell unit (e.g., "our theories we developed changed in the sickle-cell unit"), but the researcher was cautious not to infer that these passing or vague references constituted grounds to claim that the student had a linked or meaningful change in view by virtue of their activities in the unit.

Identifying appreciable change in an individual student's view was done on a case-by-case basis with respect to each nature of science aspect. That is to say, determining what should be categorized as "change" in a view from relatively more naïve to relatively more informed was done separately for each nature of question of the survey.

Individual Change/Enrichment in Student Views of the Meaning of Theory

The researcher felt that when a student's view moved from one in which there was no conception of a theory in terms of its explanatory role to a post-instruction view in which they explicitly articulated theories in terms of explanations (and the student was able to articulate a valid, general example of a theory in support of their post-view, then that student gave evidence of a change in his or her view. Alternatively, for those students whose pre-instruction view held theories as explanations but their understanding of how theories are created shifted from relatively naïve (vague reference to empirical data or belief in a scientific method) to relatively informed (articulating distinct empirical approaches and/or creative
interpretation) then change is also thought to have occurred. Moreover, when a student showed evidence of change in his or her view and provided a valid example that was linked to the sickle-cell unit, then the status of the change is termed as a “linked change.”

From this heuristic, the researcher found that 24 of the students (30% of total) experienced a change in their view of scientific theories. A subset of 7 of this group of 24 students (9% of total) had a change in view that was linked to the sickle-cell unit. Also noteworthy are that a total of 7 students had an enrichment in their view, and 2 of these seven students (2% of total) had an enrichment linked to the unit.

“Change” in view can be further divided. Of the 24 students who had a change in their view of the nature of scientific theories, 11 of these students articulated a change only with respect to greater characterizing a theory in terms of its explanatory role. Eight of the students only changed their view with regard to how they perceived a theory to be developed. These students expressed in the post-instruction responses that theories can be developed from distinctly different approaches (either experimental or observational approaches, or both). Five of the 24 students who exhibited a change in view articulated the most informed changes (both the meaning of a theory and how theories are developed).

These results indicate that the unit was moderately successful in changing students’ views of the nature of theories. Caution should be taken no to overstate the degree of change. At best, change in student views was modest. This is because the grains of analyses used to determine “change” were relatively fine. That is, no student
was able to articulate a very informed view as defined by science educators (e.g., Abd-El-Khalick) or philosophers of science (e.g., Suppe, 1977). Taken in this light, one could argue that the unit was not overly effective at changing students' views toward the most informed understanding.

Despite this, it is encouraging that some students' conception of a theory was positively affected toward a relatively more informed perspective. There are several reasons that may account for this. First, one of the main objectives given to students at the outset of the sickle-cell unit was for them to construct explanations to account for various facets of the mystery disease. Thus, the idea of constructing explanations based on the evidence available to the students was a theme visited often throughout the unit. Moreover, there were several instances (both planned as indicated in the lesson plans of Appendix E and spontaneous) in which the instructor challenged students to reflect upon the type of methodological processes (e.g., observing, inferring, etc.) that students were doing to develop and interpret data.

Second, there were several instances in which the instructor facilitated a discussion about students' views on the validity of knowledge in science developed from observational approaches. These conversations and the insights that students achieved from their work in the unit certainly had a bearing on their view of the development of theories. For example, during the sixth class of the unit, students were asked to re-examine the earlier theories they developed to account for anomalously high and heterogeneous frequencies of sickle-cell heterozygotes living in Uganda. New data given to them during this class caused them to reconsider their earlier
explanations. Students understood that they were recapitulating the analysis of the data Anthony Allison derived from his hematology work with Ugandan children.

While students were working in their groups to account for the data, the instructor gave them probes (Appendix G) to consider. These probes invited them to examine the validity of their explanations in light of the methods they (and Allison) adopted. During the whole-group discussions that followed, the instructor asked students to share their insights. Moreover, if it was not invariably suggested by a student, the instructor asked the class if they felt experimental evidence is “necessary” to substantiate their newly resultant theory of heterozygote protection. This led into discussions in which students likely considered that like Allison, they too proposed a rather sound explanation to account for the anomaly based on the observational approaches that were available to them.

Finally, it is fair to say that students in this class, in general, were likely more sensitized or receptive to articulating an informed view of scientific theories. In their pre-instruction instruments, a relatively large percentage (50%, n = 42) of students articulated an understanding that theories are explanatory elements in science. Moreover, these students either explicitly or implicitly conveyed in their answers the idea that scientific theories require evidential support to substantiate the validity of the theory. This rather large percentage of students is inconsistent with similar research that has examined students’ pre-instruction views of the status of theories (e.g., Abd-El-Khalick, 1998; Abd-El-Khalick & BouJaoude, 1997). In this latter
research, a larger proportion of students held the view that theories are more akin to mere opinions or guesses in the vernacular sense of the word.

Abd-El-Khalick (1998) situates an informed understanding of a scientific theory in terms of Suppe's (1977) articulated definition. That is to say, he regards theories as fairly robust, internally-consistent systems of explanations. Moreover, such a theory has withstood numerous attempts of refutation, provides for rather comprehensive predictive power, unites somewhat diverse scientific disciplines, and opens new avenues for fruitful research endeavors. Certainly, no student in the present study articulated such an understanding in either their pre- or post-instructional view. However, the majority of students also did not possess what was characterized by Abd-El-Khalick as naïve views. That is to say, students in the present study seemed to understand that theories are more than just opinions or guesses in the vernacular sense.

One possible reason that accounts for the discrepancy between the pre-instruction views of students in the present study and those found in the aforementioned research is that the topics of the empirical nature of science and the status of a scientific theory were themes that were discussed throughout the two units that preceded the sickle-cell unit. Prior to the sickle-cell unit, students examined both genetics and molecular biology. Each of these units, like the sickle-cell unit, relied upon an open-ended, problem-solving approach to have students examine various conceptual issues. Moreover, an overarching theme that was stressed for each of these units concerned the importance of developing models (explanations) in science.
Students were encouraged to see how the data (evidence) they examined in class contributed toward the strength of the explanatory models they were constructing. Periodically, the instructor asked students to consider how these processes related to their more general understanding of the way in which scientists engage in the development of scientific knowledge. In other words, it is possible that students’ views of the nature of theories were more informed by virtue of their experience in the two preceding units. Therefore, it is likely that the relatively modest change in student views of scientific theories in the present study are at least partially attributable to the fact that it was a theme discussed throughout the course.

Interestingly, during the sickle-cell unit students were explicitly asked several times by the instructor to discuss how their own provisional theories to account for the mystery disease “compared” in terms of status to what scientists consider as long-standing theories. The purpose for these discussions was to have students think about what makes a robust theory in science (e.g., theory of evolution or plate tectonics) stand apart from lesser, more immature theories. Despite these sessions, no student was able to indicate in the post-instruction instruments a truly informed definition of a scientific theory.

**Individual Change/Enrichment in Student Views of the Tentative Nature of Science**

Change in an individual student’s view of the tentative nature of science occurred when the student articulated in their pre-instruction instruments that theories do not change (or that knowledge is absolute) and held the view in their post-
instruction instruments that theories (or knowledge in science) are subject to potential change. Moreover, the student must have given a valid example (or specific example from the sickle-cell case) to support their changed view in the post-instruction instruments.

The researcher found that a total of 10 students (12%) exhibited a change in their view of the tentative nature of science. Out of these 10 students, 6 of them (7% of total) were able to provide a specific example from the sickle-cell case to support their view. Alternatively, 30 students (37%) experienced an enrichment in their view of the tentative nature of science. Twenty-five of these students (31% of total) had an enrichment that was linked to the sickle-cell case.

The sickle-cell case was evidently influential in changing or (more proportionately) enriching students' views of the tentative nature of science. Several reasons may account for this. First, the lessons followed the chronological development of the historical understanding of the disease. As such, students recapitulated several areas of research by way of examining contextual data from class to class. Furthermore, the explanations that students developed in one class (e.g., that they concluded that sickle-cell anemia must be prevalent in anomalously-high frequencies because of chemical mutagens or because of racial predeterminations) were challenged in subsequent classes when new data became available to them. As a result, the students experienced change in several of their earlier theories as they progressed through the unit.
Second, the instructor provided targeted probes in several of the classes for
the student groups to consider while they were working with their context-specific
data:

Suppose that another group of students proposes a different theory to explain
the genetics of the mystery disease. How would scientists value (determine) which theory is more valid?

After today's problem, do you have a new theory to explain the genetics?
If yes, what (specifically) led to your new theory?

The instructor used these probes as starting points for facilitated discussion with the
whole class following the individual group work. Probing questions similar to these
were also given to students for them to consider for their daily diary entries. Here,
students were asked to be reflective about their work in the unit to more general
views of the tentative nature of science.

As shown in Table 14 of the previous section, students largely articulated the
view that change was due to new data (with or without advances in technology). Few
students articulated the more informed view that change also can occur from new
insights scientist have with existing data. This finding is not unexpected, because
students largely came to see the new data they were given in each class in terms of
some advancement in technology (e.g., the "invention" of a testing technique that
provided new data). Though, some of the students did appreciate the role that insight
plays with existing data, and this is encouraging given that part of their experience in
a few of the classes involved interpretive work with the historical data. That is, when
each group was given identical data sets, it was interesting to see how a few different
theories resulted. Though this issue more centrally regards the subjective nature of
science (discussed later in this section) it suggests that students were able to apply their understanding that science is partially interpretive to their view of why theories can change.

Individual Change/Enrichment in Student Views of the Theory/Law Distinction

No student experienced any change or enrichment in their understanding of the distinction between scientific theories and scientific laws. This finding is very consistent with other research (Abd-El-Khalick, 1998; Abd-El-Khalick & BouJaoude, 1997; Horner & Smith, 1981).

These findings suggest how mixed (or context specific) student views of certain issues of the nature of science can be. A significant percentage of students articulated the view that theories are subject to change but an overwhelming majority of students then claimed that laws are absolute or proven entities. The implication may be that students do hold the fundamental view that science is associated with finding absolute "truths."

The distinction between laws and theories was only briefly touched upon during the sickle-cell unit. Following a revision of their previous theory to account for the genetics of the sickle-cell disease, the instructor engaged students in a discussion about their views on how scientists evaluate competing theories in science (see Appendix E, class #3). Furthermore, the instructor asked students to discuss how their more provisional theories (in terms of status) to those theories that we often associate or refer to as long-standing theories of science (e.g., theory of evolution or plate
tectonics). The subject of laws was ultimately discussed, though students’ views of laws were similar to those they articulated on the instruments.

**Individual Change/Enrichment in Student Views of the Validity of Observational Methods**

Change occurred if a student moved from a view in which they initially either conflated experiments with observational approaches or believed that experiments are required for the development of scientific knowledge to the recognition that observational methods are also valid for such development. Moreover, the student must have articulated a valid example to support their post-instructional view. When a student showed change in their view as defined above and provided a valid example that was linked to the sickle-cell unit, then the nature of the change is referred to as “linked change.”

A rather large number of students (n = 20, 48%) experienced a change in their view of the validity of observational methods. Of these 20 students, 7 (17% of total) experienced a change that was directly linked to the sickle-cell unit by virtue of the supportive example they provided. Alternatively, there was no evidence of enrichment in student view.

The sickle-cell unit appeared to have been at least partially responsible for other changes. The students assumed ownership of the explanations they constructed to account for the various problems they were given to consider. Their explanations were entirely based upon data that had been collected through non-experimental methods (e.g., observation, inference, creativity). The probes given to the students to
consider challenged them to reflect upon the validity of their conclusions in light of the fact that the data was collected in this manner.

The increase in the number of students who believed that experimental approaches are "better" than observational approaches (implying a hierarchy) was also likely due to the unit. This unintended outcome likely resulted from discussions about Anthony Allison's experimental work in inoculating tribesmen with malaria to confirm his earlier prediction of heterozygote protection. It is conceivable that some students concluded from these discussions that experiments provide conclusive "proof" to predictions that were made from earlier data.

**Individual Change/Enrichment in Student Views of the Subjective Nature of Science**

Change occurred if a student moved from a view in which they initially conceived that there must be a scarcity of available data or a general view that scientists interpret differently to the specific recognition that subjective factors play a role in the differing interpretation of scientific data. When a student showed change in their view as defined above and provided a valid example that was linked to the sickle-cell unit, then the nature of the change is referred to as "linked change."

Sixteen students (20% of total) exhibited a change in their view of the subjective nature of science. Of these, 11 (14% of total) had a change in view that was linked to the sickle-cell case. Alternatively, there were no students who exhibited an enrichment in their view.
One reason why the sickle-cell unit was likely effective at changing students' view of the subjective nature of science is that there were four targeted classes in which both the activities that students did and the probes that they considered (for their group work and for their diary entries) facilitated their insights into this aspect of the nature of science. In the two genetics and two evolution classes, the student groups received the same sets of data and were asked to examine the data to come up with explanations to account for any problems they were given. The resulting whole-class discussions revealed that the explanations were different, similar to those proposed by competing historical scientists who were working with the same data. The probing questions invited students to explain how such disparate explanations were possible, and in the conversations that ensued, students unpacked this notion of subjectivity.

Summary

This chapter provides the results of an eight-class historical unit on preservice teachers' conceptions of certain aspects of the nature of science. The unit was developed from the scientific research in understanding the disease sickle-cell anemia. The specific nature of science aspects that were the focus of the research included (a) the nature of scientific theories, (b) the tentative nature of science, (c) the difference between scientific theories and laws, (d) the validity of observational methods in science, and (e) the subjective (theory-laden) nature of science. Both pre-instruction
and post-instruction views were measured using an open-ended survey and follow-up, semi-structured interviews.

Taken as a whole, students' pre-instruction views on these aspect of the nature of science were relatively naïve or uninformed. If placed on a continuum between very naïve and very informed, students tended to articulate views that were more naïve for each of the issues. This finding is consistent with prior research that has examined students’ pre-instructional views (e.g., Abd-El-Khalick, 1998).

The majority of students (n = 42, 50%) conceived of scientific theories as explanations backed by empirical support. This finding is somewhat inconsistent with prior research (e.g., Abd-El-Khalick) in which a greater percentage held a more vernacular conception of theories. Though students in the present study held a slightly more informed pre-instruction view of theories, it should be emphasized that no student was able to articulate a well-informed conception of a scientific theory akin to that defined by philosophers of science (e.g., Suppe, 1977).

A majority of students (n = 72) articulated that they believed theories are subject to change, however the larger percentage of these students indicated that new data (often brought about by advances in technology) was responsible for facilitating that change. Few students indicated that theories possibly change by virtue of new insights that scientists have with existing data.

Students overwhelmingly had naïve views of the distinction between theories and laws. The majority (n = 60, 74%) conceived of laws as absolute or proven entities while they believe theories to be tentative. Many students also conveyed that theories
eventually evolve into laws should enough evidence be gathered to substantiate the theory beyond doubt. No student was able to give a sufficient definition of a theory and a law or articulate an informed understanding of the difference between them.

Consistent with the findings of prior research (e.g., Abd-El-Khalick, 1998) student responses to the theory/law distinction underscored how mixed or context-specific their views can be. Students conceived of science as tentative when discussing the status of theory change but conceived of science as absolute when discussing laws.

Regarding the validity of observational methods for the development of scientific knowledge, a significant percentage (48%, n = 39) of students incorrectly conflated experiments in science with “hands-on” activities or observational methods. For those who correctly articulated a distinction, the majority (n = 33, 41%) believed that experimental methods are necessary for the development of scientific knowledge.

In the final question which concerned the subjective nature of science, over half (n = 42, 51%) of the students believed that the reason scientists construct different explanations to account for the demise of the dinosaurs (despite that they all have access to the same data) is that there must be a scarcity of available data. Specific reasons ranged from their belief that there is no way to go back and see what actually happened (n = 16, 20%) to that there is a lack of enough data to “prove” one explanation over another (n = 21, 26%).

Though a large percentage of students (49%, n = 40) held the view that scientists interpret the same data differently, they did not further explicate why this is
so. In this regard, only a very few students in their pre-instruction instruments articulated the more informed view that certain subjective factors (e.g., educational background, social milieu, commitment to a research paradigm, etc.) affect how a scientist “sees” the data.

Following their participation in the sickle-cell unit, students’ views of the specific aspects of the nature of science were again assessed by means of an identical post-instruction survey and semi-structured, follow-up interview. Taken as a whole, students’ post-instruction views were still largely naïve. There is, however, encouraging evidence from this study which suggests that several individual student’s views of certain aspects of the nature of science were improved or enriched because of their experiences in the sickle-cell unit (Table 23).

In the post-assessment, more students were able to articulate a slightly more informed view of the nature of theories. Here, students greater articulated the explanatory role played by theories and also increasingly distinguished certain methods (e.g., experiment and observation) scientists use to create or develop them. Concurrently, there was a decrease in the number of students who held the view (explicitly or implicitly conveyed) that scientists follow a prescribed “scientific method” toward the creation of scientific theories. Still, despite these subtle gains, no student was able to convey a truly informed view of a scientific theory as something that is a well-defined, internally consistent, system of explanations, possessing predictive power and opening up new avenues for scientific research.
Table 23
Summary of Change/Enrichment in Individual Student’s NOS Views

<table>
<thead>
<tr>
<th>NOS Aspect</th>
<th>Change in NOS View</th>
<th>Change Linked to Unit</th>
<th>Enrichment in NOS View</th>
<th>Enrichment Linked to Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nature of Scientific Theories</td>
<td>n = 17 21%</td>
<td>n = 7 9%</td>
<td>n = 5 6%</td>
<td>n = 2 2%</td>
</tr>
<tr>
<td>Tentative NOS</td>
<td>n = 4 5%</td>
<td>n = 6 7%</td>
<td>n = 5 6%</td>
<td>n = 25 31%</td>
</tr>
<tr>
<td>Theories vs. Laws</td>
<td>n = 3 4%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Validity of Observational methods²⁸</td>
<td>n = 13 48%</td>
<td>n = 7 17%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Subjective NOS</td>
<td>n = 5 6%</td>
<td>n = 11 14%</td>
<td>n = 0 0%</td>
<td>n = 0 0%</td>
</tr>
</tbody>
</table>

As evident in Table 23, there was relatively little change in individual student’s views of the tentative nature of science. This is not overly surprising, since a large percentage of students held the belief in their pre-instruction assessment that theories are subject to change.²⁹ There was a relatively large number of students (n = 25, 31%) who experienced an enrichment in their view of the tentative nature of science by virtue of the explicit sickle-cell examples they provided in the post-instruments to support their view. This is encouraging and demonstrates that students

²⁸ As indicated in the first section of this chapter, the total population of students analyzed with respect to this question was 42, instead of 81 for the remaining questions.
²⁹ Caution should be taken in inferring that students hold overly-informed views of the tentative nature of science by virtue of their answers to this specific question on the pre-survey when a vast majority also responded in the subsequent question that laws are fixed and proven (absolute) entities.
can be reflective about their own learning and experiences in science when asked about this nature of science question in the absence of a provided context.

However, students' answers in the post-instruction instruments to the question about the distinction between theories and laws revealed very naïve views that were relatively unchanged from the pre-instruction assessment. The reticence of students to abandon an absolutist view of scientific theories has been demonstrated in prior research (e.g., Abd-El-Khalick, 1998; Abd-El-Khalick & BouJauode, 1977). Moreover, their naïve views of laws as absolute or "proven" entities demonstrates how contextually-dependent their views are of the tentative nature of science. The majority of students conveyed that theories are tentative by virtue of their responses to the second item of the survey (and students gave explicit examples taken from the sickle-cell unit to support their case). But, a large number of students revealed that the tentative nature only applies to theories and not to laws as evident from their answers to the third item of the survey.

Most significant was the degree of change in individual student's views on the validity of observational methods in science (item 4 of the survey) and the subjective nature of science (item 5) as evident in Table 23. This suggests that the way in which students worked with the historical data in tandem with the facilitated probes and discussions led by the instructor was successful in getting students to reflectively reconsider their antecedent naïve views on these two nature of science aspects.
CHAPTER 5

DISCUSSION AND IMPLICATIONS

Introduction

This research measured the effect of a unit of instruction developed from the history of research on sickle-cell anemia on preservice teachers’ conceptions of aspects of the nature of science. The following chapter provides an analysis of the significance of the results with respect to the questions that guided the research and with respect to the theoretical and conceptual frameworks in which the research was situated. The chapter is divided into four sections. The first section provides a comprehensive analysis of the results with reference to the aforementioned issues. The second section discusses the limitations of the research. The third section addresses the implications of the study, and the fourth section provides recommendations for future research.

Analysis

The present study was motivated by two research questions:

1. Do explicit and reflective instructional techniques improve students’ nature of science views in a unit that emphasizes the history of science?

2. Are some nature of science views more apt to change than others using explicit and reflective techniques in a unit that emphasizes the history of science? Each of these questions is addressed separately in the subsections that follow.

Do Explicit and Reflective Instructional Techniques Improve Students’ Nature of Science Views in a Unit that Emphasizes the History of Science?
One general conclusion from the research is that the results of this study suggest that preservice teachers' views of certain aspects of the nature of science can be changed or enriched in a unit of instruction that emphasizes the history of science. This finding in and of itself is significant because there have been very few empirical studies over the past forty years (e.g., Abd-El-Khalick, 1998) that have measured the effect of the history of science on college students' nature of science views.

These results are particularly significant when we consider that many students in the present study were able to give specific examples from their work in the sickle-cell unit to support their (changed) views about the nature of science. Moreover, this suggests that for these students, they were able to successfully transfer their developed view of an aspect of the nature of science from one context (learning in the sickle-cell unit) to another (questions posed on the post-survey that were unrelated to sickle-cell anemia).

Caution must be exercised not to overstate the degree to which students' views were changed by virtue of their participation in the sickle-cell unit. In point of fact, there were differing degrees of change depending on the particular nature of science issue examined. Moreover, though the results concerning individual change in student's views of the nature of science are encouraging as revealed in the previous chapter, significant change that was attributable to the effect of students' interaction with the historical material (as defined by the researcher) was evident in less than 15% of the students for any single nature of science aspect (see Chapter 4, Table 23, p. 169).

It should be emphasized that the interpretation of the results of this study was conservative in the degree to which change was linked to the sickle-cell unit. There were numerous instances in which student views changed and the students gave vague references to their experiences in the sickle-cell unit. However, so as not to overstate the efficacy of the unit, these vague references were not coded as evidence of meaningful
change in view linked to the sickle-cell unit. Indeed, the significance of the findings of this study are strengthened when considering that the efficacy of the unit was only regarded when students gave meaningful and specific examples from the case to support their view.

The general conclusion (the positive effect of the historical unit on nature of science views) is consistent with recent empirical research that has measured the effect of the history of science on (college) students' views (Abd-El-Khalick, 1998). Abd-El-Khalick's findings suggest that courses that emphasize the history of science are relatively ineffective at changing or enriching students' views unless the nature of science is explicitly targeted. There was evidence to suggest that one of the history of science courses (an evolution course) slightly affected students' views, and Abd-El-Khalick concludes that this was due to a more explicit treatment of the nature of science by the instructor of the course.

In the conclusions of his research, Abd-El-Khalick points out several reasons to account for the relative lack of change. One of the principal factors he describes is the way in which the nature of science was addressed by the instructors of the three history of science courses he examined. Specifically, the instructors for two of the courses used what is often referred to as an implicit approach to having students learn about the nature of science. An implicit approach means that students will "pick up" an understanding of the nature of science merely by virtue of their learning of the historical content. The instructor of a third course (history of evolutionary theory) did explicitly connect students' content learning to germane aspects of the nature of science (e.g., tentative nature of science), but these instances were very infrequent and done in didactic manner. The little change in students' views that did occur in his study corresponded to those nature of science aspects that were explicitly discussed by the evolution instructor. This suggests that explicit approaches are more effective than implicit approaches.
(which were adopted by the instructors of the other two courses) at affecting nature of science views but only slightly so.

Recent research (e.g., Akerson, Abd-El-Khalick, & Lederman, 2000; Khishfe & Abd-El-Khalick, 2002) underscores the importance of having students work reflectively with the material toward achieving their own insights into the nature of science in a course in which nature of science is an explicit component. In large measure, the arguments that they make for explicit and reflective approaches (discussed below) motivated the instructional design of the sickle-cell unit used as the intervention for the present study and likely contributed to the relative success of the sickle-cell unit in affecting students' views. The results of this research do lend empirical support to the claim that explicit and reflective techniques will improve students' nature of science views. Moreover, the study supports the effectiveness of this approach in a unit that emphasizes the history of science.

Khishfe and Abd-El-Khalick (2002) argue that explicit and reflective techniques are aligned with the claim that aspects of the nature of science are something that the student must cognitively construct, in contrast to implicit approaches that situate learning nature of science as affective outcomes. The "explicit" portion refers to having issues of the nature of science as planned, instructional activities, while the "reflective" portion means that students must be challenged by virtue of the instruction to themselves achieve insight into more informed conceptions of the nature of science. Both of these (explicit and reflective) point to the need to have students actively (and reflectively) engaged with the conceptual material in concert with any germane nature of science issues.

The significance of this may explain one reason why the history of science courses examined in Abd-El-Khalick's research were less effective than the use of the history of science in the present study. Whereas the evolution instructor in his research
did (albeit infrequently) incorporate explicit methods to discuss the nature of science, the instructor didactically “told” students how the content they were examining (change in theory to account for evolution) related more generally to, for example, the tentative nature of science. In contrast, as students examined data and constructed explanations throughout the sickle-cell unit, they were periodically confronted with discrepant data that caused them to rethink their developing understanding of the sickle-cell phenomenon. Moreover, probing questions given to them by the instructor (and the facilitated conversations that ensued) invited students to consider on their own relevant ramifications of their context-specific conclusions with the historical material to more general nature of science views. The distinction is that students were encouraged to construct their own conclusions about the nature of science by virtue of the reflection that they did with the material.

This notion of “constructing an understanding” that occurred throughout the sickle-cell unit more generally points to the importance of recognizing that explicit and reflective techniques must be thought of in terms of constructivist learning theory (Piaget, 1959). This means that it is important for instructors to design and implement lessons in which the responsibility of learning resides primarily with the students. That is, effective instruction recognizes that students must actively construct their own interpretations of the material they are given with the instructor acting as a guide to facilitate such learning.

It must be emphasized that the sickle-cell unit was designed according to constructivist tenets for both students’ investigations of the historical material and for their development of an understanding of relevant nature of science issues. That is, students were placed in the role of examining evidence and constructing their own explanations in a similar fashion to those historical scientists who were grappling with similar evidence for the same problems. Furthermore, in contrast to “telling” students
(not aligned with a constructivist approach) about those germane nature of science issues that applied to the conclusions they were drawing with the material, the instructor challenged students to make their own connections by virtue of the explicit probes used in tandem with the problems and by virtue of the reflective diaries that students were required to keep.

Researchers (e.g., Abd-El-Khalick, 1998; Monk & Osborne, 1997; Solomon, Duveen, Scot, & McCarthy, 1992) also point out the reluctance students often have to embrace or see the relevance of the history of science for the learning of science. The central issue is that students have a difficult time seeing the merits of historical conclusions or historical ways of thinking particularly when such views are juxtaposed against the students' antecedent understanding of science. Abd-El-Khalick discusses this issue as another reason why the history of science courses he examined may have been relatively ineffective in changing students' nature of science views. He points out that when students have difficulty seeing historical conclusions or ways of thinking as anything other than wrong or foolish (in light of their antecedent view of science), then students are likely not able or willing to appreciate the relevant connections to such nature of science issues as theory comparison, subjective nature of science, and tentative nature of science.

Another reason why the sickle-cell unit may have been effective at promoting change given the aforementioned tension students often have about seeing the validity of historical ways of thinking is that from the outset students were placed in the role of the scientist working to develop their own account of the “mystery disease” phenomenon. That is, in contrast to having students more passively “read about” historical figures or “read about” the work (or conclusions) that such figures performed, students themselves were put into a more active role of the historical scientist and challenged to develop their own account. Having students actively construct their understanding of the
material may have lessened the tendency for students to immediately criticize or
invalidate historical views; a concern that has been voiced by researchers (e.g., Monk &
Osborne, 1997; Solomon et al., 1992) who have in many respects incorporated more
passive uses of the history of science (e.g., “read about” historical conclusions) in their
own approaches to improve students’ views.

In fairness to the approaches adopted by Monk and Osborne and Solomon et al., a legitimate argument can be made for why having students largely read about the
historical conclusions may be more appropriate when we consider the target audience.
Both of their studies focus on implementing pedagogy to improve younger students’
(middle school) views of science. Another way of looking at this is that the sickle-cell
unit used in the present study adopts a very open-ended, problem-solving approach. As
such, it assumes that the target population of students (college-age) will be comfortable
or adept in learning in such an environment. Younger students likely need more
structure in terms of explicitly drawing their attention to the germane issues that the
historical story exemplifies, whereas the sickle-cell approach places students in the role
of the historical scientist attempting to make sense of what can be at first seen as fairly
problematic data.

Furthermore, it can be argued that designing and implementing “read about”
historical cases or vignettes is less arduous for the teacher. Lessons similar to the sickle-
cell unit require some fairly robust curriculum development work. The teacher would
need not only to be familiar with historical figures and their conclusions, but also
identify and modify (if necessary) the relevant evidence that these figures considered in
order for it to be appropriate for students to examine in a problem-solving context.

Finally, the explicit and reflective techniques that occurred in the unit (both with
respect to facilitating students’ learning of the nature of science and with respect to their
learning of content through the history of science) were aligned with the major tenets of
the conceptual change approach (Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1992). Throughout the unit the explanations that students developed to account for aspects of the disease were periodically challenged by new (discrepant) data that they were given in subsequent classes. Moreover, the way in which subsequent problems situated the new data made investigation of new explanations a fruitful avenue of inquiry as students continued to develop and refine their understanding. This also applied to the manner in which aspects of the nature of science came into play.

Students' antecedent views (e.g., that science is objective or that scientific knowledge is absolute) were challenged when throughout the lesson the instructor periodically gave students probing questions to consider. These probes invited them to connect their conclusions with the problems of the unit to more general nature of science conceptions. Often the answers to these probing questions caused students to reexamine the validity of their earlier views about science in light of their experiences in the unit.

Furthermore, the explicit and reflective techniques of the sickle-cell unit were aligned with researchers (e.g., Beeth & Hewson, 1999) who underscore the need to consider key elements of instruction for facilitating conceptual change. The lessons were designed to address students' antecedent (naïve) views of the nature of science. The lessons incorporated multiple strands of learning (content and epistemology). The instructor modeled inquiry and reflection through challenging students to propose and defend multiple points of view, and there were a variety of instructional strategies (small-group work with the historical data, whole-group discussions, individual diaries) designed to have students learn both science content and relevant informed views of the nature of science.

All of these elements may support why the approaches taken in the unit were relatively effective at promoting change in students' nature of science views. However, as indicated at the outset of this section, at most only 15% of the students showed
significant change linked to the historical material in their views for certain aspects of the nature of science. Moreover, students' views for some of the aspects appeared to be more affected (higher degree of change) than others. The significance of these findings is discussed below in response to the second question that guided the research of this project.

Are Some Nature of Science Views More Apt to Change than Others Using Explicit and Reflective Techniques in a Unit that Emphasizes History of Science?

The findings from this study support that some aspects of the nature of science are more resistant to change than others when students explicitly and reflectively consider them in a unit of instruction developed from the history of science. Two of the five aspects (the validity of observational methods and the subjective nature of science) showed more appreciable change in individual student's view, while one of the aspects (the distinction between theories and laws) showed virtually no change at all. The following paragraphs discuss each of the aspects addressed in this study and analyze the significance of change (or lack thereof).

The Nature of Theories

Caution must be exercised when analyzing the overall significance of students' changed views regarding their understanding of the nature of scientific theories. The reason for this is because in this study the grains of analysis that were used to determine "change" in view were relatively fine, although the researcher did adopt a fairly conservative definition of "change in view." Moreover, the views that students articulated for a definition of a scientific theory fell largely within a somewhat narrow range between very naïve (theories equated with guesses or opinions) to very informed (theories as well-supported, internally consistent sets of explanations). A concern is that
no student was able to articulate in his or her post-view a truly informed understanding of a scientific theory, similar to those defined by other researchers (e.g., Abd-El-Khalick, 1998).

Change in students’ views largely fell into their better being able to explicitly characterize theories as explanations (supported by empirical data). Change also was evident in students indicating the multifaceted ways (experiments, observations, creativity, inference) that data could be collected and used to develop a scientific theory, in contrast to their indicating that theories emerge following rigid experiments or a “scientific method.”

That no student was able to articulate a truly informed view as defined by science educators (e.g., Abd-El-Khalick, 1998) or philosophers of science (e.g., Suppe, 1977) is not too surprising. This is because the explicit and reflective work that students did while participating in the sickle-cell anemia unit had them focus on more provisional theories, akin to explanatory hypotheses in science. In only one lesson of the unit did the instructor of the course ask the students during a whole-group discussion to consider the distinction between their provisional theories and what scientists consider as the more rarefied, robust scientific theories. That is, students were not engaged in much explicit and reflective work per se about the nature of theories (in the rarefied sense) as much as they were in understanding theories in a more introductory sense.

While it is encouraging that several students experienced a change in view that was attributable to the sickle-cell lessons, there are two potential concerns that the data raises. First, despite one facilitated session in which students were asked to consider and discuss the relationship of more provisional theories to those more robust scientific theories, the fact that no student was able to articulate an understanding of a true scientific theory suggests that either the wording of the question on the research survey was not sufficient to tease out students’ views or the unit of instruction was not overly
effective at getting students to internalize the informed conception. Second, another concern is that although the unit did contribute to change in view, it is also possible (and undesired) that the unit solidified students' conceptions of a theory in science as equated with the more provisional ones they developed and refined while in class.

The concerns that are raised here relate more generally to the focus of the unit of instruction with respect to the specificity of the issues that were discussed. The majority of class time was spent having students construct fairly specific explanations to account for fairly specific problems. The degree to which they were explicit and reflective about the nature of science in respect to the specific problems of the sickle-cell anemia phenomenon was quite high. The degree to which they were explicit and reflective about thinking about theories in relation to larger scientific issues (e.g., evolutionary theory, plate tectonics) was relatively low.

The Tentative Nature of Science

It is not surprising that there were few instances of change in view recorded in the present study, because a relatively large number of students (n = 70, 86%) articulated in their pre-instruction instruments that theories are subject to change (modification). Most encouraging is the relatively large number of students (n = 25, 31%) who experienced enrichment in their view of the tentative nature of science directly attributable to their participation in the sickle-cell unit. What this suggests is that in their responses, many students were able to successfully connect a belief in the plausibility of theory change for those more central or "core" scientific theories as given in the survey question with a specific analogy taken from their work in the sickle-cell unit. One reason why this is significant is that it highlights how learning an aspect of the nature of science can be a transferable "construct." That is, many students were able to identify
“theory change” across (at least) two different contexts. This is important because it suggests that students have not simply memorized an understanding.

Caution again must be taken with these findings, because a valid criticism is that the results may support the aforementioned concerns regarding students’ views of scientific theories. That is, the results possibly suggest that students placed their provisional theories (and changes they experienced while working with them) they constructed during their work with the history of the sickle-cell phenomenon on equal epistemological footing with those theories that science educators, philosophers of science, and scientists identify as more informed scientific theories (e.g., theory of evolution).

The Distinction Between Theories and Laws

The unit was virtually ineffective at changing or enriching students’ views of the distinction between scientific theories and scientific laws. The findings are quite consistent with those of recent research (e.g., Abd-El-Khalick & BouJaoude, 1997; Abd-El-Khalick & Lederman, 2000). In their post-instruction instruments, an overwhelming majority of students still held the view that laws are fixed or absolute entities in science, and many articulated a hierarchical relationship between theories and laws.

With respect to the lessons of the sickle-cell unit, there was only one instance (Appendix E, Class #3) in which students were asked to articulate a definition of a law in science and consider the relationship between theories and laws. What is noteworthy is that the instructor (who is also the researcher) departed from an explicit and reflective approach during this session, because students simply were not able to properly define a law in science or discuss any distinction. Therefore, the instructor didactically “told” students the distinction between theories and laws and articulated some of the
similarities and differences between them (e.g., that they are both tentative, that laws are descriptions while theories are explanations). The fact that students were not able to articulate a more informed view on the post-instruments despite the didactic treatment of theories and laws suggests how tremendously robust and resistant to change students’ antecedent understanding of laws can be (Abd-El-Khalick & BouJaoude, 1997; Lederman, 1986; Horner & Rubba, 1978; Rhodes & Schaible, 1989).

It is possible that students’ naïve views for several aspects of the nature of science (e.g., nature of theories, tentative nature of science) are quite affected by their belief that laws are fixed or absolute. Another way of saying this is that the law/theory distinction may in some respects be a keystone set of concepts to have students unpack or develop in order for them to more properly learn the subtleties of theories or the tentative nature of science. In the present study, it is difficult to truly conclude that students have articulated an informed view of the tentative nature of science (by virtue of their post-responses to the second question of the survey) when they still retain the belief that laws are fixed.

The Validity of Observational Methods and The Subjective Nature of Science

Students’ conceptions of these aspects were relatively well affected by their participation in the sickle-cell unit. The most likely reason for this is because their work with the historical data and the conclusions that they developed provided them insight into these aspects, particularly in view that these aspects were emphasized in several classes with targeted probes.

Most noteworthy are students’ improvement of views on the subjective (theory-laden) nature of science. Students’ interaction with the evidence in the unit provided them several opportunities to reflect upon an informed view on this aspect (that the observations or conclusions scientists develop are at least partially affected by a
combination of prior theoretical commitments, educational influences, social or political affiliations, etc.). By virtue of their group work in constructing an understanding to account for various problems, students could identify how their disparate explanations were influenced by their own subjective backgrounds similar to how scientists' who developed the exact same explanations to account for the sickle-cell problems were affected by such subjective factors. The argument here augments those researchers (e.g., Matthews, 1994) who point out that the history of science can help students understand or appreciate the humanistic side of science. The findings of the present study are significant in that they suggest that the history of science can be particularly affective in helping students to understand how subjective factors play an important role in the interpretation of data.

Limitations of the Study

One limitation of the research relates to the degree to which the instructor (who was also the researcher) of the course was consistent in the pedagogy among the four different sections of the course of which the sickle-cell unit was the third (of three) unit. To maximize the consistency of the teaching of the unit, the instructor developed and followed a codified series of lesson plans (Appendix E). This limitation is more germane to ensuring that the population of students (as a whole) received a consistent intervention so that during the analysis of the data, the researcher would have a principled reason to infer whole group changes in nature of science views. However, given that the research also involved identifying individual change in student views of the nature of science, the fact that there were likely different instructional experiences (despite the codification of the lessons) among the four sections does not affect the individual student analysis.
In relation to the follow-up student interviews, a potential limitation is that the researcher did not conduct the actual interviews. As required by the Human Subjects Internal Review Board of the university, the instructor/researcher of the course was not permitted to conduct follow-up interviews with the students for fear of potentially creating a coercive environment. For this reason, the researcher relied upon a collaborator to conduct the follow-up interviews (explained in Chapter 3).

One limitation of the analysis is that the researcher was largely the sole interpreter of students' nature of science views that they articulated on their pre- and post-instruction instruments. This means that the researcher inevitably interpreted students' responses from his own conceptual framework and understanding of the nature of science. As is the case with qualitative research of this kind, there is always the likelihood of bias when reading or coding students' responses.

Because of this concern, the researcher included a description of his background and brief overview of his views of the nature of science in the third chapter of this document. The purpose of this is to give a reader of the research a perspective from which to judge the validity of the researcher's conclusions in light of the evidence that is presented in the fourth chapter. Furthermore, as indicated in the third chapter, the researcher did perform an inter-rater validity test to ensure that an independent authority on conceptions of the nature of science coded students' given views in a manner similar to that done by the researcher. Finally, the researcher performed a blind re-coding of his own results to check that he was being internally consistent with his own coding protocol.

A limitation of the interpretation of the data is the degree to which the results or conclusions from this study are generalizable to a larger population. This research was conducted at a mid-sized Midwestern university of which the majority of students come from within the state. Furthermore, the population of students that were the subject of
the research was very homogenous. That is, the majority of students were white, female, between the ages of 18 to 21 years old, and with modest post-secondary science course experience. Moreover, all of the students in the course that contained the sickle-cell unit were pre-service elementary education majors. Also related to homogeneity is the fact that the sickle-cell unit was taught entirely by the researcher during four different sections of the course. It is possible that the results of this study would be different if another instructor had taught one or more sections of the course.

Also, this research analyzed only five selected aspects of the nature of science. These aspects of the nature of science were chosen because the researcher felt that these aspects were fairly central to understanding how knowledge in science is generated and develops, and the history of research on sickle-cell anemia is particularly effective at helping students to consider these aspects. However, the analyses of this research can not shed much light on students' views for the multitude of issues that fall under the realm of the nature of science that were simply not focused upon during the instructional unit.

Finally, this research only measured the effect of an intervention on students' views in the absence of having a comparison group. A comparison group may have included, for example, having a class in which (to the extent possible) the instruction was identical with the exception that the researcher not employ the explicit and reflective probes to have students on their own connect the content to germane nature of science aspects.

Implications of the Study

The findings of this study suggest that the history of science can be used to improve students' conceptions of certain aspects of the nature of science. However,
curriculum developers need to carefully design and implement the lessons that use the history of science in view of several issues.

The first major issue, as indicated by Abd-El-Khalick & Lederman (2000), is that students often have a difficult time seeing the relevance of historical conclusions or historical ways of thinking for their understanding of contemporary science. The problem is that students often struggle in “putting on the historical thinking cap” necessary to make sense or appreciate the validity of the history of science (Butterfield, 1931, 1957). This phenomenon is also analogous to claims made by philosophers of science (e.g., Kuhn, 1962, 1970) who suggest that scientists operating under one “paradigm” have a difficult time seeing the conceptual merit of scientists who operate (or operated if referring to historical figures) under another paradigm.

Therefore, those wishing to use history of science to teach students science (content and/or epistemology) should be mindful of the aforementioned concerns. To lessen the likelihood that students will immediately dismiss historical conclusions as foolish or misguided, instructors should to the extent possible have students actively work with the historical data so that, qua the historical scientist, they are challenged to themselves develop explanations to account for the data given to them. This approach contrasts with a more passive use of the history of science in which students largely “read about” historical conclusions and/or ways of thinking and are only then asked to draw conclusions in comparison to their antecedent views.

The suggestion that the lessons should have students actively recapitulate the reasoning done by historical scientists more generally underscores that the history of science should form the backbone or foundation of the lesson and in many respects drives the pedagogy of the unit. This is in contrast to using the history of science as an “add-on” to lessons that are primarily content-oriented. The former is more likely to require designing lessons that have students engage with the data taken from the
historical episodes. The latter often (although not necessarily) invites a more passive approach.

This does not necessarily imply that the active approach requires protracted, multi-day lessons as was adopted in this study. Certainly there are advantages of having more time for students to work and reflect on the material if such time is available. This was the case in the present study, and it allowed the researcher to cover a rather large range of conceptual and epistemological issues of science. However, it is conceivable that an instructor could adopt this approach within the confines of a single lesson, with the understanding that he or she would target more narrow objectives with respect to improving students’ understanding of science content and nature of science.30

The second major issue is that this study supports the significance of designing and implementing lessons in which students explicitly and reflectively consider issues of the nature of science in tandem with the history of science that forms the backbone of the lesson. Explicit attention means that any issues of the nature of science germane to the lessons should be planned instructional activities (Akerson, Abd-El-Khalick, & Lederman, 2000; Khishfe & Abd-El-Khalick, 2002). This means that the instructor must be knowledgeable enough about the historical “story” so that he or she recognizes how the historical conclusions or ways of thinking correspond to more general nature of science conclusions. Moreover, the instructor must think through how to have such issues become part of the lesson so that students will confront them.

Furthermore, in order to maximize the likelihood that students will construct (or reconstruct) their own views of any nature of science issues, they must be challenged to achieve their own insights that connect history of science with the nature of science.

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30 Abd-El-Khalick (1999) discusses the use of shorter cases (vignettes) using the history of science to help students understand targeted nature of science issues. Moreover, he underscores the need to have students explicitly consider nature of science in concert with the historical material of the vignette.

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This is in contrast to having students engage with the history of science during the lesson and then having the instructor didactically tell students how their conclusions relate to contemporary or informed nature of science views. The latter has been shown to be relatively ineffective (e.g., Abd-El-Khalick, 1998) at improving students' nature of science conceptions.

The third major issue suggested by this research is to a certain degree related to the need for explicit and reflective pedagogy for improving students' nature of science views. This issue concerns a strategy for designing and implementing techniques to facilitate students' reflection with the history of science and the nature of science. Specifically, instructors should consider incorporating a mechanism analogous to the conceptual change model to facilitate change in students' views.

The conceptual change model (Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1992) recognizes that learners enter the classroom having already constructed personal meaning of conceptual and epistemological understandings of science. Furthermore, these pre-instruction views are very robust and resistant to change. The conceptual change model involves presenting new conceptual material to students that challenges them to see inadequacies with their antecedent views toward constructing a new and more informed understanding. Moreover, the new conceptual material should be intelligible, believable, and pose new areas of inquiry for students to investigate so that they will be more likely to abandon or reconstruct their prior incorrect views.

Aspects of the conceptual change model were incorporated into the explicit and reflective treatment of the nature of science in this study. Students' antecedent views of the nature of science (e.g., that scientists are objective in the analysis of data) were frequently challenged by a particular reflective mechanism that involved using nature of science probes. The probes required students to connect their work or conclusions with the historical material to a general understanding or interpretation of some nature of
Also significant was that the instructor of the course used several different techniques to facilitate students' reflective work with the nature of science probes. On one hand, students worked in collaborative groups to solve various “problems” of the sickle-cell phenomenon. Each group was given probes to discuss among themselves. Students were also asked to individually reflect on various nature of science probes each day as a part of their diary entries. The instructor also facilitated whole-group discussions in which student groups shared each other’s ideas regarding the conclusions they drew with the sickle-cell problems and their insights into the probing questions. The implication is that instructors who wish to use the conceptual change model to facilitate reflective change in students’ nature of science views should also incorporate varied instructional techniques (Beeth & Hewson, 1999) to help facilitate such change.

Recommendations for Future Research

As discussed at the beginning of this chapter, there have been very few studies that have empirically examined the effect of using lessons involving the history of science on college students’ views of the nature of science. This is particularly the case for the specific subset (pre-service elementary education teachers) examined in the present study. The validity of the present study would be enhanced with additional empirical research that examines similar pedagogical techniques (students’ explicit and reflective work) applied to different lessons developed from the history of science.

Furthermore, the findings of the present study would be strengthened if subsequent research employed a comparison group. This means that one or more
sections of the course would act as a group to be compared against those sections identified as the intervention group. Ideally, the comparison group would participate in all aspects of the sickle-cell unit in a manner similar to the intervention group except that the comparison students would not be given explicit probes for them to reflectively consider during their group work and daily diaries.

Also recommended is a longitudinal analysis of those students who exhibited a change or enrichment in their nature of science views attributable to their explicit and reflective work with the material. The purpose of this would be to examine the degree to which students’ more informed conceptions (as revealed in their post-instruction assessment) remain fixed as a part of their understanding of science. Empirical research that has examined students’ longitudinal views (e.g., Clough, 1995) finds that changes in students’ views are short-lived. That is, students who exhibit more informed nature of science conceptions following a unit of instruction generally revert to more naïve views several months following the instruction.

Moreover, it would be interesting to examine if students continue to refer to aspects of their work from the unit (e.g., sickle-cell) as support of their informed views or if students use different examples as support. On the one hand, it would be noteworthy if several months after the unit of instruction students were able to give valid and specific examples from the sickle-cell unit to support their informed views. This would speak to the power of the unit in affecting students’ views. On the other hand, it would be interesting to see if students would be able to give a different, yet equally valid example to support their (still) informed view. This would speak to the ability of students to transfer an understanding of the nature of science to a context different from that given in the respective survey question and from their experiences in the sickle-cell unit.
Finally, the pedagogy used in the present study suggests that students engage in a social construction of their views of the nature of science. A significant part of students' experiences during the sickle-cell unit involved group work in which members collectively examined data toward developing explanations to account for the various problems. The members were also given probes that invited them to discuss their work with the sickle-cell data in connection to certain more general nature of science conceptions. This method suggests that students may engage in a social construction (Cobb, 1999) of their nature of science views in which may they negotiate "taken as shared" meanings for the connections between their conclusions with the sickle-cell data and more informed views of any germane nature of science conceptions. An interesting line of research would involve examining students' group work to see specifically how they (as a social unit) interact with the conceptual material and the nature of science probes. This research would likely involve videotaping students' work and analyzing the transcripts of the videos in conjunction with the artifacts that the students use.
Appendix A

Reform Emphases in the Nature of Science
Below is a summary of the central nature of science issues promoted in two major science education reform documents (AAAS, 1990, 1993; National Research Council, 1996). Note that the order of their listing is not indicative of relative importance:

1. Science is a “way of thinking” that involves developing explanations and descriptions to account for phenomenon. The validity of these things is predicated on the amount and character of supportive evidence. Science is distinct from other ways of knowing about the world.

2. Science is largely an empirical discipline. This means that science involves making observations about the natural world.

3. Theories are central in the development of scientific knowledge. Theories serve as explanations to account for various phenomena in science.

4. Scientists follow several investigative methods when engaged in the processes of science. This includes, for example conducting controlled, manipulative experiments and making observations and inferences.

5. Replication is an important part of scientific experimentation.

6. Scientific knowledge is subjective (theory-laden). This means that what scientists observe is influenced by their prior theoretical commitment, social and political affiliations, values, educational experiences, and so on.

7. Science is infused with ethical dimensions.

8. Science is infused with historical perspective.

9. Criticism, review, and communication are part of the process of the development of scientific knowledge.

10. Science involves creativity. Scientists often rely upon creativity in their interpretation of scientific data.

11. Scientific knowledge is tentative. This means that facts, theories, and laws are subject to potential change (modification or abandonment).
Appendix B

The Pre/Post Survey Instrument
1. Often in science, we hear words like “theories” used to describe scientific knowledge.
   (a) What is a theory?
   (b) How are theories developed?
   (c) Can you give an example of a scientific theory?

2. After scientists have developed a theory (e.g., atomic theory, theory of evolution), does the theory ever change?

   If you believe that scientific theories do not change:
   (a) Explain why theories do not change.
   (b) Defend your answer with examples.

   If you believe that scientific theories do change:
   (a) Explain why (and how) you think theories change?
   (b) Give an example from your experience in which a theory has changed.

3. Is there a difference between a scientific theory and a scientific law?
   Illustrate your answer with an example.

4. Scientists often conduct experiments to gather data. In general, an experiment is a controlled intervention that involves manipulating something of interest by holding certain things constant and varying others.

   Does the development of scientific knowledge require scientists to do experiments?
   (a) If yes, explain why, and give an example to defend your position.
   (b) If no, explain why, and give an example to defend your position.

5. It is believed that about 65 million years ago the dinosaurs became extinct. Of the reasons formulated by scientists to explain the extinction, two enjoy wide support. The first, formulated by one group of scientists, suggests that a huge meteorite hit the earth 65 million years ago and led to a series of events that caused the extinction. The second explanation, formulated by another group of scientists, suggests that massive and violent volcanic eruption were responsible for the extinction.

   (a) How are these different conclusions possible if all of these scientists have access to and use the same set of data to derive their conclusions?
   Defend your answer.
Date: June 10, 2002

To: David Rudge, Principal Investigator
    Eric Howe, Student Investigator for dissertation
    Uric Geer, Student Investigator

From: Mary Lagerwey, Chair

Re: HSIRB Project Number: 02-05-12

This letter will serve as confirmation that your research project entitled “SCI 270 NOS Research” has been approved under the expedited category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: June 10, 2003
Project Description

Purpose

The purpose of this research is to assess the effect of a particular method of teaching & learning (using history and philosophy of science) on students’ conceptions of the nature of science/biology. The research group will consist of willing students who are taking the course BIOS 270, Life Science for Elementary Educators II.

Procedure and Research design

BIOS 270 is a course offered to preservice elementary education majors at Western Michigan University. The course consists of three units of instruction, including genetics, molecular and cellular biology, and a capstone unit that focuses on a single biological disease (sickle-cell anemia). Each unit comprises an equal third of the course. The dissertation research will focus upon the capstone unit (the final third of the course). Note: The student investigator (Eric Howe) will be the instructor for all sections of the course that are to be offered during the project timeline.

At the beginning of the course, an independent agent (i.e. not associated with the course) will give the class a brief overview of the research that will be done during the third unit of the course (see BIOS 270 Recruitment/Consent Script). He will then read over the consent form to the students and have those students who agree to participate in the research sign the consent form.

At the start of the first class of the third unit of the course, the independent agent will administer to those students who have consented to participate in the research an open-ended pre-instruction survey (see instrumentation) which is designed to assess their level of understanding of certain aspects of the nature of science. Following this initial assessment, students will be exposed to a series of classes (the final eight classes in the current BIOS 270 course) that emphasize a subdisciplinary (e.g., ecology, molecular biology, genetics) examination of the disease sickle-cell anemia. These eight classes incorporate connected historical episodes about this disease. The goal is that through using an historical approach, students will improve their understanding of certain aspects of the nature of science / nature of biology. At the end of the final class, the independent agent will administer to students an identical version of the assessment survey (now termed “post-test”). Both the pre- and post-tests will be administered in the classroom and will require approximately 40 minutes to complete. The student investigator (Eric Howe) will perform analyses on the pre- and post-surveys to both categorize student conceptions of the nature of science issues covered in the survey and to look for relevant changes in those conceptualizations.

A percentage of the students (approximately 40%) who agree to participate in the study will additionally be selected to participate in a semi-structured interview
about their responses to the survey. At the beginning of the third unit, half of the students (again, those who have agreed to participate in the research study) will be randomly selected to be in the “interview pool.” From this initial pool, the interviewees will again be randomly assigned to participate in one of two interview groups. The first group will be interviewed about their responses from the pre-test survey. The second group will be interviewed about their responses to the post-test survey. For example, in a class of 24 students (assuming all 24 consent to participate in the study) 12 students will be randomly selected to be interviewed. From this initial group of 12, 6 will be randomly selected as “pre survey” interviewees, and the other 6 will be randomly selected as “post survey” interviewees.

To arrange for the interview, students will be contacted via telephone by the independent collaborator (the number will be provided by the course instructor). A script of this “interview contact” is attached (see BIOS 270 Interview Recruitment Script). If a student wishes not to participate in the interview, the researcher will randomly draw another name from the respective group to fill the sample. General Note: Recall that from the initial contact at the beginning of the class, students are told by the independent agent that there is a possibility that they will be requested to participate in an interview.

The interviewer will ask questions related to the answers that students provide to either their pre or post surveys. A script of the interview is attached (see BIOS 270 NOS Research: Interview Script). The purpose for the interview is two-fold. First, results of the interviews will be used to validate the students’ answers to the survey, thereby allowing insight into the construct validity of the survey itself. Second, the survey will be used to further interpret potential survey responses that were ambiguous. As done with the pre- and post- surveys, an independent agent will be used to administer the interviews. The purpose of using an independent agent is to minimize feelings of coercion on the part of students. The interviews will be scheduled to occur in the same location that the survey was administered. Should the room be unavailable, the interviews will occur in a private library used by the faculty and graduate students of the Mallinson Institute for Science Education.

Two other data sources will be used for the research:

*Videotape (Transcripts).* Throughout the entire course, students commonly engage in group work of approximately 3-4 students per group. The composition of the groups generally remains constant for the duration of the course. The student investigator will identify a representative group prior to the start of the third unit. During the third unit, this group will be videotaped as they engage in group problem solving activities. As indicated in the initial presentation at the start of the class by the independent agent and as indicated in the consent form, students will be made aware at the onset of the class that there is
a potential for their being videotaped. Furthermore, students will be made aware that the videotapes will not be viewed in any fashion until after their grades have been submitted.

**Student Diary Entries.** During the third unit, students are required to keep a daily diary of their experiences that they have exploring the sickle-cell disease. The instructor of the course provides them with daily “seed” questions which are designed to elicit their interpretation of the pedagogy that is being used. The diaries are collected at the end of the unit and constitute approximately 1/2 of the total grade for the unit. The instructor will assign a grade to the student diaries and put them aside until after final grades have been submitted. Then, the student investigator will use the diaries to examine how students have interacted with the historical material toward constructing their understanding of the nature of science.

**Videotaping Protocol**

Throughout the entire course, BIOS 270, students frequently engage in group work activities. The groups generally consist of three to four students and involve having them solve biological problems. Groups are normally separated spatially from one another by several feet.

During the second unit of the course, the instructor will identify a group (i.e. a group in which the quality of the discourse is high). The instructor will confirm that the potential group members have agreed to be part of the overall research (i.e. confirm that they have signed the initial consent form). Following this, the instructor will indicate to the members that their problem solving efforts as a group will be videotaped. The instructor will reiterate to the members what was originally stated in the consent form. That is, the members will be told that they have the option of electing not to be videotaped. The instructor will also indicate to the group members that the videotapes will not be viewed until after grades have been submitted for the course.

The camera will be set as discreetly as possible a short distance away from the group, with the lens pointed downward at a steep angle so that the image captured will be essentially the members’ heads and the common workspace among them. Rather than rely upon the microphone from the video camera which captures undesirable ambient noise, a special microphone will be placed discreetly on the table next to the group members.
The camera will be left on while students do their group problem solving. When this is completed, the instructor will turn off the camera at a noninvasive time. Each day thereafter during the second unit, the instructor will periodically videotape the work of this representative group.

There is a specific reason why videotaping is to begin during the second unit of the course rather than during the third unit of the course (when data is to be collected for the purposes of the student investigator’s dissertation). The purpose for beginning videotaping during the second unit is to acclimatize the group to being videotaped. This way, during the third unit, when the instructor will again videotape the same group as they engage with the research problems, the group members will already be used to the camera and as such will act more normally.

In summary, the data sources are 1) Pre & post survey responses, 2) interview transcripts of student responses to the surveys, 3) transcribed videotapes of representative student group work, 4) student daily diary entries. All of these data sources will be used for Eric Howe’s dissertation research.

Location

The administration of the surveys, the follow-up interviews, and the 8-class unit will occur in 1337 Wood Hall, the regular classroom for BIOS 270. Duration: BIOS 270 meets twice during the Fall 2002 and Winter 2003 terms. Each class of BIOS 270 enrolls approximately 24 students.

Benefits of Research

To the participants: While participating per se will not benefit the individuals, the information gained by this research will be used in the modification and improvement of the course taken by later participants.

Recruitment

All students enrolled in BIOS 270 will be potential participants in the study. No outside recruitment will occur. Students will be given the option of whether or not to participate in the research. Should students excuse themselves from participating, they will be provided the option of moving to an adjacent (and private) laboratory room while the remainder of the class completes the survey. As this laboratory has several computer terminals (with internet connections), those students who elect not to participate in the survey may spend the duration (approximately 40 minutes) checking e-mail, doing course homework, etc.
At this time, there is no plan to offer extra credit or other compensation for participation in the research. The participants will be informed that the research results will be used to better the classroom teaching of science education, in general.

Those students who elect not to participate will in no way compromise their performance in the class.

**Risks to Subjects**

The risks include: Perceived discomfort at having to participate in “extra work” and potential sensitivity of disclosure of the assessment results (although the intent of the researcher is to maintain privacy/confidentiality).

**Protection to Subjects**

The researcher will maintain the confidentiality of the results in a secured location. The results will be secured in a stored and locked cabinet in the principal investigator’s office (or located proximally to the P.I.’s office) for at least three (3) years and then destroyed. The researcher is not (relatively) concerned with the risk of student discomfort as the students will have the choice not to participate. Testing, as a matter of course, is generally recognized as a discomforting process.

**Confidentiality**

The results of the survey(s) or the interviews are not anticipated to be sensitive in nature. However, the researchers will maintain strict adherence to confidential protocol. Prior to administering the survey, the researcher (not the instructor of the course) will be given a role sheet of the class participants. That particular class will be designated an identifier commiserate with the season/year/code. The “code” is to be used if there is more than one section of the course being taught during that given semester. The researcher will alphabetize the list of students (likely this is done on the role sheet) and give them numbers (again on the role). For example, Jane Doe may be the fourth student on the list for the Fall semester of 2002. Her designator would be F02-04. “John Smith”, the 18th student in the Winter or 2003 would be W03-18. If there is more than one section in a given semester (e.g., on Tuesdays/Thursdays there are two sections) the first section will be denoted “A” and the second “B.” From above, “Jane Doe” in section A would be F02A-04.

When the independent agent is used to either administer the pre/post tests or to perform follow up interviews, the independent agent will be responsible for creating the code numbers in accordance with the above protocol.
The principal investigator will store the results from the assessment tools and interviews in a locked cabinet in the principal investigator's office (or proximal location) for a period of at least three years.

**Instruments**

An abbreviated version of the survey is attached. In the full version of the survey, the six questions will be individually separated such that they occur on an individual page.

Each of the questions on the survey addresses a particular topic of the nature of science/biology. Broadly construed, student answers to the questions will generally fall into either a "traditional" view of the nature of science (with respect to a particular question) or a "modern" view. The student investigator will be responsible for interpreting student answers and categorizing them as such.

**Consent Form**

Attached
I have been invited to participate in a research project entitled, BIOS 270 NOS Research. This research is intended to study student perceptions of the nature of science/biology. This project is a part of Eric Howe's (a PhD candidate in the Mallinson Institute for Science Education) dissertation work.

Near the end of the course, I will be asked to respond to a survey that will require me to provide my answers to various questions. I may also be asked to participate in a follow up interview so that the researcher can gain additional information about my responses. There is also a possibility that my group work will be videotaped during this course or that some of the materials I submit will be evaluated for research purposes. The results from this research will in no way be used in the evaluation of my performance as a student of BIOS 270. In fact, the analysis of any data will be done after submission of grades for the course.

As in all research, there may be unforeseen risks to the participant. If an accidental injury occurs, appropriate emergency measures will be taken; however, no compensation or additional treatment will be made available to the subject except as otherwise stated in this consent form.

One way in which I may indirectly benefit from this activity is in knowing that the answers I provide may be used to better the teaching and learning approaches in biology. The research tool may also benefit my understanding of the nature of science/biology - topics deemed worthy by the national standards.

All of the information collected from me is confidential. That means that my name will not appear on any papers on which this information is recorded. The forms will all be coded, and the researcher will keep a separate master list with the names of participants and the corresponding code numbers. Once the data are collected and analyzed, the master list will be destroyed. All other forms will be retained for three years in a secure location in the principal investigator's office.

I may refuse to participate or quit at any time during the study without prejudice or penalty to my grade in this course. If I have any questions or concerns about this study, I may contact either Eric Howe at 387-5398 or David Rudge at 387-5398. I may also contact the chair of Human Subjects Institutional Review Board at 387-8293 or the vice president for research at 387-8298 with any concerns that I have.

This consent document has been approved for use for one year by the Human Subjects Institutional Review Board as indicated by the stamped date and signature of the board chair in the upper right corner. Subjects should not sign this document if the corner does not have a stamped date and signature.

My signature below indicates that I have read and/or had explained to me the purpose and requirements of the study and that I agree to participate.

_________________________  ______________________
Signature                        Date

Consent obtained by:  ______________________
initials of researcher

_________________________  ______________________
Date

Signature  Date
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BIOS 270 Recruitment/Consent Script

[Note: This will be administered by the independent agent]

Good (Morning/Afternoon/Evening). My name is _________________, and I’m here to facilitate a research project for the next 40 minutes.

During the final unit of this course, you will be asked to participate in research from which the results will be used to improve the teaching and learning of biology. We hope that you will elect to participate.

1. Your participation is entirely voluntary and will have no effect (positive or negative) upon your performance (i.e. grade) in this class. I will be coding your names so that you remain anonymous.

2. The research will involve having you fill out a brief survey about your thoughts of aspects of the nature of science. Some of you may also be asked to participate in a short interview about your responses. Additionally, some of you may be videotaped during your group work in this final unit of the course. Again, all aspects of the research will be anonymous, will not affect your grade, and will require minimal time on your part.

3. If you elect to participate, I have a brief consent form that I will now pass out to you.

4. [pass out consent form and read it aloud]. [Recollect signed forms]

At the beginning of the third unit of this course, I will return to administer the survey.
Survey Administration Script

[Note: This will be administered by the independent agent]

Good (Morning/Afternoon/Evening). My name is _______________. If you recall, at the beginning of class you were asked to participate in a research project about improving the teaching and learning of science. For those of you who elected to participate, I have a brief survey to have you complete.

5. Now I will pass out a survey to you. There are six questions. Please take your time and be thorough. [pass out survey to each student]. When you are finished, you may bring the completed survey to me.

6. [recollect finished surveys as students complete them. Ensure that the students have put their names on the surveys]

Thank you for participating. Some of you will be randomly selected to participate in a follow up interview. While this won’t require much of your time, your participation again is voluntary. This interviews will take place in this room at a time that is convenient for you. If selected, you will be contacted by phone for the interview.
BIOS 270 NOS Research: Interview Script

[Note: This will be administered by the independent agent]

“Good (Morning/Afternoon/Evening) __________. Thanks for agreeing to participate in this follow up interview about your responses to the survey that you completed recently. I am going to ask you a series of questions about your responses to the items on the survey.

Before we begin, you should be aware that I will be audio taping this interview [show the subject the tape recorder and microphone]. The purpose of the audio tape is so that I can later transcribe our interview such that I can think more clearly about your responses. You should also know that the audiotape will be kept secure and confidential. Finally, the results from this interview will in no way affect your grade/performance in your class.

Do you have any questions before we begin?

1. For both the Pre- and Post- Interviews:

   Review each question of the survey with the student.

   a) For each survey question, first read aloud the question to the student.
   b) Then have the students read their responses (from their pre- or post-surveys) that pertain to each question.
   c) For each question, ask the students if there was anything unclear in the wording of the question.
   d) For each question, probe for student uses of ambiguous wording or areas that need further explanation.

2. For the post interview:

   For those questions in which students' answers between the pre- and post- surveys are substantially different (e.g. going from a traditional to a contemporary view of a nature of science question) the following three questions should be asked:

   a) “When did you first learn/believe the answer you wrote?”
   b) “Did you always believe this?”
   c) “What caused you to change your belief?”

   “We're all finished here __________. Is there anything else you’d like to add before I turn off the tape?” [turn off tape] “Thanks again for helping out. If you have any further questions, I can be reached in Wood Hall on the Third Floor in the Institute for Science Education.”
Appendix D

Pedagogical Detail of the Sickle-cell Unit
General Method of Using the History of Sickle-Cell Anemia

The lesson plans for the unit were developed from aspects of the historical research done to understand the disease sickle-cell anemia. The researcher was aware that the disease has been understood from several distinct subdisciplinary perspectives in biology. Thus, the approach taken toward developing a unit of instruction included identifying the major research “problems” associated with these subdisciplines. This identification was greatly facilitated by collecting and reading the primary research articles and then considering which aspects of the disease would be most germane to develop into the lesson plans. The general flow of the selected historical events is given in Table 24. These seven events in the history of research on sickle-cell anemia form the basis of the first seven classes (the eighth class of the unit serves as a review).

Throughout the eight-class unit, students recapitulated the historical research by way of problem-solving activities. The problems were based upon issues largely associated with a focal understanding of the disease from the perspective of the particular subdiscipline being studied in a daily class. A summary of these daily problems is also given in Table 24. As such, the lessons followed the general temporal development of the understanding of the disease. Though students' overall goal was to identify the mystery disease as sickle-cell anemia, each class presented historical evidence for them to consider toward understanding some aspect of the subdisciplinary problems they were working to solve.

An advantage of emphasizing a problem-solving approach, in contrast to other uses of history, is that the students “do science” by way of actively engaging with different facets of the disease over an extended time period to construct their own rich understanding. They examined evidence, developed explanations, and discussed the conceptual merits of those explanations. All of this occurred in the context of a
Table 24

Historical Bases of the Daily Classes of the Lesson Plan

<table>
<thead>
<tr>
<th>Class</th>
<th>Year(s)</th>
<th>Description</th>
<th>Class &quot;Problem&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1910</td>
<td>Dr. Jim Herrick first encounters and diagnoses the mystery patient.</td>
<td>Examine histology slides and cellular models to explain symptoms of mystery patient.</td>
</tr>
<tr>
<td>2</td>
<td>1923</td>
<td>Using the Emmel Test (<em>in-vitro</em> test) to identify sicklers from non-sicklers, Drs. Taliaferro &amp; Huck propose the Dominance model of inheritance of the disease from pedigree information they have collected.</td>
<td>Examine pedigree data developed from results of Emmel test.</td>
</tr>
<tr>
<td>3</td>
<td>1949</td>
<td>Dr. Jim Neel resolves the distinction between full sicklers and heterozygotes by way of new pedigree information.</td>
<td>Examine pedigree data developed from results of <em>in-vitro</em> and <em>in-vivo</em> tests.</td>
</tr>
<tr>
<td>4</td>
<td>late-1940’s to mid-1950’s</td>
<td>Hematology work in East Africa uncovers high frequencies of carriers for the sickle-cell disease. Several initial theories are developed.</td>
<td>Examine ethnographic and geographic data from Uganda to explain the high frequencies of sickle-cell heterozygotes.</td>
</tr>
<tr>
<td>5</td>
<td>mid-1940’s to mid-1950’s</td>
<td>Parasitology work in East Africa also examines the distribution of the disease malaria.</td>
<td>Examine Plasmodium falciparum lifecycle and propose mechanism of inhibiting its growth and development.</td>
</tr>
<tr>
<td>6</td>
<td>1952 – 1954</td>
<td>Dr. Anthony C. Allison proposes theory of heterozygote protection of sickle-cell carriers to the malarial parasite.</td>
<td>Consider how malarial data affects students' earlier explanations for heterozygote frequencies in Uganda.</td>
</tr>
<tr>
<td>7</td>
<td>1957</td>
<td>Dr. Vernon Ingram sequences the peptides of hemoglobin and determines the molecular difference between normal and mutated forms.</td>
<td>Examine DNA fragments for hemoglobin proteins from electrophoresis.</td>
</tr>
</tbody>
</table>

devolving historical story. This type of approach was advocated by Rutherford (1964), “using the historical work of several scientists in the context of explaining a central
problem (versus concentrating upon the work of a single scientist or to settle for some abstract formulation of inquiry divorced from content),” (p. 82).

Furthermore, the problems that students were working on in each class were not disconnected from one another. Rather, a strength of these historical problems is that there are relevant links among the classes such that students frequently were required to consider how the facts and theories they were examining (or developing) in one class had potential bearings on aspects in other classes. For example, the issues students considered after having examined problems in the ecology class (Class #5) had ramifications for their understanding of the evolution of the frequency of the sickle-cell gene (Classes #4 & #6). In short, students were required to construct their learning by way of considering how their own conceptual understanding of the subdisciplinary issues were linked.

Finally, the use of history was explicit. What this means is that students were made aware that they were recapitulating the understanding of historical aspects of the disease, rather than merely having history form the underlying basis of the problems that students were working on. Moreover, when aspects of the nature of science were germane to a given daily lesson, the instructor facilitated the lesson by having students explicitly consider how the historical aspects helped inform (or inhibit) a contemporary understanding of the nature of science.

General Pedagogical Approach

For each of the classes in the unit, two general pedagogical approaches were used in order to maximize students' experiences as they interacted with the historical content. These two approaches involved a combination of problem solving and group discourse. This combination was used to facilitate the classroom dynamic in which
students "do science" by way of examining evidence, constructing explanations for that evidence, and discussing the merits of those explanations with fellow classmates.

The problem-solving aspect was multifaceted. First, there was the overall goal students were challenged to consider during the initial class when they were introduced to the "mystery patient." The goal was for them to discover what ailed the mystery patient and furthermore to consider how their explorations in the subsequent classes connected to this overall goal. Second, there were more specific problems that formed the bases for student explorations in each of the subdisciplinary classes. The general format was that students were given historical data relevant to the line of inquiry for a given class and were challenged to consider how a biologist from within that subdiscipline would form an explanation to account for the data. Furthermore, an important feature was that the problems among the classes were linked. In examining the data from a particular class, students often were required to consider how their understanding of the disease from another class played a role in framing their current explanation.

Problem solving was done in a small-group format. Generally, the instructor provided a brief historical overview at the beginning of the class and set the context for the problem(s) that students considered during the class. Following this, students assembled into small groups of 3-4 students per group and worked on examining the data in the context of the given problem. In several of the classes, the instructor interrupted the group work either to give the groups supplemental data for them to incorporate into their work or to have the groups discuss their ongoing work in a class forum.

Used in tandem with problem solving, group discourse played a significant role in each of the classes. Part of the experience in “doing science” was predicated on having students construct and defend their explanations based upon their interpretations.
of the historical data. Moreover, for several of the group sessions, the instructor provided each group with a few probing questions for them to consider (Table 25). These questions encouraged students to connect their developing understanding of the sickle-cell disease to those germane aspects of the nature of science that were potentially represented by the conclusions that the group members reached in response to the daily problem.

Table 25

NOS Questions Given During the Daily Group Problems

<table>
<thead>
<tr>
<th>Class</th>
<th>&quot;Problems&quot; Examined</th>
<th>NOS Probes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Examine pedigree data developed from results of Emmel test. Attempt to construct inheritance models.</td>
<td>Suppose that another group of students proposes a different theory to explain the genetics of the mystery disease. How would scientists value (determine) which theory is more valid?</td>
</tr>
</tbody>
</table>
| 3     | Examine pedigree data developed from results of in-vivo test. Revise earlier inheritance models. | • Was your theory (simple dominance) that you developed last class based upon the pedigree data from last class (1923 data) "wrong"?  
• After today’s problem, do you have a new theory to explain the genetics?  
• If yes, what (specifically) led to your new theory? |
| 4     | Examine ethnographic and geographic data from Uganda to explain the high frequencies of sickle-cell heterozygotes. | • As "scientists" you all have access to similar data for the Uganda Problem. Do you think that you will all come to the same theory to explain the unusually high frequencies? Why or why not? |
| 6     | Consider how malarial data affects students' earlier explanations for heterozygote frequencies in Uganda. | • Is it troubling to you that you are basing your explanations for the high frequencies of the mystery disease on data derived from observation rather than the results from scientific experimentation?  
• Do you think experiments are necessary for knowledge to develop in science?  
• Has your theory to explain the high frequencies changed? What caused you to change? |
Following the small group activity, the instructor reassembled the entire class for a whole-group discussion. Here, the instructor acted as a facilitator by way of encouraging members from each of the individual groups to present their findings and to have students from other groups provide comments. The idea was to foster an environment in which students were comfortable with the notion that part of doing science involved the sharing and critiquing of each others' ideas.

At the same time, during the whole-class discussions the instructor used various probing techniques to have students share their insights of aspects of the nature of science that were germane to the conceptual issues they were exploring in the context of a given session. Often this involved having students elaborate to the class how were addressed the probing questions they were given while in their groups. Here, they were challenged to explicitly connect aspects of their developing understanding of the disease with various epistemological aspects of science (e.g., how theories are constructed, whether and how theories are evaluated, how knowledge is tentative, etc.). Again, the goal was to link their understanding of aspects of the nature of science to their own problem-solving work.

Group discussions also focused on how the conceptual issues addressed in each of the subdisciplinary classes were linked. The instructor may have, for example, challenged students to verbalize how their understanding of the disease from a genetic perspective was linked to aspects of the cellular or physiological anatomy. The idea was to impress upon students the interconnected nature of the biological subdisciplines and to explicitly develop their own conceptual schema of the disease.

Student Journals

During the sickle-cell unit, students were also required to keep a daily journal of the activities that they did in each class. As a part of this journal, students were
instructed to be reflective about how their learning impacted their understanding of the nature of science. At the beginning of each of the class periods during the unit, the instructor placed one or two “seed” questions on the board for students to consider when they engaged in the daily activities and when they wrote in their journals. These questions often directly related to the specific nature of science aspects that were the focus of this study. Appendix F contains a list of the seed questions given to the students at the start of each class.

Pedagogy for Each Class of the Unit

The unit was designed to accommodate approximately 20 students, although it is conceivable that groups as small as eight or as large as 30 would be feasible. As with most classes in which group interaction plays an important role, larger classes severely limit the communication among groups and/or between the instructor. As such, it becomes difficult to facilitate the intended open-ended nature of the classes.

The unit consists of eight classes, requiring approximately 2 hours per class period. Each class is devoted to examining the disease sickle-cell anemia from the perspective of a particular subdiscipline of biology (e.g. histology, physiology, genetics, etc.). Much of this work is quite open ended, with the instructor acting as a facilitator both with respect to guiding the students’ inquiry of their (current) explorations and with respect to asking probing questions that set up potential links to issues the students have considered in prior classes or will examine in subsequent ones. Furthermore, when aspects of the nature of science are exemplified by issues that students are exploring in the context of the classes, there are two ways in which the instructor facilitates students to consider the relevance of their work to more general insights into the nature of science. First, as students work in groups during each class to solve various problems associated with understanding the mystery disease, the instructor provides each group
with a few probing questions to consider. These questions (see Appendix G) invite students to talk among each other about the connection between their context specific work to one or more targeted aspects of the nature of science. Second, following their group work, the instructor facilitates a whole-class discussion in which he/she asks students (in the whole-group forum) to talk about their responses to the probing questions. In this manner, the instructor facilitates more explicit discussions about the nature of science that invite students to share the insights they have learned as a result of their experiences with the activities of the class.

Class #1 - The Mystery Patient\textsuperscript{31} Cellular and Physiological Perspective

The instructor introduces the unit by way of indicating to students that they will be examining a "mystery disease\textsuperscript{32} over the course of the following eight class periods. Prior to beginning the exploration, the instructor reviews the unit objectives to familiarize students with the goals of the unit and the methods by which students will be evaluated. Specifically, the instructor emphasizes to the students that they will be examining the mystery disease from an historical perspective with one goal being that they should consider how the historical examination affects their understanding of aspects of the nature of science.\textsuperscript{33}

The instructor then draws attention to a particular aspect of the nature of biology. Here, students are reacquainted with reductionist and holistic approaches to understanding a biological phenomenon by way of a short lecture, a brief reading, and a whole-group discussion facilitated by the instructor. The purpose for this discussion is

\textsuperscript{31} The mystery patient suffers from the disease of sickle-cell anemia. To maintain the enigma of the disease throughout the eight classes, the instructor and the class materials refer to the disorder as the mystery disease, or some synonym.

\textsuperscript{32} Credit should be given to the case-method approach of DeRosa & Wolfe (1999). Although the pedagogical approaches and goals are substantially different, certain aspects of the sickle-cell unit were adapted from their writings.
to explicitly draw students' attention to the methodological and conceptual ways in which biological phenomena can be explored such that they consider these issues when examining the "mystery disease" from the subsequent subdisciplinary perspectives in the eight classes.

The instructor then passes out to students a copy of symptoms of a patient described by the physician James Herrick in 1910. Students are encouraged to read the symptoms and are given the overall objective that they develop an understanding of this "mystery disease" throughout the remaining classes. As a means of motivating the exploration, the instructor invites students to propose various lines of inquiry that they feel would shed light on helping to understand the curious symptoms. This process inevitably results in one or two students suggesting that a possible avenue of exploration might involve examining the patient's blood.

Student groups$^{34}$ are then given histology slides of both a healthy patient's blood smear and the smear from the mystery patient. After giving them sufficient time to make observations through microscopy, the groups are encouraged to make inferences that connect the structural abnormalities of what they view in the slides of the mystery patient with the symptoms that the patient suffers.

To augment their microscopy work, the instructor provides to each group a cellular/physiological model consisting of red clay simulations of both normal and crescent shaped erythrocytes and adjustable tubes that mimic the interior of an example blood vessel. Through manipulating the size of the vessel and through experimenting with different ratios of normal to abnormal cells, students gain insight that certain conditions increase the likelihood of clotting (e.g. when aberrant erythrocytes become

$^{33}$ The unit objectives are given at the beginning of Appendix E.

$^{34}$ Throughout the unit, students often work in groups of between 2 - 3 students per group.
stuck in the small passages). Again, during this work, groups are encouraged to infer how structural abnormalities may contribute to the physiological symptoms.

After giving groups sufficient time to examine the histology slides and cellular models, the instructor has the class reconvene. He then facilitates several discussions. First, students are asked to connect what they observed in their cellular examination with the various physiological symptoms of the mystery patient. The idea here is to have students begin the process of constructing provisional theories by way of having them consider how the evidence they are examining shapes their explanations. For example, students may discover through manipulating the cellular models that the crescent shaped red blood cells of the mystery patient have a higher likelihood of becoming stuck when the students make the passages of the vessels smaller (as would be found in the capillaries). This bit of evidence may be used as support to account for the patient's suffering from periodic pain in the joints.

Following this, the instructor transitions the specific discussions about the mystery patient into more general discussions about the nature of scientific theories. Here, the instructor uses the introductory explorations and discussions to have students consider fundamental aspects of scientific theories, for example the distinction between theories and predictions, that theories are made more robust by the amount and character of supportive evidence, and that there are different “levels” of scientific theories.\textsuperscript{35}

Invariably, the activities of the initial class influence students to suggest that one potential avenue of research would be to investigate whether or not the patient’s family

\textsuperscript{35} By different levels, it means that students should understand that all theories are not on equal footing. The theory of evolution, for example, is a central or core theory of biology that is well substantiated and has withstood numerous attempts of refutation. These central or core theories are epistemologically different from the introductory explanations or provisional theories that students construct during the course of their investigations.
members suffer from the same disease. This line of inquiry nicely sets up the next class on genetics.

**Class #2 - Genetics I**

In this class students consider how genetics provides insight to their question about potential inheritance of the disease from the first class. After facilitating a review of Mendelian genetics, the instructor provides student groups with pedigree data of the mystery patient's family. Although fictitious, the pedigree was intentionally designed not to differentiate between carriers and homozygous recessive individuals (full sufferers of the disease). This replicates an historical aspect of the research done by scientists who first derived the mechanism of genetic inheritance in the early 1920's. The groups are also given probing questions to consider related to aspects of the nature of science. From their group work, students likely propose several explanatory inheritance models of which the simple dominance (dominantly expressed allele) is the best candidate.

Given that students have proposed differing explanatory models to account for the pedigree problem, the instructor uses this opportunity to build upon the groups' work with the pedigree problem and probing questions to a more general discussion about how scientific theories are compared with one another. Here, the instructor raises such issues as the degree of supportive evidence, the degree to which a theory solves empirical problems (and avoids conceptual problems), and the idea that a preferred theory accounts for a greater amount of available evidence.

After having students read a short article about the limitations of *in-vitro* testing, the instructor gives a brief historical lecture about the specific *in-vitro* technique (Emmel Test) used by Drs. Taliaferro and Huck during their initial pedigree work in the early 1920's. The goal here is to have students discuss how the Emmel Test potentially limits
the degree to which the morphological changes exhibited in the pedigree data can be properly resolved between what appear to be differing severities of the mystery disease. Students likely wonder about the possibility of a technique that would more realistically measure morphological changes in the red blood cell under conditions found similar to inside of the body. From here the instructor discusses the development of Sherman's technique in the early 1940's for analyzing patients' blood.

Class #3, Genetics II

At the beginning of this class, the instructor spends several minutes facilitating a whole class discussion to remind students about the distinction between the two types of historical tests used to examine the blood of persons afflicted with the mystery disease (or relatives of diseased individuals). The instructor uses probing questions to ask students to comment on why the more recent, Sherman (in-vivo) technique is preferable to the more antiquated Emmel (in-vitro) technique. These discussions help frame the context of the subsequent revisiting of the pedigree problem.

Student groups are challenged to examine a similar pedigree problem with the distinction that the patient information in the new problem is derived using the technologically more advanced Sherman test. Groups are also given probing questions related to the nature of science. From this group work, students are again charged with constructing an explanation based on their knowledge of Mendelian inheritance models. The instructor then facilitates a whole class discussion to critique students' proposed explanations.

Students are likely to implicitly realize that as a result of technological advances, their provisional theory to account for the inheritance of the mystery disease has changed from a dominantly-based mechanism to a recessively-based mechanism. As a result, the activity provides the instructor an opportunity to explicitly probe for students'
insight into aspects of the tentative nature of science. One such aspect is that students' theories to account for the inheritance of the mystery disease have indeed changed (modified) by virtue of new evidence (predicated on advances in technology).

Furthermore, the instructor asks students to comment on whether they believe theories can change by other mechanisms than through technological advances. Here, the discussion may focus upon change as a result of reconceptualization of the problem or new insights achieved by the scientists. The point is to see if students link their own problem solving work in the context of the genetics of the mystery disease with these aspects of the tentative nature of science.

The experience also allows the instructor to have students consider whether their earlier theory for the genetics of mystery disease was "wrong" or seemingly foolish in light of a more modern understanding afforded by virtue of the technology of the in-vivo test. Here, the point is to explicitly have students think about the misconceptions involved when people tend to dismiss historical views as misguided when they view the historical work/conclusions from a contemporary understanding. Additionally, the instructor can use this opportunity to (again) probe students for their understanding of how theories are compared and general processes that lead to theory change.

These discussions inevitably lead students to raise the question about the distinction between theories and laws. The common misconception held by many of the students is that there is a hierarchical relationship between facts (evidence), theories and laws. The instructor can use the opportunity to point out that while theories may evolve (account for more evidence, solve more empirical problems, avoid more conceptual problems, etc.) students should recognize the epistemological distinction between theories as explanations and laws as descriptions.

Given the understanding of the inheritance of the mystery disease students have developed in the context of this class and the preceding, the instructor facilitates a final
activity in this class to have them build upon their knowledge. The instructor asks students to consider what they would predict to happen to the frequency of the mystery disease gene in a population of interbreeding individuals given that the disease is ostensibly harmful. This question is further motivated by having students engage in a simulation and whole-group discussion. Lastly, the instructor indicates that the next class on evolution will examine whether or not their predictions for the decline in the frequency of the mystery disease gene hold true in a certain part of the world, Central Africa.

Class #4, Evolution I

At the beginning of this class, the instructor reviews with students what their predictions were for the expected frequency of the mystery disease gene in a population of interbreeding individuals. This is followed by a short historical lecture to set the context of the subsequent evolutionary problem that they will be given. The lecture involves familiarizing students with historical research done in Africa during the late 1940's and early 1950's to examine hematological interests, including the characterization of various polymorphisms. To motivate this seemingly tangential topic, the students are told that the mystery patient's family came from a particular country in Central Africa, Uganda.

Student groups are given ethnographic data for tribal groups that existed in Uganda during that period. What they initially discover is that there are unusually high

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36 Under normal circumstances, deleterious alleles should be selected against (given that they reduce the fitness of the organism). As a result, one would expect the mystery disease allele to be reduced significantly in a population given enough generations of random mating.

37 The authentic mystery patient seen by Dr. James Herrick in 1910 actually came from the West Indies. For the purposes of motivating students by way of making the "story" connect with historical research on sickle-cell anemia in Uganda (and other parts of
and heterogeneous frequencies of carriers of the mystery disease prevalent throughout the country. The challenge to the student groups is to examine the ethnographic and geographic data in an attempt to explain these otherwise anomalously high frequencies. Through this experience, the three most common explanations that emerge from student groups are that the heterogeneous presence of carrier frequencies are due to sociological (intermarriage) and/or selective mutation factors and/or racial predetermination.

The activities during this class further allow the students to build off of their problem-solving work by connecting their specific explanations to more general insight about the development (construction) of scientific theories and the manner in which competing theories are evaluated against one another in light of available evidence. The instructor facilitates a discussion of these issues by having students comment on their responses to the probing question given to them during their group work.

Class # 5, Ecology

In this class, students are challenged to consider another aspect of the hematology work done during the late 1940's and early 1950's in parts of Africa. The instructor begins the class by showing a film that depicts the history of the research on the drug quinine. Through viewing the film students gain a fairly comprehensive understanding of the disease malaria. Students see that the disease malaria causes very similar symptoms to what has been described as affecting the mystery patient, and as such, the instructor facilitates a whole class discussion about whether or not the mystery patient indeed is afflicted with malaria. This conversation requires students to build off of their prior knowledge about the mystery disease as an inherited condition in contrast to what is revealed in the film that malaria is a disease transmitted by a mosquito vector.

Africa), the background of the mystery patient has been altered to make it appear as if he originated from Uganda.
Furthermore, the film wonderfully illustrates how an understanding of an entity in biology (in this case malaria) is achieved by considering both holistic and reductionistic approaches. As such, the instructor facilitates a discussion with the whole class to have students identify examples of both approaches as depicted in the film.

Student groups are then asked to examine a diagram of the lifecycle of the *Plasmodium falciparum* parasite, and the instructor facilitates a whole-class discussion that asks students to propose various mechanisms to inhibit the growth of the parasite (either internal or external to the human host). The point of this activity is to familiarize students with the lifecycle of the parasite in relation to its effect upon the physiology of the human cardiovascular system (particularly with respect to the effect on the structure and function of the erythrocyte). This knowledge foundation becomes necessary in a subsequent class on the molecular biology of the mystery disease.

At the end of this class, the instructor explicitly indicates to the students that the mystery patient does not suffer from malaria (although most have already come to this conclusion). To alleviate student concerns that the class was seemingly unrelated to the mystery disease "story," the instructor hints that malaria may yet still have a part to play in the developing understanding of the mystery disease, and as such, students are told that they will be revisiting aspects of these discussions in the subsequent classes.

**Class #6, Evolution II**

In the sixth class, students again consider issues associated with population genetics/evolution of the mystery disease. This time, they are given two new pieces of data from Uganda to augment their earlier analyses from class #4. The first piece depicts the epidemiology of malaria in Uganda, while the second includes observational results of the density of malarial parasites in normal and carrier children for sickle-cell anemia (mystery disease). Through incorporating these new data sources into their
existing set, students have the opportunity to revise their earlier theories that explained the presence of high frequencies of carriers. They are given the chance to construct a new theory that rests upon the assumption that the mystery allele confers some advantage against the ravages of malaria. This work recapitulates that done by Anthony C. Allison (1954a, 1954b, 1955) in which he successfully established a connection between the selective advantage of the sickle-cell allele in endemic malarial areas as evidence of natural selection in man.

Student groups are then asked to consider how their new theory of heterozygote advantage might apply in the scenario of future global warming. Here, students are required to connect a prior reading on the likely increase of the spread of malaria-carrying mosquitoes into more northern climates with their new understanding of the frequency of the mystery disease gene. The discussions focus upon the potential for long-term increases in the frequency of carriers in newly endemic malarial areas.38

During this class, the instructor facilitates several discussions about the nature of science, including having students reexamine the process of theory change. They are also encouraged to consider how explanations in science are often framed by one's subjective background. Here, students are asked to consider their work with the problems and the probing questions toward thinking about why certain scientists are able to propose scientifically more accurate theories while others adopt less valid explanations despite that all of these scientists had access to similar data and experiments. Finally, the instructor facilitates a discussion about the role that observational evidence plays in the construction of scientific knowledge. In this class (as is in the fourth class) the explanations that students pose are entirely based on observational evidence rather than data derived from controlled, manipulative
experimentation. This experience allows the instructor to question students about the validity of knowledge in science that has been created by way of assimilating observational data.

Class #7, Molecular Biology

The instructor poses a fundamental question at the end of the sixth class that challenges the students to hypothesize what differences exist between the deleterious and the normal allele such that an advantage is conferred in heterozygotes in endemic malarial areas. This sets up the seventh class, in which students explore the molecular biology of the hemoglobin protein. They analyze fragment data via electrophoresis and use the genetic code to determine that the deleterious allele differs with respect to a single amino acid.

The instructor initially facilitates a review using concept mapping of the distinction between malaria and the mystery disease. This review highlights the basic commonalities and differences between the two diseases. Following this, the instructor probes students for their understanding of the function of the red blood cell as it relates to the cardiovascular anatomy (particularly the functioning of the red blood cell in the capillary). This discussion helps frame students’ learning about why changes in the hemoglobin protein adversely affect the structure and function of the red blood cell in mystery disease patients under low oxygen concentrations.

The instructor then asks student to consider by way of a lecture and discussion how the classical connotation of a gene as a unit of inheritance has a connection with the molecular connotation of a gene as a unit of DNA that codes for an expressed protein. This conversation includes a review of the central dogma. Finally, the instructor provides

\[^{38}\] This claim is predicated on some rather tenuous assumptions (e.g. lack of significant admixture, lack of medication to treat malaria sufferers, etc.). These tenuous
a brief overview of the mechanics of electrophoresis as a means to qualify differences in protein fragments. Included here is a discussion of the research work of Linus Pauling in 1949 and Vernon Ingram in 1958. Pauling sought to characterize hypothesized differences between the hemoglobin of sickle-cell patients from normal patients. Ingram's work followed thereafter as he sought to identify the specific changes in the amino acid composition of the altered beta gene of the hemoglobin tetramer. The instructor provides the historical context of Pauling and Ingram's work intermittently as student groups examine two "fragments" of hemoglobin DNA using the genetic code while attempting to find the molecular differences between the hemoglobin of the mystery patient with that of a normal person.

The final activity in this class is a comprehensive discussion in which the instructor challenges students to connect their understanding of the changes in the hemoglobin molecule seen in mystery disease patients with their understanding of the pathophysiology of the malarial parasite. The goal is to have students understand that as the parasite consumes hemoglobin, there is an increased likelihood that the red blood cell will sickle, and as such, there is a reduced probability that the parasite will survive in that cell. Hence, students come to understand how their cellular understanding of the malarial parasite connects with the molecular understanding of the mystery disease in terms of the mechanism of affording protection against malaria.

Class #8, Review

The final class serves as a review. The instructor begins by showing students a film about sickle-cell anemia entitled, "Blood." In this manner, the name of the mystery disease is finally revealed to the students, and the film reviews many of the aspects that students explored throughout their historical examination.
The instructor spends the remainder of the class revisiting several of the aspects of the nature of science by way of having students talk about what they learned in the context of their daily group work and subsequent discussions in relation to a contemporary understanding of the aspects of the nature of science most germane to that work.
Appendix E

Lesson Plans for the Sickle-Cell Unit
The following is a brief chronological overview of the major events in the development of the understanding of the disease sickle-cell anemia. This overview was developed by the researcher from his analysis of the primary research literature. This information provides the instructor of the course (who is also the researcher of this study) with a feel for the major issues at play and the central scientific figures who were working toward developing the major findings concerning sickle-cell anemia.

Dr. James Herrick is generally credited with "discovering" the sickle-cell condition in 1910. He examined the blood of a Jamaican patient and noted the tendency for the red blood cells to assume the characteristic condition of sickling. In 1917, V. Emmel discovered the in-vitro tendency of blood to sickle by using glass cover slips (and sufficient time – approximately 24 to 48 hours).

The first formal model for examining the potential inheritance of sickle-cell disease was proposed in 1923 by W.H. Taliaferro and J.G. Huck. This was actually a follow-up analysis to a prior examination done that year by Huck in which he simply did a series of pedigrees to show the existence of inheritance. Their subsequent work examined a particular pedigree of an African American family in which the ancestral parents had phenotypes of "normal" (female) and "sickle cell" (male). The determination of sickling vs. non-sickling was made by in-vitro analysis of the blood using the test developed by Emmel.

Based on their pedigree analysis, Taliaferro and Huck proposed a dominance model of Mendelian inheritance. Under this model, the possession of a sickling phenotype was due to the expression of a dominant allele from a single locus. Normal individuals did not have the sickle allele.

The authors further provided support to their assertion that the inheritance is non-sex linked (in addition to being dominantly expressed). Two other comments are noteworthy:

1. Unbeknownst to Taliaferro, all the individuals on the pedigree denoted "S" were carriers. Children who died (presumably some of the full disease) were denoted as "dead" of other causes.
2. Although tangential to their specific results, there was later (roughly 25 years) controversy regarding the in-vitro technique that was used to elucidate whether or not an individual's blood would sickle under hypoxic conditions. There was a tendency to introduce false positives....normal red blood cells would also quasi-sickle (false sickling). In a later paper of 1955, Hermann Lehman makes an admonition that his earlier quantification of sickle-cell carriers of portions of C. African tribes (done in the early 1950's) may have been overstated as a result of the false positive effect.
In 1927, Hahn and Gillespie elaborated on Emmel's work by demonstrating that the sickling effect was linked to de-oxygenation.

During the time of Taliaferro and Huck, there had not yet been the distinction between sicklemia (being a carrier) and full-blown sickle-cell anemia. It was not until L. Diggs in 1933 proposed a distinction between sicklemia from sickle-cell anemia that theoretical evidence existed to challenge Taliaferro's model. Diggs exposed erythrocytes in-vitro to a wide range of oxygen concentrations (from essentially zero oxygen to full atmospheric). He found that the erythrocytes of those individuals previously termed as "sicklemics" remained essentially normal-shaped when oxygen concentrations were somewhere between full atmospheric and zero levels. Full-sufferers of the disease exhibited erythrocyte changes at the same levels of oxygen.

In 1940, I. Sherman, a physician from Johns Hopkins University, conducted an experiment in which he showed a clear distinction between those individuals who were carriers for the disease compared to full sickle cell anemias. Prior to his work, there was little distinction (other than degree of severity) between those with the "trait" and full anemia. Sherman sampled venous blood from anemics and carriers using a technique that maintained oxygen concentrations and pressure levels similar to those found in the venous system. He found that full anemics have from 20 - 60% of their RBCs sickled (in-vivo) in the venous system. Trait individuals or carriers had virtually no sickling in vivo.

In 1949, Linus Pauling et al., made the connection between hemoglobin as the oxygen carrier and the causal relationship between relative oxygen concentrations and the sickling phenomenon. Pauling used electrophoresis to examine migration differences of hemoglobin samples between a normal, a carrier, and a full-sickle cell anemic. His results showed that the heterozygote maintained two forms of hemoglobin; one similar to the "normal" phenotype and one similar to the sickle cell anemic phenotype.

In 1949, J.V. Neel proposed that the heterozygote represented the carrier of sickle cell anemia and the homozygote recessive as the sickle-cell anemic patient. He engaged in a mathematical analysis of allele frequencies and pedigree examinations to support his contention that the most appropriate model of inheritance was not based on dominance, but rather upon heterozygosity as the carrier.

In 1950, Max Perutz concluded from experimentation that hemoglobin blood solubility of carriers was lower than normal individuals when exposed to low oxygen

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39 Diggs work in 1933 was a theoretical prediction using in-vitro testing of the erythrocytes.
concentrations. He further proposed that a crystallization of hemoglobin was a factor responsible for distortion of the erythrocyte.

Anthony C. Allison is largely associated with linking the resistance of sickle-cell heterozygotes to the ravages of the disease malaria. The central problem which Allison attempted to address in the early 1950’s regarded the persistence of the sickle-cell allele in the heterozygote form. His (and other colleagues) findings of high frequencies of heterozygotes throughout Central and Eastern Africa, Greece, India, and other equatorial/sub-tropical regions was an anomaly. He referenced from Ford (1940) four possible mechanisms that could account for the polymorphism of the sickle-cell allele:

a. Low levels of polymorphisms that arise from mutation
b. Polymorphisms of alleles that have no bearing on fecundity
c. A true balance of selection for polymorphs
d. Advantageous varieties that sweep in a population

Regarding mutation, Allison referred to J.B.S. Haldane’s work concerning the mutation rates for alleles in man. He proposed that for mutational replacement to keep the frequency of the HbS allele constant in the population, the rate of mutation would need to be 5000 times that postulated by Haldane. Additionally, mutational replacement would need to be population specific to account for tribal differences in allele frequencies. Allison also discounted neutrality as a driver of polymorphisms. He contended that lack of evidence concerning the selective advantage of one form over another was simply due to ignorance of the reality of those forces (a standard selectionist argument).

Foy/Kondi in 1954 proposed a model of selective reproduction of heterozygotes. They referred to the phenomenon as the “stable equilibrium with reproductive over compensation as the explanation of the high HbS frequencies.” Allison argued that there was no empirical evidence that such reproductive behaviors were occurring.

In 1953 (although the findings were reported in 1954), Allison used earlier observational work (Beet, 1947, Brain 1952, Allison, 1949) to link malarial resistance in carriers with balanced polymorphism. He experimented on 30 tribal volunteers (15 confirmed carriers and 15 normal (genotype)) by inoculating them with the malarial agent, P. falciparum. The results confirmed his earlier observations that carriers had a resistance to parasitemia.

He further used mathematical analysis to explain the findings of J.V. Neel (1951) that African American trait frequencies were no larger than 9% (Allison proposed the mechanism of non-selective advantage of the heterozygote in the
Americas; thus the decrease of the allele given admixture of caucasian/indian influence and subsequent generational dilution).

Although some would classify Linus Pauling's earlier work in 1949 as "molecular" interpretations of the disease (in a point of fact Pauling himself did as such), the true molecular work was not done until 1956 by Vernon Ingram. Pauling's group isolated changes to hemoglobin that were responsible for characterizing a normal, a carrier, and a patient of sickle-cell anemia, but they could only postulate abstractly as to possible causal mechanisms responsible for those changes.

Ingram used digestive enzymes to "cut" the hemoglobin molecule into various pieces. He analyzed both forms of hemoglobin HbS and HbA, in addition to the C form. Through peptide mapping (essentially electrophoresis and paper chromatography), Ingram discovered that the fundamental difference between the hemoglobin molecules concerned the 6th amino acid position of the beta chain. Essentially, two steps were involved. First, he isolated the large fragment (using digestive enzymes) between the HbS, HbA, and HbC that contained the point of difference. Then, by sequentially removing the end peptide from each fragment and reanalyzing the map, he eventually discovered that the 6th position was different between the three hemoglobin types.

The background work regarding the interaction of different forms of hemoglobin was done in the later 1950s by several researchers, including Anthony Allison (1957). In addition to the normal and sickle-cell forms of hemoglobin, humans may express other forms (including the fetal form in varying quantities - although generally at low levels post three months after birth), the C form, the D form, and the O form. The D and O forms are associated with Punjab and Arab groups respectively. Combinations of hemoglobins in the heterozygote form contribute differently to the formation of deoxyhemoglobin gels (agglutination).

In 1957, Greenberg provided a summary of the effects of the increased viscosity. He proposed that the increase contributed to the production of capillary erythrostasis, formation of plugs of impacted erythrocytes, vascular occlusion, occasional hemorrhage, infarction and ischemic necrosis in various parts of the body. He also postulated that the shortened lifespan of sickled cells, combined with their tendency to undergo hemolysis, provided evidence to the anemic condition. There are a host of other cascading disorders distally related to the presence of anemia and the increased concentration of lysed, sickled red blood cells in the bloodstream. This includes splenetic problems, kidney dysfunction, coronary problems, etc.

In 1966, M. Murayama provided the first explanation as to why the sickling occurred based on the findings of Ingram. He claimed that the substitution of the hydrophobic valine in the place of the normally hydrophilic glutamic acid caused a change in the affinity of the outer structure of the hemoglobin in HbS. The change of
both beta chain 6th position glutamic acids in HbS allows for a lock and key
arrangement of repeating inversions of alpha to beta (chain) alignment of HbS
molecules such that long chains are formed. This contributes to the formation of long
tubules and thus sickling vis-à-vis distortion of the erythrocyte.

There is a nice link to the behavior of sickling only when under low oxygen
conditions. When oxygen is present, there is a shift in the beta chain alignment such
that it no longer affords the conditions for alpha-beta matching and tubule formation.
Disassociation of oxygen from the HbS realigns the beta chain and permits the tubule
formation to occur.

A relatively simple explanation of the 6th position amino acid shift uses a
point mutation (non-synonymous). This may simply be represented as a change in the
G-A-G codon (for glutamic acid) to G-U-G (valine).

In 1964, Charache, demonstrated that one result of sickling is the increase in
the viscosity of blood. This contributes to the pathogenesis of sludging and vascular
occlusion in sickle-cell anemia. He postulated that the viscosity increase was
correlated to the number of sickle cells, the hematocrit and the mean corpuscular
concentration of HbS, and the degree of interaction between hemoglobins when more
than one major type is present.
Unit 3: Sickle-cell unit

Overview

The third unit of BIOS 270 is intended to be an encapsulation of the students' experiences from units explored in BIOS 170 and BIOS 270. For those students who have not taken BIOS 170 prior to taking BIOS 270, this third unit will provide a good introduction to the various subdisciplines of biology that can be used (as was the case in BIOS 170/270) to examine a particular phenomenon. In BIOS 170, students engaged in open-ended problem solving in the domains of anatomy/physiology, ecology and evolution. In the first two units of 270, students explored genetics and molecular/cellular biology. The final unit is called organismal biology. As such, students will examine a single mystery disease (sickle-cell anemia) from each of the subdisciplines explored in both 170 & 270. As with the previous units in BIOS 270, the unit is designed with an historical emphasis. The students are presented with activities and problems that roughly mirror the history of scientific work that provides our contemporary understanding of the disease.

This unit has been constructed with two goals in mind. First, the work that students do in the course of this unit will provide them with insight into how different levels of the biological hierarchy (as explored through examining the disease from the perspective of various subdisciplines of biology) are related to one another. From this, it is hoped that students will gain insight into a unique feature of biology: that a genuine understanding of any biological phenomenon requires both a reductionist and holistic interpretation of that phenomenon. This aspect is discussed on pp. 13-14 of the course manual.

The second and related objective emphasizes using the history of research on sickle-cell anemia to improve students’ understanding of the nature of science. In the lesson plans that follow, attention is drawn to instances in which the instructor should explicitly discuss NOS issues relating to the problems or activities that students are examining. Second, the work students do in the course of this unit will reveal how history of research of a phenomenon can improve their understanding of the nature of science.
UNIT 3: OBJECTIVES AND EVALUATION
(given to students)

Up until now, in your experience in this class (and also in the companion course BIOS 170) we have examined biological phenomena from the perspective of separate subdisciplines of biology (e.g. genetics, molecular & cellular biology, physiology, ecology, evolution). In this third unit of BIOS 270, we will examine a single biological phenomenon from the perspective of each of these subdisciplines. We hope that this will help you appreciate how the same phenomenon can be understood at multiple levels as well as helping you become aware of the important explanatory relationships models in different subdisciplines have to one another.

Objectives

In addition to the global objectives of the course, the third unit emphasizes the following specific educational objectives:

1. Students will further their appreciation that part of the unique character of biological phenomena concerns the nature of biological explanations: that an integrated understanding of any biological phenomenon requires both a reductionist explanation (i.e. explaining the phenomenon with reference to its components) and a holistic explanation (i.e. explaining the phenomenon with reference to its contribution to the functioning of a greater whole of which it is part).

2. Students will appreciate how a single biological phenomenon can be understood with reference to multiple levels in the biological hierarchy using insights gained by studying the phenomenon from the perspective of multiple distinct subdisciplines in biology.

Each represents a more specific instantiation of the first objective listed on our course syllabus, “aid students in developing a meaningful and functional understanding of key biological concepts and their interrelations.”

Evaluation

Even more so than your previous experiences in this class and BIOS 170, this capstone unit will place you in a very open-ended, problem solving environment. Much of your success will depend on your independent ability to pose problems, engage in problem solving, and persuade others regarding the models you create that explain the phenomenon at a given level and how these models are related to one another.

As noted on the syllabus, the third unit of the course is worth 100 points of your overall grade for BIOS 270. It is broken down in the following way:
Unit three exam: 51 points
Daily Diary entries: 49 points

Exam (51 points)

The Unit 3 exam will cover the conceptual material contained in the third unit, including any readings from the course pack and/or handouts you receive during class. Approximately 1/5 (10 pts.) of the exam will focus on concept mapping.

Daily Diary Entries (49 points)

During (and after) several of the classes in the third unit, you will be expected to write a diary entry of approximately 3 - 5 pages (handwritten) reflecting on the activities of the day’s class. There are eight total classes in the third unit of the course, and you are required to turn in 7 diary entries for evaluation. Diary entries should review what happened during that class, discuss how you think the phenomena we study are related to one another, what issues or problems seem unresolved, and what issues you think we should explore further. Your diary can be a collection of essays, diagrams, and data, but it should be more than just a summary of what we did in class.

Below you will find a list of sections you should be incorporating into your diary. Each of these sections should receive equal weighting in your diary entries. That is to say, don’t spend two pages summarizing the daily activities and then give only a brief comment on the remaining two sections.

- **Daily Summary** (1 page or greater)
  Your entries should briefly and accurately document what happened in class. They should be written in the context of the minimal set of outside readings you are assigned.

- **Attitude of inquiry** (1 page or greater)
  Your entries should pose new questions regarding the course material and its implications that demonstrate your active involvement with the material. The entries should suggest you are thinking about how models of the phenomenon at different levels are related to one another.

Your instructor will provide you with a “seed” question at the beginning of each class that concerns issues related to inquiry. You should address this question in this section of your diary by using your own reasoning and your experience in the classes (therefore no outside research).
In addition to answering the “seed” question, you should discuss any issues or ideas from the class that were problematic for you or were left unresolved. What further questions do you have, and what other issues would you like to explore? You should use specific examples from class to support your claims.

- **Meaning and Relevance (1 page or greater)**
  Your entries should discuss the practical significance of the third unit for your understanding of biology and for the teaching of biology. You may wish to contrast the manner in which you are learning in this unit with your previous experiences in learning biology or science.

  Also, you should consider how your experiences in the classes give you insight into the nature of science and/or the nature of biology. Again, your instructor will provide you with a “seed” question at the beginning of each class related to the nature of science to orient your thinking. If you are not sure what is meant by “nature of science” you should reread the section that discusses the nature of science that is contained at the beginning of your course manual.

For each daily diary, you should identify what class you are writing about (e.g., “Class #1, Introduction) at the top of the page. You should also separate each section (summary, inquiry, meaning) by placing it on a separate page (put your name on each page and indicate what the page is addressing (i.e. summary, meaning, inquiry). You will be expected to turn in your diary entries for each class at the start of the subsequent class. Here is an example (using class #1) of how you should be labeling your diary pages:

```
Class # 1: Introduction
  Summary
  1

Class # 1: Introduction
  Inquiry
  2

Class # 1: Introduction
  Meaning/Relevance
  3
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Each of your daily diaries is worth 7 points for a total of 49 points (seven required diary entries) over the eight classes of the unit.
Class #1

The Mystery Patient/Cellular Perspective

This class begins the third unit of BIOS 270. This unit covers whole-organism biology by virtue of examining a mystery disease from the various perspectives, or subdisciplines of biology that the students have explored in the course of having taken either BIOS 170 or BIOS 270.

During class today, students will be introduced to the major goals and objectives of the third unit. They will then be challenged to think about the nature of biology by virtue of examining hierarchical relationships/representations. Subsequently, students will be introduced to the mystery patient and be charged with explaining various aspects of the mystery patient’s condition by virtue of a cellular and through manipulation of physiological models of the cardiovascular blood vessels.

Day 1 Objectives
1. To become familiar with the Unit 3 Objectives and Evaluation
2. To conduct student presentations (if appropriate)
3. To introduce the mystery patient
4. To begin constructing explanations of the patient’s disease by considering cellular biology and physiology

Day 1 Materials and Equipment
1. Copies of the Unit 3 Objectives/Evaluations
2. Subdiscipline/Hierarchy overhead
3. Reductionism/Holism overhead
4. Overhead of the “Five Ways” example
5. The necessary number of handouts of the “Mystery Patient”
6. Sickle Cell and Normal Erythrocyte Histology Slides (6 - 8 of each)
7. Microscopes (6 required)
8. Capillary/Erythrocyte Models (6 required)
9. Overhead of Capillary Structure
10. Overhead of mystery patient vs. normal histology slide

Day 1 Background Reading Materials

Set-up Prior to Class
1. Equipment
   - Be familiar with the location and operation of the microscopes
   - Know where to locate the blood slides and the simulated models of the vessels/blood cells
   - Have the necessary overheads and handouts ready for use
2. Homework (Posted on the right hand side of the white board):
   Write a daily diary entry based on your experiences last class.
   Summarize what took place, and consider the diary "seed" questions on the board. Create a concept map of the first set of Organismal Biology concepts listed on p. 203 with reference to the reading "Anatomy and Physiology of the Cardiovascular System" (pp. 209-222).

3. On Board:
   • Diary "Seed" Questions
     - Inquiry
       What curious things did you notice about the patient’s red blood cells?
       What effect might these features have upon the patient’s cardiovascular function?
       What further research questions do you have about the mystery disease?
     - M/R
       How do your research questions relate to the distinction between reductionistic and holistic approaches in biology?

   • Agenda:
     1. Class Business
     2. Student Presentations (if applicable - from the BIOS 270 Student Projects)
     3. Hierarchy Introduction
     4. Five Ways of Looking at Frogs
     5. Mystery Patient
     6. Examination of Histology Slides/Models
     7. Discussion
       • Cellular Conclusion
       • Nature of Science
         - Reductionism/Holism
         - Theories/Evidence
     8. Return exams from Unit II (if applicable)
Class #1
The Mystery Patient/Cellular Perspective
Overview

1. Class Business (~5 min)

General Comments (to be made to the students):

1. The instructor should first go over the objectives of the third unit with the students.

   Note: pass out copies of the unit 3 objectives and evaluations (or refer students to the course manual).

2. He/she should then specifically review how the students will be evaluated in the unit. This is listed on the unit three objectives/evaluation. Acquaint them with the format of the exam (51 points). Also reacquaint them with the mechanics and particular expectations of the third unit.

   Note: Students should be told that they are expected to begin working on their diaries from this day forward. See the “Unit Objectives/Evaluation” for more information.

3. The readings required for the third unit are minimal. Students will be expected to read, interpret, and refer to (go beyond) the readings during their work in the classes.

4. The experience will be very open-ended. Students will be expected to reflect on their experiences, ask questions, probe for information, and collaborate with their colleagues.

   General Note:
   This manual often refers to the terms, “sickle”, “sickle-cell”, etc. This reference is for the instructor’s benefit only. Keep in mind that the unit is designed along the perspective of a “mystery disease.” Therefore, the instructor should refrain from using terminology that will prematurely disclose the name of the disease.

2. Student Presentations (~30 min)

   Each group should be allotted approximately 15 minutes to present the results from their organ system research. Generally, the group members divide the presentation into two portions – one student presents a description of the disease and how to explain it from the perspective of a couple of the required subdisciplines (e.g., ecology and evolution). The other student completes the presentation by covering

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those subdisciplines not chosen by the first student. Also included should be a
discussion of the potential treatment for the disease.

The instructor should encourage other class members to ask questions at the
conclusion of the presentation. Additionally, the instructor should draw students’
attention to the possibility that a potential exam question may result from a general
issue raised in the context of a presentation. The latter is done to keep students’
attention focused.

3. Hierarchy Introduction (~5 min)

The instructor should feel comfortable using the overhead of
subdiscipline/hierarchy to give a general introduction of the third unit (as it compares
to their experiences in either BIOS 170 or BIOS 270). Take care that students aren’t
overwhelmed by this overhead. The purpose of showing them this is to give them a
general feel of the type of conceptual issues associated with hierarchies in biology
(that there is at once a delineation based upon scale, based upon differences in either
information flow or matter/energy flow). The instructor should point out that
students will be analyzing the various subdisciplines of biology (the same that they
examined in the earlier units of both 170 and 270) although in this case they will
examine a single phenomenon from an integrated framework of all the subdisciplines.
The larger goal is for students to think about how entities and processes in various
hierarchical levels have a relationship with one another – whereby a change in
something at one level may be explained in how it affects entities at levels below it
(related to reductionism) or can be examined by virtue of how it affects levels above
it (related to holism).

This overhead should be followed up with the overhead concerning
reductionist/holistic perspectives of understanding the heart. Note that this diagram
presents a hierarchical interpretation of the heart. The point to make here is that in
addition to the fact that biological phenomena exhibit a hierarchical arrangement (as
evidenced in the previous overhead and in this one), the instructor should point out
that this diagram provides insight to a uniqueness of the nature of biology. The
uniqueness relates to how an entity (in this case the heart) can be analyzed from a
reductionist perspective (e.g., understanding the heart by explaining the
structure/function of its component parts) or can be analyzed from a holistic
perspective (i.e. an understanding of the heart with reference to its contribution(s) to
the whole of which it is a part). The critical point is that a genuine understanding of
the heart requires both a reductionist and holist explanation.

The instructor should indicate to students that the general flow of the third
unit will have them examine a single entity (a disease) by taking a subdisciplinary
approach in which students will be able to see for themselves how a genuine
understanding of the disease will require an interplay of both a reductionist
examination and a holistic examination.
Furthermore, an important distinction to draw to their attention to is that a subdisciplinary approach exposes how the levels of the biological hierarchy (e.g. cells, genes, ecosystems, tissues, organisms) are related to one another with respect to understanding the phenomenon. The subdisciplinary approach provides a method of exploring these levels.

4. Five Ways of Looking at Frogs (~10 min)

The instructor should use the overhead related to the article to facilitate the discussion.

The article students were to have read presents a view of explaining/interpreting a biological phenomenon that is partially at odds with what the students will do in the context of the next seven classes. A few questions initiate the discussion:

- What impression does this article give you about the relationship between the subdisciplines?

  It gives the impression that the subdisciplines are isolated from one another.

Perhaps it would be best to explore how this is/is not so with the students.

- How might this article properly represent a hierarchical nature of biology?

  The reader gets the impression that biological phenomena can be viewed from several different perspectives which appear to be somewhat delineated by scale. This may itself indicate that a hierarchy (of sorts) exists. Likely, the molecular biologist is concerned with smaller entities, for example, molecules and genes. The Ethnologist may concern him or herself with larger entities.

The discussion about this article could go several directions. Students may perceive that there is no relationship between the various subdisciplines. One aspect that the instructor should explore is the issue raised in the article about “why” explanations and “how” explanations in biology. Certain aspects of study concern themselves with seeking “how” explanations (also known as proximate causes). An example of this would be the reductionist approach taken by the molecular biologist. Conversely, other modes of inquiry involve “why” explanations. The evolutionary biologist (who takes a holistic approach) exemplifies this.

The summary point here is that a complete understanding of any phenomenon (in this case understanding the frog jumping) requires both reductionist (“how”) and a holistic (“why”) perspectives. The instructor should reemphasize to the students that the purpose for the next seven classes (regarding the mystery disease) is to have the students experience learning about a biological phenomenon (sickle-cell anemia).
from multiple biological perspectives and as such synthesize both reductionistic and holistic approaches.

5. The Mystery Patient (~10 min)

Note: The instructor should refrain from mentioning throughout the unit that the mystery disease is sickle-cell anemia!

Given the preface of the “Five Ways of Looking at Frogs”, students should be conceptually prepared to address a more substantive task. The instructor should pass out the single sheet handout that describes a “mystery patient.” The instructor should begin by stating that the class will be examining a mystery disease over the next eight class periods. During each session, the class will focus on understanding that disease from a subdisciplinary perspective of biology. In the first class, they will explore how histology and physiology can provide insight into explaining the disease.

After allowing sufficient time for the students to read the sheet, their attention should be drawn again to the two goals listed in the prose.

1. To attempt to understand the specific condition in terms of its mechanism of action.
2. To consider how different levels of the biological hierarchy are related to one another.

Encourage students to retain this sheet and to periodically examine the symptoms as they explore the activities to follow in the subsequent sections of the course (and development of their diaries).

The instructor should facilitate an open discussion in which he/she asks the students how they would approach “researching” the mystery patient. One way to do this is by thinking aloud with them how the various symptoms expressed by the mystery patient may or may not be related to one another. Students should be encouraged to consider what they would do (i.e. what bits of evidence would they like to have) in order to further study this mystery disease.

For example, students may propose that since the mystery patient seems to suffer respiratory distress following exercise, then perhaps the cardiovascular system is involved. This often precipitates a suggestion that perhaps a sample of blood from the mystery patient would be helpful. From here, the instructor can make a transition to the histology activities.

The instructor should “guide” the discussion. Students may suggest several things that they’d like to explore in connection with the symptoms. Some of these suggestions will be re-visited in subsequent classes (e.g., if the disease is heritable).
while others may not. Ultimately, the goal is to get them thinking about blood and the cardiovascular system.

6. Examination of Histology Slides (~20 min)

Students should be encouraged to work in groups of four (for a class of 24 students, this would equal 6 total groups). Students should be told that they will be given the opportunity to analyze slides from the blood of the mystery patient and compare it to slides from a normal patient. They will also be given the opportunity to work with models.

The instructor should set up the histology and cell model labs by saying to the students that each group should attempt to construct (as best as possible) an explanation regarding how what they observe in both the histology examination and the cell model lab may contribute to the mystery patient’s symptoms.

It would also be beneficial to put up the overhead regarding the structure of the vascular anatomy. This is important to provide a context for the use of the cellular models. The instructor should review the general relationship between arteries and veins by discussing how arteries connect to veins by way of the capillary system. The purpose here is to acquaint students with the notion that capillaries are the location where oxygen, nutrients, etc. is transferred from the red blood cell to the tissues (and where carbon dioxide is picked up from the tissues into the red blood cell). To facilitate this process, the capillaries must be extremely small (just large enough to permit the passage of a single red blood cell).

This discussion will help students think about why it’s necessary to construct vascular models that are narrow (see cellular modeling section).

Make it clear to the students that each group will be expected to informally present their initial interpretations to the class following the subsequent two activities.

Each group should be given a histology slide of both the mystery patient’s (a sickle-cell anemic patient) and a slide of normal patient’s red blood cells. The instructor should take care not to mention anything regarding the nature of the disease and should refrain from using the term “sickle” so as not to lead students. Each group should set up the microscope, examine the slides, and make any necessary recordings/observations in their diaries.

Note: Students may wonder how best to proceed. This is intended to be a very open-ended experience. The instructor may wish to put the following questions on the board (or use them as discussion probes) midway through the histology examination to guide student’s thinking:
• What differences do you see between the patient’s blood and the normal blood?

• Based on the readings, how might these changes affect a person’s circulatory “health”?

• What further information would be helpful in exploring these questions?

• What other questions (unresolved issues) do you have?

Note: Due to the nature of these slides, seeing substantial differences between the “mystery patient’s” blood and the normal blood may be problematic. As such, the instructor may wish to put up the example overhead of the two blood “slides” roughly 10 minutes into the microscopy exercise.

6. (cont.) Examination of Cellular Models (~20 min)

Each group should be given the materials to explore how the morphological changes seen in the histology slides may affect the flow of blood. The materials include:

a. The blood vessel wall models
b. Micromodels of “sickled” cells and “normal” red blood cells.

Students are encouraged to examine how differences may exist between the flow of the simulated cells through the capillary/venule system. Here again, this is an open activity. Students can use differing ratios of sickled to normal cells (e.g., all normal, 25% sickled/75% normal, 50/50, etc.). They can also vary the width of the vessel (smaller width being analogous to capillaries).

7. Class Discussions (~ 30-40 min)

Cellular Conclusions

Each group should be given an opportunity to present their findings, to discuss unresolved questions, and to pose suggestions for explorations they may wish to conduct. This could go in several directions, but the instructor should be mindful to simply facilitate the discussions with relevant probing questions.

NOS Discussion – The Nature of Biology (reductionism/holism)

After concluding the discussion about the explanations that the students developed during their analysis of the cellular models, the instructor should ask students to suggest other avenues of research which they feel may shed light on understanding the mystery disease. Likely, student responses will run the range of both reductionist and holistic lines of investigation. For example, students may suggest that they wish to study possible inheritance patterns. Others may wish to examine the DNA structure of the mystery patient. Still others may suggest that a
parasite might be involved. The point we wish to draw is that a genuine and complete understanding of the mystery disease will require that we consider both reductionist and holistic lines of research (evidence).

**NOS Discussion – Theories and Evidence**

Following up on the previous discussion about developing lines of evidence to support an understanding of the mystery disease, now is a good time to encourage students to consider how their specific conclusions they have reached during their activities in class relate to a more general understanding about the nature of scientific theories. One way to begin is by pointing out that a major goal of the next seven classes is for students to develop various “theories” about the mystery patient’s disease. From this, a general question should be raised:

**What is a Theory?**

What follows below is a general discussion of the types of responses that the instructor may encounter. Most importantly, the instructor should refrain from didactically telling students the definition of a theory and rather encourage them to share their own understanding in light of their prior experiences in science. Student responses to this question may range from a very naïve understanding to a scientifically more acceptable one.

Young children often equate a theory with simply a restatement of the problem. For example, when asked for a theory about why heating a hot air balloon makes it rise, some children merely restate that the reason is that the hot air causes it to be so. Another relatively naïve interpretation of a theory equates it with making a prediction and is often expressed by students in terms of making an “educated guess.” This is often paired with the belief that a theory is something to be empirically tested. A more informed understanding of theory involves articulating its explanatory function. Here, the strength of a theory is predicated on evidence. The more evidence in support of the theory, in general the stronger or more robust the theory is considered to be.

Even at this level, there are varying degrees of correct conceptions. Some students express that a theory simply involves providing causal evidence to explain the phenomenon in question. So for example, students may claim that the hot air balloon rises because the flame lights the air and the air heats up, which in turn causes the balloon to rise. The more informed conception of a theory is that the explanation is understood with reference to general principles and is backed by specific evidence. When asked, what is your theory for why the hot air balloon rises, a robust theory couches the explanation in terms of a discussion of the general properties of thermodynamics.
Theories also serve an additional fundamental role. As an explanatory model, a theory provides scientists with the conceptual framework from which to make specific predictions. For example, given a theory to explain the observations regarding the hot air balloon, we are able to make predictions about unseen observations or potential "problems" (e.g. what will happen when the air in the balloon cools) based on the explanatory framework of the theory. In fact, scientists test the validity of theories by seeing how well the predictions that the theory would support indeed hold up to empirical testing.

Philosophers of science point out that scientific theories can be categorized according to the degree to which they solve empirical problems and avoid conceptual problems. Thus, the most robust scientific theories provide large explanatory power, have massive supportive evidence and have withstood numerous attempts at being refuted. Such theories (e.g. theory of evolution, theory of plate tectonics) are regarded as core scientific theories. What students will be doing over the course of this unit should be regarded as constructing introductory or "provisional" theories. It may be worthwhile for the instructor to point out to students the distinction between such provisional theories and the more core theories so that students recognize that these distinct theory "types" are not on equal epistemological footing.

There are other important aspects related to the nature of scientific theories (e.g. how theories are compared against one another, the tentative nature of scientific theories). These aspects will be further explored in the second and third class of this unit.

One significant advantage of this third unit is that it will allow students to construct provisional theories for a variety of things related to the mystery disease. Students will engage in such theory development by virtue of examining numerous pieces of evidence (data) in the historical problems they will encounter. And, students will have ample opportunities to compare one another's theories/evidence as well as examine how historical figures disagreed about certain explanations for the mystery disease. All of these things encapsulate focal issues of the nature of science.

Given all of this, the instructor should begin the process of getting students to consider, "What is a theory?". Answers to this question could go many directions, and the instructor should feel comfortable facilitating the discussion by having students attempt to connect their specific explanations of the symptoms of the mystery patient (with reference to the cellular and physiological evidence) to the general understanding of the nature of scientific theories.

Another way to facilitate this discussion is by putting the words, "theory" and "prediction" on the board. Then offer the following starting question:

_Is a theory the same thing as a prediction?_
• Theories are explanations. These are separate from predictions.

*When can something be predictive without providing an explanation?*

• A perfect example to consider is the relationship between a barometer and a low-pressure system. When asked to provide a theory that explains the behavior of low pressure, the barometer acts only as a prediction (i.e. when the barometer drops we can predict that the low pressure system is arriving).

Ask your students to consider the activities that they have done in this class. They are gathering evidence to construct fundamental explanations to account for the mystery disease on many differing levels.

**8. Return Unit II Exam (~30 min)**

Leave plenty of time for questions and also for the students to respond to specific issues with their exam. Pass back the exams to the students and have them look over the exam to note points where they might have questions about your evaluation of their answers. I generally share the average score and distribution with students as well as identifying a total point value below which they should meet with me individually to discuss how they prepared for the exam and how to improve study strategies.

Point out that you recognize you may have made a mistake in either adding up their points or perhaps not providing sufficient partial credit. Pass out blue sheet of paper and red ink pens to students and invite them to write conceptual arguments for why they deserve more points, clearly indicating their name, question number, and the defense of their answer. Nothing should be changed on the exam itself. When they have defended their points, they should attach the blue sheet to their exam and turn in the exam. Even if students do not have questions about their exam, they must return the exam to the instructor. Students are not allowed to keep their exams. (We only have a limited number of versions of the exam and want to discourage cheating by students in future sections of this class that may know some of the members of your class).

Go through the exam question by question explaining what you were looking for in their answers. Tell them you will answer general questions about the exam, but would prefer they restrict specific questions about their exam to the blue sheet. I often go as far as to say I will not discuss how a particular exam was graded until they have submitted a conceptual argument for why their answer deserved more credit.

After the class, check the blue sheets and the arguments presented to determine if points will be awarded. Any points that are awarded will be noted on the
blue sheets and returned to the students. This is the point where you should invite students to talk with you about the exam if they have any questions.
Understanding the Heart

Holistic

Organism (e.g. exercising)

Cardiopulmonary System

Myocardial Muscle Tissue

Myofibril Cells

Actin/Myosin Proteins

Reductionism/Holism Overhead

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170/270 Biology Subdisciplines

Ecology
Evolution
Cellular Bio./Physiology
Genetics
Molecular Biology

Ecological (energy flow) Hierarchy
Regional Biota
Communities
Populations
Organisms
Somatic Cell Line
Somatic Cells
Molecules

Geneaological (more-making) Hierarchy
Species
Demes
Organisms
Germ Cell Line
Gametic Cells
Chromosomes
Genes

Subdisciplines/Hierarchy Overhead
Evolutionist
- Through evolution, it was advantageous to have adapted to jump

Ethologist
- The frog had a goal to avoid being eaten

Physiologist
- Retina - brain - nerve signal - muscles - jump

Developmental Biologist
- The frog developed the "wiring" to be able respond to the predator

Molecular Biologist
- The biochemical properties of its muscles (determined from DNA) allow it to jump
A Mystery Patient

In 1904, a young patient from Africa came to a Chicago physician, Dr. James Herrick, with a puzzling condition. Below is a summary of some of the observations that Dr. Herrick made. Your job task is two-fold, first to learn more about this condition and to find out how the disease is affecting this person's body. Second, this should provide you with an opportunity to gain insight in how the various levels of the biological hierarchy are related to one another in the context of explaining this disease.

The seventeen-year old patient reports feeling well most of the time. But he also reports odd recurring events. For instance, one day after a short swim he became so tired that he could hardly move. He became short of breath and complained of pain in his joints and muscles, especially the arms and legs. He felt unusually weak and required bed rest lasting a few weeks. These symptoms occurred repeatedly during his childhood. He also had frequent fevers and infections.

The patient complained of fatigue and soreness in the joints. Upon inspection, the whites of his eyes had a yellowish tint. He complained of pain in the left abdominal area, which was tender to the touch.
Normal Patient's Blood

Mystery Patient's Blood

Histology Slide Overhead
Class #2  
**Genetic Perspective**

During this class, students will continue their examination of the mystery patient through the perspective of (classical) genetics (and to a lesser degree physiology). The instructor will guide students through the uses of a pedigree, and students will engage in group work to solve a pedigree problem that concerns the mystery patient's family. Following this, students will be invited to consider differences between *in-vitro* and *in-vivo* testing.

**Historical Background**

From an historical perspective, following James Herrick's examination of the blood of the “mystery patient”, a subsequent phase of research concerned identifying whether or not the disease was a function of genetics (heredity). This involved identifying patients who exhibited similar symptoms to the mystery patient, sampling the blood of the surviving relatives, and examining pedigrees to determine possible (Mendelian-based) inheritance patterns.

In 1923, Drs. Taliaferro and Huck, from the United States, used a common *in-vitro* technique (developed by another medical physician, Dr. Emmel in 1917) to identify for the presence or absence of “sickling” in the blood. From this information, they constructed pedigrees of families who had members that suffered from symptoms similar to (and to a lesser degree than) the mystery patient. Taliaferro and Huck concluded that based on their *in-vitro* testing and based on the clinical symptoms shown by the mystery patient and his family members, the disease was transmitted via the Simple Dominance Model. It’s important to understand that they believed that the presence (severity) of the disease was based on having a dominant allele. Homozygote Dominant individuals were severely afflicted. Heterozygotes were moderately afflicted, and normal individuals possessed no apparent phenotype.

The first part of this class will have students explore constructing an inheritance model in the manner done by Taliaferro and Huck. Students will be challenged to consider the evidence from their pedigrees and construct a theory to account for the possible inheritance of the disease. The second portion of the class will examine various conceptual difficulties with the Emmel test that cast doubt on its ability to fully resolve the physiological changes in the blood of afflicted individuals.

**Day 2 Objectives**

This class further immerses students into an open-ended learning environment in which they engage in problem solving. The hope is that students will begin to integrate the information they learned during the genetics portion of BIOS 270 (genetics models) into their solutions for the pedigrees. Through the genetics problems students are invited to consider and discuss several aspects of the nature of science.
Day 2 Materials and Equipment
1. 12 copies of the Pedigree Analysis Handout
2. Sample Pedigree Overhead
3. Saturation Overhead

Day 2 Background Reading Materials
• The instructor should carefully read through the historical background provided in this section of the manual

Set-up Prior to Class
• Equipment

• Homework (Posted on the right hand side of the white board):
• Write a daily diary entry based on your experiences for this and previous classes. Summarize what took place, and consider the diary “seed” questions. Create a concept map of the second set of Organismal Biology concepts listed on p. 203 with reference to the reading "Anatomy and Physiology of the Cardiovascular System" (pp. 209-222). Combine these with the first set in your comprehensive concept map for the entire unit.

• On Board:
  • Diary “Seed” Questions
    Inquiry
    What connections did you see between the genetics discussions last time and our exploration of the physiology and cellular anatomy during the first class?
    How could you account for the differences between individuals who seem to have some of the symptoms of the mystery disease, as compared to those like our mystery patient who have the full-blown disease?
  • M/R
    Is the theory you developed today a “good” theory? Why or why not?
    What characteristics make a theory a “good” theory?

• Agenda:
  1. Class Business
     a. Turn in diary entry?
  2. Student presentations
  3. Concept Mapping
  4. Intro. Pedigrees
  5. Pedigree Problem
     - Discussion
- NOS: Comparing Theories
6. "Between Body and Dish"
7. In-vitro vs. In-vivo
Class #2
Genetics i
Overview

1. Class Business (~5 min)
The instructor should cover any miscellaneous issues related to the course.

2. Student Presentations (~30 min)
See class #1

3. Concept Mapping (~5-10 min)
The instructor should facilitate a discussion with students in which they construct a small concept map from the list of concepts assigned to them last class as practice work:

- blood
- deoxygenated blood
- oxygenated blood
- capillaries

Note: The example concept map represents just one possible way of properly depicting the relationships between these concepts. It's conceivable that students will come up with alternatives that are equally acceptable.

4. Introduction to Pedigrees (~20 min)
First, it would be appropriate to set up the context of the class. Given that students have explored some of the cellular dimensions of the mystery disease, they will now make a transition to explore if the disease is heritable. One mechanism of doing this is with the use of the pedigree.

One way of beginning the class is to ask students how they would go about determining if a disorder (or entity of interest) is inherited in humans. The
conversation could likely go many directions, although it is common that a student or students will suggest that they should look to see if family members display the characteristic. The instructor can further probe to see if students can think of ways to construct a visual “map” to help identify patterns for genetic analyses. This will lead into a discussion of pedigrees. Note, the instructor should bear in mind that the context of the data that students will be examining in this class was obtained during 1923. As such, keep in mind that this was well before the “discovery” of DNA and modern molecular techniques. Therefore, while a student might suggest that examining the DNA (or protein structure, etc.) would help elucidate possible inheritance relationships, this just simply wouldn’t have been possible in 1923.

It would be useful to put up the simple overhead of a sample pedigree and walk students through the basics of the structural elements. Considering a larger perspective (a theme of the courses 170 and 270), pedigrees provide insight into the nature and usefulness of models. They are constructed from the observation of patterns. They are used to represent and explain phenomena.

The instructor can use this hypothetical example to explain the structure of a pedigree (what the lines, circles, etc. indicate).

- Do any patterns emerge from the example?

  *It appears as though only females are afflicted.*

- Is there something significant in the fact that only females seem to exhibit symptoms?

  *This should lead into a general review of Mendelian Genetics.*
Review of Classical Genetics

This should be a relatively cursory review of Mendelian concepts/mechanics such that students will be able to do their own interpretations of the mystery patient’s pedigree. The instructor should ensure that students are familiar with the concepts of homozygote, heterozygote, and the mechanism of allelic inheritance. It would be useful to review the Punnett Square - that it is used to show how gametes combine to form potential zygote combinations. This skill will be useful as students examine both of the patient pedigrees (version 1 from this class and version 2 from the next class).

A useful example would be to walk through a hypothetical mating on the board. Step 1, model that a homozygote man marries a heterozygote female. Note: Keep the example simple by not mentioning dominance or recessiveness. You want to let them work through those issues in their own classroom problem.

In step 2, have them help you create a Punnett Square. Then, in Step 3, create a very simple pedigree from that Punnett Square. Note: The example here depicts (for no reason) that the couple had two boys and two girls.

The larger point is to illustrate to students how the concepts of alleles and genotypes can be used in conjunction with the visual representation of the pedigree. In the simple example above, we worked forward from genotypes to a pedigree representation. In their own problem work, students will likely have to consider the reverse (that is given the pedigree, can they think of possible genotypes and matings).

5. Pedigree Problem I (~40 min)

Note: The instructor should feel comfortable paraphrasing the historical information (in this and subsequent classes) to the class.

The instructor should use the overhead of the problem to facilitate.

One way of beginning is by setting the context. In 1923, two American scientists, Taliaferro and Huck, were interested to find out if the “mystery disease”
was a heritable disease. They collected blood from individuals who suffered from the disease and also examined blood from relatives. Note, the lesson plan corrupts history to a degree here for pedagogical reasons. Though Taliaferro and Huck did work on the sickle-cell phenomenon, they did not examine the blood of the original “mystery patient” nor any of his family members. For the purpose of keeping an historical “story”, this lesson makes it seem as if they did.

Students should be instructed to assemble in groups of three. Each group should be given copies of the pedigree data. Students will be expected to use Mendelian inheritance models to come up with a mechanism that explains the pedigree. Students should be encouraged to note any outstanding questions they may have regarding the pedigree. They should also be making respective recordings in their diary.

The groups’ attention should be drawn to the following probing questions that the instructor has placed on the board:

1. Suppose that another group of students proposes a different theory to explain the genetics of the mystery disease. How would scientists value which theory is more valid?

In addition to working through the given pedigree problem, students should be encouraged to talk about the probing question(s) on the board in relation to their insights gained by examining the historical data. The instructor should emphasize that the class discussions will build off of this initial probing question.

Recall that there are essentially three basic models for inheritance. Students will likely consider 1) simple dominance (with either dominantly or recessively determined phenotypes), 2) sex-linkage (a variant of simple dominance), and 3) codominance.

Although there is room for interpretation, the morphological evidence from the pedigree leans toward the simple dominance model. Under this model, a homozygote dominant (e.g. AA) would express the mystery phenotype (the changing of the red blood cells under the test conditions). The heterozygote, Aa, would also exhibit the mystery phenotype. As suggested in the problem, a distinction between these two would be based on severity of symptoms. Here, the mystery patient, his grandmother, his uncle, and his niece would likely by “AA” and experience the severe symptoms by virtue of having two copies of the mystery allele. Those individuals who suffer milder symptoms would be heterozygotes. The genotype, aa, would be normal (as evidenced by a non-shaded circle or square in the pedigree. It should be expected that students construct the Simple Dominance Model (with a dominantly-based expression). Note, be careful not to confuse that the pedigree is depicting only whether or not the person’s blood changed shape following the Emmel
test. That is, the pedigree does not directly measure the symptoms that are given in the initial paragraph.

After a period of time, the class should reassemble, and student groups should (informally) present their interpretations. Randomly select a couple of groups to propose and explain their models. *Use the overhead of the sample problem to facilitate- by way of writing on it with an overhead pen.*

The instructor should feel comfortable probing for the students’ evidence. For example, why is it not sex-linked? The instructor should also challenge other groups to agree/disagree. Again, the instructor should throughout these remaining classes challenge students to link their developing theories with evidence.

*NOS discussion – Theory Comparison*

The instructor should feel comfortable exploring with students an aspect of the nature of science that concerns how scientific theories are evaluated against one another. Likely, the previous group work (and group discussions of the probing question) revealed that there were different possible interpretations for which genetic model was most applicable.

It’s not uncommon for student groups to have conflicting theories. The point we wish to make is that we judge the superiority of one theory over another in many ways. One of them is by virtue of the amount of supportive evidence that one theory has over another. In this manner, the simple dominance model is most explanatory.

One way to facilitate the discussion is simply by asking students to address the probing question:

- Suppose we had two differing theories for a given phenomenon. How do scientists value which theory is more valid?

The conversation could go many directions. The instructor can facilitate this conversation by way of placing two “theories” on the board:

  “Simple Dominance”    “Sex-Linked”

Then, probe students to see how they would compare these two theories. The following aspects of theory comparison may play into the conversation if opportunity arises:

1. A more valid theory generally has more supportive evidence. Furthermore, a more robust theory has withstood more attempts to refute it (i.e. has “stood the
test of time”). In the example from above, there is more evidence to support the Simple Dominance Model as versus the Sex-Linked Model.

2. An alternative to consider is that if a theory “A” explains evidence “1” and “2”, and theory “B” also explains evidence “1” and “2” but also accounts for evidence “3”, we would judge theory “B” to be more explanatory.

6. Reading: Between Body and Petri Dish (10 min)

Transition – One way to make a transition is by pointing out (or perhaps by asking students for their insight) that researchers were puzzled that the blood of both the severe sufferers (like the mystery patient) and the mild sufferers both exhibited the curious property that the red blood cells changed shape under the 48 hour test. What was perplexing was that despite seemingly similar phenotypes (i.e. the shape changes) there was this other distinction between the severity of symptoms. The question is/was why? Is there some change happening in the blood with respect to shape of the erythrocytes that simply was not being resolved by the in-vitro test? From here, students should do the reading.

In class, have the students read the section in their manual regarding the differences between in-vitro and in-vivo testing. The point of this reading is to contrast measurements taken outside of normal body conditions with those that measure (as close as possible) what actually occurs in the body (or more specifically in the blood in our case). Understanding that in-vitro data (the type that was collected for the pedigree problem) has potential liabilities is important in order to appreciate why scientists sought to distinguish mystery disease full blown suffers from those had very mild symptoms despite their blood changing under the in-vitro test. Scientists began to wonder if by virtue of the fact that the in-vitro tests had a potential limitation they were missing certain distinguishing characteristics of both patient groups. This reading will set up the historical discussion.

7. Historical Lecture: Invitro vs. Invivo: Trait vs. Full Disease (~20-30 min)

The purpose for this section is to set the stage for the developing the distinction between the carrier of the disease and the full sickle-cell anemic (the heterozygote versus the homozygotic recessive). It would be best to begin with a general overview of the in-vitro methods that were historically used to test for sickling of the blood.

Review with students that the results of the first pedigree problem (whether or not these mystery cells appeared) were based on a particular test, the Emmel Test, known as an in-vitro test:
Researchers like Taliaferro and Huck used a technique (Emmel Test) developed in which blood was taken from an individual and placed in the middle of a wax ring which was affixed to the center of a slide. Perhaps drawing a simple picture on the board will clarify this concept (see right).

A cover slip was placed over the blood, effectively sealing it from air through the contact of the wax ring. Researchers noticed that for some individuals, sealed blood preparations that were allowed to sit for an extended period (approximately 48 hours) induced the change to the erythrocytes. These patients were characterized as sufferers of the mystery disease (as evidenced by the darkened square or circle on the pedigree).

The following questions to the class would be appropriate:

- Based on the article you just read, what was problematic about this type of test?

  *From the standpoint of preserving realism, having blood removed from the body and allowed to sit for an extended period is not closely mimicking the conditions within the body.*

- Based on your reading, did it depart from their understanding of physiology? If so, how?

  *Blood cells would continue to metabolize oxygen. After 48 hours, no oxygen would be left.*

This may require the instructor to do a short discussion of more detail that describes what happens under the cover slip during those 48 hours when the blood sample becomes anoxic. It is at this time that metabolic processes from the cells in the blood (for example the leukocytes) utilize all the existing oxygen. This level of anoxia does not happen normally in the circulatory system (Note: This information was covered in the reading that the students just completed).
Given that for some of the family members their blood did change shape under these conditions, what can be hypothesized about a possible cause of the shape change?

There appears to be a link between lower (or lack of) oxygen (or possibly something else that was being metabolized) and shape change in the red blood cells of some people.

Another significant piece of evidence that researchers found was that when oxygen was added back to the anoxic blood, in many cases, the red blood cell shapes reverted to their normal form (perhaps draw a simple picture on the board - see diagram). For the patients with only minor symptoms of the disease, nearly all of their blood cells reverted to the normal shape. In those patients who exhibited very severe symptoms (like the mystery patient), many of the red blood cells did not revert following the reimmersion in oxygen.

Place the following chart on the board to guide the discussion:

<table>
<thead>
<tr>
<th></th>
<th>Mystery Patient</th>
<th>Mild “Sufferer”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emmel Test</td>
<td>Red Blood Cells</td>
<td>Red Blood Cells</td>
</tr>
<tr>
<td>(No O2 at 48 hours)</td>
<td>Change Shape</td>
<td>Change Shape</td>
</tr>
<tr>
<td>Reimmersion in Oxygen</td>
<td>Mostly normal RBCs</td>
<td>Normal RBC’s</td>
</tr>
<tr>
<td></td>
<td>(some cells still strange)</td>
<td></td>
</tr>
</tbody>
</table>

Then, in 1933, a scientist by the name Diggs continued to work on the phenomenon. Diggs understood the inconclusiveness with respect to the potential for sickling under very low (anoxic) levels in both trait and full individuals. His research found that there were quantitative differences in the degree of sickling between trait individuals and full sickle-cell anemics depending on the level of oxygen concentrations. In short, Diggs was interested to see if there were differences in the degree of shape changes between the full and mild sufferers of the disease at levels of oxygen that were somewhere...
between anoxia (no oxygen) and very high levels.

One way of illustrating his interests is by using the overhead of the graph for the above table data. In this graph, the mystery patient (MP) and his brother (who suffers from mild symptoms) both have cell changes at the full anoxic condition of the Emmel test. When reintroduced to high levels of oxygen, the brother’s cells appear normal, and the mystery patient’s cells are nearly normal (some residual strange shapes remain).

Diggs found that (draw this on the overhead) when the oxygen levels were varied from high levels to anoxic levels, there was a difference between the degree to which the cells changed shape between the mystery patient and the mild sufferers. The data raised an interesting issue. Between levels of oxygen that were high and relatively lower (but not anoxic), as shown at the midpoint of the graph, there were marked differences between the full sufferers of the disease and the mild sufferers.

- Where in the circulatory system do oxygen concentrations change from higher to (relatively) lower and back again?

The answers should hopefully emerge that the arteries generally have blood erythrocytes with higher levels of bound oxygen. The veins have erythrocytes with lower levels of bound oxygen. The cycling of blood in the circulatory system models a scenario in which the blood goes from a state of high oxygen (arteries) to a lower state (veins). This transfer occurs in the capillaries. At the beginning of the capillary, the red blood cells begin to give off bound oxygen. By the time that they have reached the end of the capillary bed, they have given off the majority of their bound oxygen and have acquired the majority of their carbon dioxide.

Though scientists at that time speculated that there were possible differences between full sufferers and mild sufferers between the shapes of their red blood cells in the veins, there was no practical way to measure the differences. That is, at this time they could only rely on the Emmel test (which had it’s limitations).
Sample Pedigree Overhead
Pedigree Analysis

A family history reveals that the mystery patient has two brothers and three sisters, and although several of his siblings have minor symptoms, none of his siblings have problems nearly as severe as those experienced by the mystery patient. His grandmother and one niece used to have similar severe symptoms to the mystery patient. His grandmother died a young woman.

Researchers were able to take blood samples from each of his surviving relatives to see how they compared to the sample of blood from the patient. All blood samples were drawn and placed under airtight cover slips on slides for later analysis. This involved first placing a paraffin (wax) ring on a slide. Blood was taken from an individual and placed in the center of the ring. A cover-slide was then placed down onto the slide such that the blood was sandwiched between the cover slip and the slide. After 48 hours under these conditions, researchers looked to see whether or not there were any changes in the blood cells.

Below, you will find a pedigree chart that summarizes the family genealogy and hematology data. When a person’s blood slide showed blood characteristics (the strange shapes of the red blood cells) similar to the mystery patient’s, their respective square or circle was darkened. Take caution – the pedigree only depicts whether or not blood cells changed shape. It does not depict the differences in symptoms discussed above (e.g. severe, mild and none).

Your job is to determine:
1. Is this disease heritable (i.e. is it a function of inheritance)?
2. If so, which of the models we used in BIOS 270 accounts for this pattern? What is your evidence?
3. If not, what is your evidence?

[Pedigree chart showing family relationships and blood cell changes]

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Class #3

Genetic Perspective ii

In this class, students will continue their pedigree examinations of the mystery patient’s family. In this session, new technology (in the form of new methods for testing the blood) provides evidence that conflicts with their prior explanatory theory of a genetic model based on dominance. This activity provides an ideal opportunity to discuss the nature of science concerning the relationship of theories to the development of scientific knowledge. Here, students will consider such issues as how scientific knowledge (in the form of theories) is tentative and how competitive theories are evaluated.

The final activity involves a simulation in which students consider how the frequency of deleterious alleles change in a population of interbreeding individuals over successive generations.

Historical Background

Here again, the instructor should feel comfortable paraphrasing the following historical information to the students during the course of this class.

In 1947, JV Neel, a physician and researcher from the University of Michigan, used Dr. Sherman’s new in-vivo venous sampling technique to develop new pedigree information for sickle-cell (remember – “mystery”) patients. Recall that prior to Neel’s work, the paradigm was that sickle-cell anemia was inherited via a simple dominance model by virtue of a dominantly expressed allele. Under this model, doctors recognized that there were differing forms of severity - from full sickle-cell anemic sufferers to those individuals termed “sicklemics.” The latter referred to the fact that while these patients suffered virtually no symptoms (except under extreme circumstances), their blood did change shape when placed under the anoxic conditions via the Emmel test (in-vitro).

Neel’s conclusions initiated a theory change. He used the results from the new test in which a patient’s venous blood was drawn and kept under conditions similar to those found in-vivo. As a result, Neel was able to construct a different picture of if and when a patient’s blood changed shape. Under venous blood oxygen levels, (what would be characterized) homozygous recessive individual’s blood changed shape. Sicklemics, or carriers, did not. Neel determined that the disease was inherited via the autosomal recessive model. Specifically, the full sickle-cell anemic had two copies of the recessive allele. The carrier, or sicklaemic, was the heterozygote.

This class period will have students partially replicate the pedigree examinations done by Dr. Neel. Following student model reconstruction (i.e. constructing a new theory to explain the inheritance of the disease), the instructor will
facilitate an activity and discussion about the tentative nature of science and about predicting population dynamics (allele frequencies). This activity will illustrate what should happen to various alleles given certain conditions. It will be a helpful activity to set up the subsequent class on population dynamics / evolution.

**Day 3 Objectives**
To continue to analyze how genetics provides insight into the mystery disease.

**Day 3 Materials and Equipment**
1. Materials for the allele frequency simulation
   1. Simulation cards
   2. 4-sided die
2. Sufficient copies (12 for groups of 2) of the Pedigree II handout
3. Overhead of Pedigree II problem

**Day 3 Background Reading Materials**
- The instructor should carefully read through the course pack materials assigned for this day
- The instructor should carefully read the historical background provided in this section of the manual

**Set-up Prior to Class**
- Equipment
  - Ensure that the simulation cards and die are at hand
  - Have the overheads and handouts ready
- Homework (Posted on the right hand side of the white board):
  Write a daily diary entry based on your experiences in this and previous classes. Summarize what took place, and consider the “seed” questions.

- On Board:
  - **Diary “Seed” Questions**
    - **Inquiry**
      Are the results from this class a “better” interpretation of the genetics than the last class? Why or why not?
    - **M/R**
      Do you think that the results from today “proves” the genetics of the mystery disease? Why or why not?
  - **Agenda:**
    1. Class business
      a. Turn in diary entry?
    2. Student Presentations
3. Concept Mapping
4. In-vitro vs. In-vivo review
5. Pedigree Part II
6. Discussions
   - Pedigree Problem
   - Tentative NOS
   - Theories vs. Laws
7. Allele Prediction Simulation/Discussion
1. **Class Business (~5 min)**
   The instructor should cover any miscellaneous issues related to the course.

2. **Student Presentations (~30 min)**
   See class #1

3. **Concept Mapping (~5-10 min)**
   The instructor should facilitate a discussion with students in which they construct a small concept map from the list of concepts assigned to them last class as practice work:

- oxygen
- iron
- erythrocytes
- heme group
- bone marrow
- hemoglobin
- tetramer
- proteins

*Note: The example concept map represents just one possible way of properly depicting the relationships between these concepts. It's conceivable that students will come up with alternatives that are equally acceptable.*

4. **In-vitro vs. In-vivo review (~10 min)**
   The class should begin with a review from the results of the previous section. The instructor may wish to use some of the overheads and tables from the last class to facilitate the review. Specifically, recall that scientists speculated that there were differences between the shapes of the red blood cells of patients like the mystery patient and those mild sufferers of the disease when oxygen concentrations were lowered to conditions that were normally found in the venous system. The problem was that there was no practical way to test this hypothesis.
The Emmel test was at the time the only in-vitro test that could be done. Recall that the test involved placing blood under cover slip and wax (on a slide). After approximately 48 hours, an anoxic condition develops.

However, in 1940, a Chicago-based medical physician named I. Sherman developed a new test. Using his technique, scientists were able to draw blood from the vein and examine the structure of the red blood cells. This test involved drawing venous blood and placing it onto a slide in which the conditions (pressures and concentrations of oxygen) were similar to those found (and are maintained) in the vein. The Sherman test is more akin to an \textit{in-vivo} interpretation of what occurs to the red blood cells.

- Why do we prefer the \textit{in-vivo} test?

\textit{It more closely mimics the real conditions that exist in the blood (in the body). It allows for the distinction to be made between full sufferers and those people who only exhibit mild symptoms. (be careful not to use the term “carriers” at this stage for it may lead the students toward prematurely concluding the recessive nature of the disease).}

The instructor should also spend a few minutes reminding students what theory they had constructed from the previous class – that the mystery disease was inherited / expressed via a dominant allele manifested in the simple dominance Mendelian model. One way of motivating this is by drawing students’ attention to a table that could be placed on the board and facilitating a review of the evidence to account for this:

\begin{center}
\begin{tabular}{|c|c|}
\hline
1923 – Taliaferro & Huck & Simple Dominance – Dominant Expression \\
\hline
\end{tabular}
\end{center}

5. \textbf{Pedigree Analysis Part II (~30 min)}

Students should be encouraged to break up into groups (two to three per group). Each group should be given a copy of the pedigree II problem handout. The instructor may wish to preface the handout by indicating that the venous blood (\textit{in-vivo}) test was performed many years later on the surviving members of the patient’s family. The results are contained in the handout.

The groups’ attention should be drawn to the following probing questions that the instructor has placed on the board:

1. Was your theory (simple dominance) that you developed last class based on the pedigree data from 1923 “wrong”? 

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2. After today's problem, do you have a new theory to explain the genetics?
3. If yes, what (specifically) led to your new theory?

In addition to working through the given problem, students should be encouraged to talk about the probing question(s) on the board in relation to their insights gained by examining the historical data. The instructor should emphasize that the class discussions will build off of these initial probing questions.

Students should be challenged to see if evidence from this new pedigree conflicts or supports their previously constructed theory for the inheritance of the disease.

6. Group Discussions (~ 30 min)

As before, student groups should be expected to informally present their models of inheritance. Given the evidence in the second pedigree, students should be able to conclude that the inheritance of the disease involves a homozygous recessive condition. The previously characterized "mild sufferers" are denoted as heterozygotes or carriers.

Nature of Science Discussion – The Tentative Nature of Science

Students typically have several misconceptions about the nature of scientific theories. One is that theories, once constructed, are not subject to change. This misconception likely contributes to another more fundamental misunderstanding about the nature of science. Many students see science as a body of knowledge that is robust, proven, and unchanging. This is often shown through comments that the students make about theories themselves. Students may claim that theories are something used to “prove” scientific knowledge. The misconception here is twofold – students believe that science is associated with truths and that theories can be proven (rather than the correct conception that we can only refute theories). What we want to draw their attention to is that scientific knowledge is tentative, with new theories often replacing old by virtue of new lines of evidence (often predicated on advances in technology as modeled in class today) or by way of new conceptions of the “problem” by the scientists themselves. This later way in which theories change is important to consider. It’s not too uncommon for students to recognize that changes in technology impact theories. It’s not common for students to recognize that theories may change simply by virtue of changes in thinking, e.g., when scientists achieve new insights.

This should form the crux of the discussion that the instructor initiates with the students. On one hand, we want them to come to the understanding that the validity of scientific knowledge is grounded upon its correct explanatory power (i.e. the strength of its theories). On the other hand, we want to impart that scientific knowledge is tentative. It is the nature of science that as newer evidence emerges or when new insights are gained, scientists engage in the
process of revising existing theories (or abandoning them altogether for alternative ones). Additionally, we should challenge students to consider that one aspect of the nature of science concerns the existence of competing theories to explain a given phenomenon. Here, science regards the more robust theory as the one which has greater explanatory power (predicated on more conclusive evidence). Note: This latter point about comparing theories based on their supportive evidence will be visited again in the second class on population/evolution.

Given the students’ theory from the last class (autosomal dominance) and the (new) theory from this class (autosomal recessive), the instructor can probe for students’ understanding about this aspect of the nature of science/theories. The following are suggested questions to initiate the discussion (then follow up with several of the issues raised in the preceding text):

- Was their (the students’) first theory (simple dominance) “wrong” after completing the first genetic class? How is it “wrong” after this class? Why or why not?

*The instructor should feel comfortable probing for understanding of the tentative nature of science – that new evidence has caused them to change their explanation of the casual mechanisms of inheritance.*

- What caused you (students) to change your theory from the preceding class?

*The instructor should question students to see if they conceive that other mechanisms (e.g. insights made my scientists, reconceptualizing the problem) can be used to initiate a theory change.*

- How do we (science/scientists) judge whether one theory is “better” than another? What do we mean by “better”?

*Again, the question can allow the students to express their understanding of how theories are compared by comparing simple dominance, dominant expression with simple dominance, recessive expression.*

**Nature of Science Discussion – Theories vs. Laws**

The instructor should also bear in mind that another related misconception about theories may be raised by the students. If they do not raise this issue, the instructor should ask students to differentiate between theories and laws. Students commonly consider that facts (evidence), theories, and laws are hierarchically related. In this manner, they feel that evidence may eventually evolve into theories and furthermore that theories themselves in time potentially become laws. What prevents a theory from achieving the status of a law (according to the
misconception) is simply a lack of supporting evidence or a competing theory that presents conflicting evidence.

What we want to impart to the students is that theories and laws do not have such a hierarchical relationship. Theories and laws are distinctly different entities. Theories are explanations that are predicated on supporting evidence (facts). Laws are general descriptions about some aspect of the way the world works. Theories do not "become" laws.

One way to facilitate this discussion is by simply asking students:

- Given that we've discussed how theories are developed and how they change, what do you think scientists mean when they refer to a scientific law?

_The instructor may wish to use an example of a "law" in biology, Mendel's Law of Segregation or Independent Assortment. In discussing either of these two examples, the instructor can point out that the identifying characteristic of the "law" is that it is a description of what occurs. Furthermore, it is a "law" because the actions described by the law hold true (are repeatable and predictable). The students should note that there is no explanatory element in the law. Explanations are given from theories. For example, there would be theories to explain how or why the Law of Independent Assortment exists._

7. **Allele Prediction Simulation (~20 – 30 min)**

Given the [autosomal] recessive model, the instructor should pose a fundamental question related to a population level:

- Given that the allele appears to be deleterious (i.e. it causes a disease associated with increased morbidity), what should we expect to happen to it over time in a population of interbreeding individuals?

A simulation may be useful to illustrate the dynamics of this question:

The following materials will be required -

- The simulation "cards"
  - 2"x3" cards of approx. 30 w/ "++", 20 w/ "+-", 10 w/ "--"
- A four sided die

---

40 Several philosophers of biology have drawn attention to the notion that in truth there are no laws in biology (e.g. meiotic drive provides evidence against the law of independent assortment). For pedagogical reasons, these subtleties are ignored.
1. The instructor should draw the following table on the board:

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>Generation 1</th>
<th>Generation 2</th>
<th>Generation 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;+/+&quot;</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;+/−&quot;</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;−/−&quot;</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency &quot;+&quot;</td>
<td>5/8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency &quot;+&quot;</td>
<td>3/8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Initially, there will be three different genotypes (see table). You should give two students each a "+/+" card, one student a "+/−" card, and the final volunteer a "−/−" card.

3. The instructor should indicate that the students are simulating a small population. By drawing reference to the board, students can see how the initial values are represented. At the start, there are two normal individuals, one carrier, and one full sufferer.

4. The four students should be encouraged to randomly "mate" (i.e. in this case there should be two matings - for example volunteer #1 with #3 and #2 with #4).

5. Using the Punnett Square, students should write down the possible offspring.

   Note: This simulation assumes that all potential offspring are born and survive to reproductive age EXCEPT for a majority of the homozygote recessive "−/−". After offspring have been calculated (see below), roll the 4-sided die for each "−/−" that results in the population. Pick one of the four numbers (for example, number 1) to represent "survival" of the homozygote recessive. This is to simulate that each homozygote recessive has about a 25% chance of reaching reproductive age.

   Note 2: For the first "−/−" in the population (at the start) assume that this person has already reached reproductive age.

   Note 3: Assume that parents are not counted in subsequent generations.

   For simplicity, assume that parents "die off" shortly after producing children.

6. For example, let's assume that +/+ x +/- and +/+ x -/- in the first round of mating. The following offspring would be produced:
7. The instructor should fill in the information for generation 1 (see table).

8. The instructor should form a new population pool based on the types of individuals in the first generation (in this case, place 2 "+/+" and 6 "+-" in a box. Note: If there are any "-/-" individuals, the instructor should role the die (roll separately for each "-/-") to determine if each gets added to the population pool.

<table>
<thead>
<tr>
<th>Start</th>
<th>Generation 1</th>
<th>Generation 2</th>
<th>Generation 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;+/+&quot;</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>&quot;+/-&quot;</td>
<td>1</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>&quot;-/-&quot;</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Frequency "+" = 5/8, 10/16
Frequency "+" = 3/8, 6/16

9. Select volunteers to reach in and randomly pick two cards to "mate" with each other. In the above example, a total of four students will be required to select two cards. Students should work through their own Punnett square calculations and the instructor should tabulate the results. For example:

+/+ x +/- 
+/+ x +/- 
+/- x +/- 
+/- x +/- 

note: If there is an uneven number of individuals in the total pool, the last unpaired individual will simply not be used to produce offspring (assume monogamy in this simulation)

This will result in the following summary:
10. The class should then repeat steps 8 - 9 using the appropriate cards. Given that the recessives are mostly removed from further mating, the frequencies in the third generation will begin to decline.

**Discussion**

The instructor can ask for student interpretations of the simulation data. Essentially, it should become apparent that given the deleterious nature of the "-" allele (i.e. that it causes a mystery disease in which 3/4 of the individuals do not survive to reproductive age), its removal from the population in the homozygous state will effectively cause it to decline in frequency in time. The instructor can refer to the time required to remove the allele from the population. From the simulation, it appears as if the total removal will take many generations, however, the allele frequencies do appear to be declining. The point is that the disappearance of the allele won't occur rapidly, but through many generations, one should expect that the allele would be effectively removed.

This discussion should nicely set up the section on population dynamics.
Pedigree Part II

Several years later, further research was done with the mystery patient’s family to try to better understand the mechanism of inheritance of the disease. Whereas the previous blood analysis used *in-vitro* results (blood that had remained under a cover slip for a couple of days) a new technique was employed that could analyze *in-vivo* samples.

A family member’s blood was drawn from their vein, put under a cover slip that already maintained environmental conditions similar to the person’s veins (pressure, acidity, etc.), and examined using the microscope. What resulted from this research is depicted in the pedigree contained below.

Using the *in-vivo*, venous technique, scientists were able to distinguish between those individuals whose red blood cells changed shape in the veins versus those whose shape remained “normal” while in the veins. Note that the symptoms have not changed from the earlier pedigree - those surviving members (e.g. the patient’s brother) who suffered milder symptoms in the previous sample still suffer from mild symptoms.

Given this pedigree, do you believe that genetics is still a factor in the transmission of the disease? If so, how (i.e. what model)?

Note: A diagonal line means that the person has deceased. *In-vivo* data for that person was not available.
Students will be confronted with an apparent anomaly – that in certain parts of Africa, the mystery disease allele exists in relatively high, stable frequencies. This is contra to their prediction from the last class for what should happen to deleterious alleles. Today, students will examine ethnographic and geographic data to determine a possible cause. Again, this is an opportunity for students to engage in theory construction (explaining "why" the anomaly exists) by virtue of the evidence that they are examining.

**Instructor Information**

For the students, this class will be very open-ended. For this reason, it will be important for the instructor to facilitate when necessary. However, students should be thoroughly encouraged to develop their own theories (explanations).

This class should confront a fundamental anomaly with respect to the issues explored in the previous class. From the simple dominance model of autosomal recessive inheritance constructed by the students and from the allele prediction made in the subsequent simulation, students should expect that the frequency of carriers, or the deleterious alleles, should be very low (if not absent altogether).

The instructor will present them with the anomaly by way of acquainting them with allele frequency data from Uganda. Certain places in the world (in our example, Uganda Africa) have populations of individuals in which the allele frequencies for the deleterious allele are quite high (and appear to be stable).

This initial class (the first of two) on population/evolution is intended to model the early historical work of ethnographers who were grappling with explaining the allele frequency anomalies in Central Africa. From the period of roughly 1945 - 1954, researchers worked to solve this apparent mystery. The scientific name for the anomaly is human polymorphism (differing forms). Scientists sought answers as to why differing forms of alleles (or traits) seemed to be maintained in a population given that the apparent deleterious nature of the recessive allele (or trait) would have them removed in time from that population.

**Day 4 Objectives**

- To use open-ended problems to examine evolutionary aspects of the mystery disease.

**Day 22 Materials and Equipment**

1. Have enough copies of the four problem handouts:
   a. Uganda Language Group Immigration
   b. Uganda Language Groups
c. Uganda Allele Frequencies  
d. Uganda Topographical Features  

2. OH of each of the four handouts  
3. Africa research OH  
4. Simple Allele Frequency OH

**Day 22 Background Reading Materials**  
- The instructor should be very familiar with the historical overview provided later in this section of the manual

**Set-up Prior to Class**  
- Equipment  
  - Make sure that the overheads and handouts are ready.
- Homework (Posted on the right hand side of the white board):  
  - Write a daily diary entry based on your experiences in this and previous classes. Summarize what took place, and consider the diary “seed” questions. Read "Malarial Safari" (pp. 235-239).

- On Board:  
  - Diary “Seed” Questions  
    - Inquiry  
      - What was the anomaly (unexpected finding) we discovered about the mystery disease from this class? Develop a theory that would explain this anomaly, and identify the evidence you have in favor of your theory.  
    - M/R  
      - Since 1947, the evidence (e.g. pedigrees) in support of the genetics of the mystery disease strongly favors the theory of (recessive) simple dominance. Suppose in 2003 you collect pedigree information and your new data conflicts with the long-standing theory. What does this do to the status of that original theory?

- Agenda:  
  1. Class Business  
     a. Turn in diary entry?  
  2. Student Presentations  
  3. Concept Mapping  
  4. Review Allele Frequency Predictions  
  5. Historical Lecture  
  6. Uganda Problem  
  7. Discussion
1. **Class Business (~ 5 min)**
   The instructor should cover any miscellaneous issues related to the course.

2. **Student Presentations (~ 30 min)**
   - See class #1

3. **Concept Mapping (~ 5 min)**
   The instructor should field questions regarding student work on the concepts.

4. **Review Allele Frequency Predictions (~ 20 min)**

   Announce that today we’ll examine the mystery disease from an evolutionary and population-level perspective.

   The purpose of this lecture is to refresh students about what they thought should happen to deleterious alleles in a population. It may be worthwhile to incorporate a graph, etc. on the board to illustrate frequency results. The bottom line is to remind them that they predicted that deleterious alleles are expected to decline in a population of interbreeding individuals over successive generations.

   Also, it will be important to introduce another question / issue:

   - Where do alternative alleles like the mystery allele come from in the first place?

   Generally speaking, alternative alleles (those other than the “normal” allele) represent mutations that have occurred and which arise in the population.

   It would be helpful to model this phenomenon on the board by thinking about an example population of ladybugs, all of which contain the genotype of “A/A” (which confers spots on the body). Suppose a mutation arose (an “a” allele) such that no spots were produced when in the homozygous state. At first, the mutation would appear as a heterozygote “A/a” (center illustration). Over time, should two heterozygotes (both of whom would have had independent “a” mutations in the spot gene) happen to mate, an “a/a”, “no spot” ladybug might
result (right illustration). Assuming the “a/a” had no deleterious effects, the “a” allele may continue to increase in the population.

But, if the “a/a” phenotype was more easily recognized by predators, it (and the “a” allele itself) would be removed from the population in time similar to what we predict to happen to the mystery allele.

The bottom line: The mutation rate can be thought of as the rate in which new alleles arise (in the population) over a period of time.

• What if the mutation rate was higher than the rate that the allele was removed from the population? For example, what if the “no spots” mutation rate was higher than the removal of the “no spots” allele (by predation) from the population?

If this was the case, then one would expect to see a consistent proportion of the population to exhibit the deleterious “no spots” phenotype.

5. Historical Lecture (~ 5 min)

The purpose of this brief historical lecture is to give the students a context that will help frame what will be the fundamental question: Why are the carriers of the disease (or high frequencies of the allele) persisting in the population?

Perhaps the best way to begin is to point out that during the early to mid 20th century, researchers became interested in characterizing human polymorphisms, particularly from a genetic perspective. Population genetics was still in its infancy, and the opportunities to explore potential problems were enticing to new researchers.

The continent of Africa was attractive for a number of reasons (use overhead):

1. There was easy access to relatively stable populations of tribal people.
2. There seemed to be dramatically different environmental conditions demarking where these populations lived. Thus, there was a good potential to explore environmental variables.
3. The Sub-Saharan people were afflicted with many inherited disorders, and thus there were several potential diseases to examine.
4. There was a relative lack of governmental constraints that would otherwise impede scientists’ ability to conduct human research.

One common research methodology was called hematology. This involved examining the blood of individuals for various disorders. Essentially, scientists would select a tribal group, draw blood from a number of the members, and categorize that blood with respect to several variables. In this manner, a number of polymorphisms could be analyzed.
The instructor should also point out to students that the theory they developed last class (inheritance based on recessive gene via simple dominance model) should allow them to make certain predictions. One such prediction is that we shouldn’t expect to find very many mystery disease alleles in a population of individuals (whether in terms of carriers or less likely in terms of full sufferers of the disease).

6. **Uganda Problem (~45 min)**

Students should work in groups for this task, however, they should also be encouraged to collaborate with other groups if necessary.

One way to begin this problem is by using the overhead of Uganda Language Groups and Allele Frequencies and drawing students’ attention to the data contained on the map. One of the polymorphisms studied by scientists during the mid-1940s to early 1950’s concerned whether or not a person was afflicted with the mystery disease by virtue of his or her blood changing using the diagnostic techniques similar to those done in the prior class. The frequencies represented (in terms of percentages) on the map correspond to the frequency of carriers for the mystery disease in various parts of the country of Uganda. If it is not apparent to the students, the instructor may wish to point out that scientists were very surprised at the anomaly depicted on the map. Namely, the mystery disease was shown to be prevalent in relatively high numbers and moreover was distributed in very heterogeneous frequencies.

Following this introduction, the instructor should pass out copies of the five handouts to each student for them to consider as data for the subsequent problem. The instructor should point out to the groups that the purpose of this segment is for them to examine the data from Uganda and attempt to come up with theories to explain why:

a) There appear to be a high number (frequency) of carriers in certain locations

b) Why there is such a mixture of high frequencies and low frequencies across the country.

The groups’ attention should also be drawn to the following probing questions that the instructor has placed on the board:

- As “scientists” you all have access to similar data for the Uganda Problem. Do you think that you will all come to the same theory to explain the unusually high frequencies? Why or why not?

In addition to working through the given problem, students should be encouraged to talk about the probing question on the board in relation to their insights gained by examining the historical data. The instructor should emphasize that part of the class discussions will build off of this initial probing question.
The handouts are as follows (note - use overheads of the handouts to explain to the students the contents of each):

1) Uganda Language Group Immigration

This handout depicts the four major ethnic groups (termed language groups) that existed in Uganda. The arrows show from what direction these groups colonized (and at what time) Uganda.

2) Uganda Language Groups

This chart gives information about the four major ethnic groups (termed language groups). It may be helpful to refer to the second handout (Immigration) for a map of the relative location of the groups.

Note: It will be important to emphasize to students that each language group contained several different, distinct tribes. For example, the Bantu group contained in excess of a dozen different tribal groups.

There are three pieces (columns) of information for each group. The first column concerns “Allele Frequency.” This refers to the relative degree of allele frequency that one group has with respect to the others. For example, the chart indicates that the Eastern Bantu tribe has a relatively high degree (or prevalence) of the deleterious allele than does the Hamitic group.

The column “Europoid Features” is essentially a characterization of the language group with respect to the degree in which the average tribal member possessed Caucasian-like features.

The instructor and students should bear in mind:

a) Within each language group, there were several different tribes (with much intra-language group tribal variability). That being said, there were distinct differences between language groups with respect to physical characteristics (as generally summarized in the handout).

b) Be careful not to carry the characterization to an extreme. That the Hamitic group has/had a high degree of Europoid Features does not mean they most closely resemble Caucasians. The Hamitic Group were certainly Negroid. However, they had somewhat lighter skin, more narrow nose ridges, were taller in stature, etc. BE SENSITIVE TO HOW STUDENTS MIGHT REACT TO THIS DISCUSSION.

The column “Between Group Contact” identifies if (and to what degree) a group may have had contact with the listed group. As denoted in the notation,
contact should be regarded as a reflection of the amount of intermarriage that occurred between the groups for mixing alleles.

*Note: At some point during which students are working with the data, the instructor may wish to use the simple allele frequency overhead (or draw it on the board) to give students a feel for how to interpret the frequency data on the Uganda map. In using this overhead, students may gain insight into possible mechanisms of allele origination or allele “movement” via marriages, etc. The instructor can use this overhead (or drawing) to illustrate how alleles can “mix” when certain more proximally located people intermarry.*

3) Allele Frequency Map

This map provides a more detailed depiction of the allele frequencies. The percentages in the map reflect the frequencies of some of the major tribes that existed within each of the language groups.

4 & 5) Topographical Maps

Student may wish to consult a topographical map of Uganda to note any geographical features that may play into their developing theories.

The instructor should explain (in the manner described above) each of the handouts.

*Note: This will be one of the most difficult and open-ended activities that the students do in this unit. Be prepared to facilitate with probing questions.*

Students should be challenged to see if they can explain (based on the data) why the allele frequencies are distributed as they are on the Uganda map, given that the predictions from the genetic theory would have the mystery disease nearly absent altogether.

7. Discussion (~ 20 min)

Have student groups discuss their theories. Note, the instructor may need to facilitate with respect to establishing the three fundamental mechanisms. Again, during this discussion it is appropriate to draw student’s attention to the construction of *theories predicated on evidence* (in the form of data from the handouts). One way of doing this is by asking them pointedly:

- How is your theory connected to the evidence available to you?
One way of facilitating this is by writing on the board student’s (or group’s) theories as they are proclaimed. Then, the instructor should challenge the proponents to back up with their explanation with the evidence or inferences that they used to construct it.

It can be expected that students will derive some version or combination of the following explanations:

- Isolated mutation - that mutation occurs with higher frequency in certain location and persists at a level to offset that of negative selection of the deleterious alleles.

- Admixture or Intermarriage - that the disease is associated with a certain group or groups and that as one becomes less black via admixture, or inter-mixture, the allele frequency diminishes.

- Environmental factors (perhaps something in the water acts as a mutagen).

The instructor should also probe for students’ understanding of the subjective nature of science (theory-laden nature of science). Here, the instructor can refer to the original probing question given to the student groups prior to their beginning the Uganda problem:

- As “scientists” you all have access to similar data for the Uganda Problem. Do you think that you will all come to the same theory to explain the unusually high frequencies? Why or why not?

Student answers may go several directions. A view often held by students is that they believe that careful observation of the data inevitably leads to an emergent theory. As such, students often believe that scientists are unaffected by their own theoretical commitments or experiences. This question is designed to have them consider that their own explanations may differ from one another due to aspects of their own backgrounds that cause them to “see” the data in a particular way.

Following this, the instructor should make a transition (set up) the next class. The instructor may simply wish to tell students that in the next class, they will further their understanding of the mystery disease by way of a holistic examination of certain aspects of the environment.
Why Research African Populations in the 1940's?

- Easy access to stable populations of tribal people
- Great diversity in environmental conditions as potential variables
- Several prolific epidemic diseases to research
- Lack of governmental control (ethical constraints)

Africa Research Overhead
data adapted from:

Uganda Allele Frequencies Handout

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### Uganda Language Groups

<table>
<thead>
<tr>
<th>Language Group</th>
<th>Allele Frequency</th>
<th>Europoid Features</th>
<th>Between Group Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bantu</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Eastern)</td>
<td>High</td>
<td>+</td>
<td>With Nilotic</td>
</tr>
<tr>
<td>(Western)</td>
<td>Moderate</td>
<td>++</td>
<td>Little</td>
</tr>
<tr>
<td>Hamitic</td>
<td>Low</td>
<td>+++</td>
<td>Little</td>
</tr>
<tr>
<td>Nilotic</td>
<td>High</td>
<td>+</td>
<td>With Eastern Bantu</td>
</tr>
<tr>
<td>Pygmoid</td>
<td>Very High</td>
<td>0</td>
<td>Little</td>
</tr>
</tbody>
</table>

* Note: Intra-language group marriages/mixtures (i.e. between tribes) did occur, for example, one Bantu tribe mixing with another.

* Europoid Features means the degree to which researchers believed that the tribal people within a language group maintained caucasian-like characteristics, including height, head shape, skin color, etc.

** Contact means the amount of immigration, emmigration, and intermarriage that occurred with potential neighbors.

Data adapted from:

Uganda Language Group Immigration

Nilotic
800 yrs. ago

Hamitic
800 yrs. ago

Bantu
1500 yrs. ago

Pigmoid
2000 yrs. ago

Arrows indicate direction of immigration

Note: Pigmoid group originated in the Uganda area.


Uganda Language Group Immigration Handout

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Class #5  
Ecological Analysis (Malaria)

During this class, students will consider how issues in ecology play a role in the “story” of the mystery disease. First, students will watch a video about the disease malaria. Following this, they will consider how the malarial parasite lives and reproduces inside the human bloodstream. The purpose for this latter exploration is to have them develop possible theoretical mechanisms to prevent the parasite from successfully living in the body.

Instructor Information
This class may represent an interesting diversion for the students. The symptoms associated with malaria are very similar to those associated with sickle-cell anemia. As a result, during this section students may conclude that the mystery patient suffers from malaria.

The purpose for examining malaria is not simply to derail students’ thinking about out the mystery disease. Rather, understanding the dynamics of malaria is critical to properly understand the anomaly of the population genetics of sickle-cell anemia. Therefore, it is useful to first establish a knowledge foundation about malaria. The latter portion of this class (during which students attempt to propose mechanisms for inhibiting the growth/reproduction of the *Plasmodium* protozoan) will be particularly useful for bridging to the subsequent class on population/evolution (part II). It will be in this subsequent class where students grapple with why the sickle-cell allele confers an advantage against malaria.

Day 5 Objectives
• To understand via open-ended problems and discourse how a holistic view of the mystery disease is afforded by an analysis of the ecology of malaria

Day 5 Materials and Equipment
• The VCR movie, “Quinine”
• Discussion question handout for the Quinine Movie
• The overhead of the *P. falciparum* lifecycle
• Copies of the lifecycle handout

Day 5 Background Reading Materials
• Be familiar with the movie “Quinine” before class begins so that you can facilitate the discussions.
• Read through the coursepack and instructor’s manual material.
Set-up Prior to Class

- Equipment
  - Make sure the VCR is hooked up properly and that the video tape for "Quinine" is rewound.

- Homework (Posted on the right hand side of the white board):
  Continue writing a daily diary based on your experiences last class. Summarize what took place, and consider the diary "seed" questions. Read "Is Global Warming Bad for Health" (pp. 243-244). Create a concept map of the third set of Organismal Biology concepts listed on pp. 203-204 with reference to the reading "Anatomy and Physiology of the Cardiovascular System" (pp. 209-222). Add these to your comprehensive concept map for the entire unit.

- On Board:
  - Diary "Seed" Questions
    - Inquiry
      What similarities and differences exist between malaria and the mystery disease? What reasons do you have for believing or doubting that the mystery patient has malaria?
    - M/R
      Thus far, much of what you’ve done in the course of this third unit still remains unresolved. How might this teaching approach (a lengthy mystery) enhance or detract from students’ experiences in learning about biology?

- Agenda:
  1. Class Business
  2. Student Presentations
  3. Concept Mapping
  4. Quinine Movie
  5. Parasite Lifecycle/Immunity
  6. Minimizing the Parasite
Class #5
Ecological Analysis (Malaria)
Overview

1. Class Business (~ 5 min)
The instructor should cover any miscellaneous issues related to the course.

2. Student Presentations (~ 30 min)
• See class #1.

3. Concept Mapping? (~ 5 min)
The instructor should field questions regarding student work on the concepts.

4. Quinine Movie (~ 50 min)
Announce: Today, we’ll examine how the subdiscipline ecology can be used to gain insight of the mystery disease.

The instructor should motivate why students will be watching a movie about malaria. To build off of the discussions from last class, the instructor should indicate that malaria was one (of many) of the diseases that scientists studied during the period of the 1940s and 1950s, when the goal was to characterize polymorphisms in human populations. Malaria was particularly enticing because it was a disease associated with the blood – thus obtaining samples from native individuals was relatively easy.

Prior to showing the movie, give each student a copy of the Quinine Handout. Instruct them to look over the three questions (perhaps read it aloud with them) and to think about them as the movie progresses.

Discussion (of Article and Movie)
The instructor should open the discussion with questions or general comments from the students. Then, the instructor should transition to the specific questions raised by the handout. It may be more beneficial to tackle them in the following order:

1. Do you see any relationship between Malaria and the symptoms of the Mystery Patient?

One way of facilitating this discussion is putting student’s answers on the board in bullet form. Example similarities include:

- Yellow eyes
- Fevers
c. Pain in the abdomen (malaria affect liver; possibly mystery patient has liver problem)
d. Effect on erythrocytes
e. Pain in joints

2. Based on your research so far with the genetics of the Mystery Disease, what is or is not problematic about the possibility of the Mystery Patient having malaria?

The work in genetics suggested that the Mystery Patient suffered from an inherited disorder. Malaria is a disease that is transmitted via a vector, the Anopheles sp. mosquito. While vector-borne diseases can often be transmitted to progeny, in general there is no basis for a model of inheritance that would suggest that the transmission is discriminatory. In other words, a vector-borne disease affects the phenotype of the individual (which may certainly be transmitted to offspring). However, vector-borne diseases (as with malaria) do not affect the genotype and are thus not transmitted via the mechanism of Mendelian Inheritance models.

3. At the beginning of the unit, we discussed that a genuine understanding of a biological phenomenon requires both a reductionist and holistic explanation. How did the film provide examples of both with respect to understanding malaria?

Both perspectives were well represented in the movie. Below are a few examples that are likely to emerge from the classroom discussions:

Reductionist
- Conceptualizing the invasion of the protozoan into the red blood cell
- Thinking in terms of potential molecular or genetic changes in the parasite or host

Holistic
- Considering the dynamic relationship of a two-host / parasite system.
- Thinking about the physiological effects of the parasite on the rest of the body.
- Thinking about malaria in the context of pharmacological treatments.

On a related topic, both the article and the movie suggested that the parasite was developing resistance to the drugs (chloroquinine).

- How might genetics and evolution be used to study this phenomenon?
Resistance is generally a function of genetics and evolution. This speaks directly to natural selection (fundamentally explored in BIOS 170). Perhaps there was a genetic mutation in an individual parasite such that its genotype conferred an advantageous phenotype (resistance). This advantage must have been heritable. The environment (hostile with respect to drug therapy) would have strongly favored resistance. Change would then happen on a population level, with more and more resistant parasites appearing.

5. Parasite Lifecycle and Immunity (~ 10 min)

One way to transition to this segment is by indicating that the class will take a reductionist approach to studying the malarial parasite. The instructor should use the overhead of the *Plasmodium falciparum* lifecycle.

The purpose of this section is to familiarize students with the dynamic nature of the parasite’s lifecycle. To mitigate concerns, the instructor should indicate that students are not expected to memorize the specific stages, etc. Rather, what we want students to do is to think about the processes that occur at each of these stages to see if they raise any interesting questions about similarities to the physiological or cellular aspects of what they studied with the mystery patient.

The instructor should walk students through each of the 8+ steps in the cycle, beginning with step one. It is important not to get too consumed with the details of each process, however the instructor should concentrate on the actions surrounding the parasite’s behavior in the human’s blood stream (steps 7 - 8+).

One thing to emphasize concerns the responses of the immune system to the rupture of the erythrocyte and release of the new daughter cell merozoites (a process known as schizogony). It is important for them to consider how the protozoan uses the red-blood cells as a staging area for asexual reproduction. The net-result is that the reduction of red blood cells (via hemolysis) leads to a cascade of symptoms:

- When the merozoites are released *en masse*, they literally dump their own metabolic wastes, etc. into the host blood stream. This triggers a massive inflammatory response which manifests itself as fever, etc.

It would be worthwhile to briefly discuss that people can develop immunity (an immune response) to the merozoite release, but it takes several years. Because of this, it is important that students understand that both young children and newly infected (for example the Malarial Safari individual) people are most susceptible to the ravages of malarial episodes. This is because while their immune systems are responsive with respect to general first line defenses (overwhelming fevers, etc.) their immune systems have not had sufficient time or even exposure to develop a degree of immune-targeted recognition to the merozoite release.
In some parts of Africa, malaria is a periodic phenomenon (rather than continual or hyperendemic). Seasonal fluctuation in rain, etc. cause periods of higher mosquito populations (and thus transmitters of the parasite). Children who survive malarial episodes (the survival rate is higher in periodic areas) have a greater likelihood of developing their own internal targeted immune response to the merozoites. Development of this type of immunity (targeted) allows the body to recognize and eliminate the merozoites through lea mechanism of leukocyte recognition endocytosis. This dramatically reduces the severity of subsequent merozoite attacks.

6. Minimizing the Parasite - Group Work (~ 20 min)

Students should assemble into groups of two or three. The instructor should refer students to the copy of the parasite lifecycle which is contained in their coursepack and instruct them that their goal will be to analyze the lifecycle of *P. falciparum* and come up with various possible mechanisms of minimizing it’s effectiveness as a parasite. Students are encouraged to explore as many avenues (both within the host and external to the host) as possible.

Note: Students may view this as a very nebulous task. What we want them to do is to use their own creativity to postulate various mechanisms that may occur in which the parasite is either wholly prevented from entering the body or is prevented from flourishing once inside. One way to facilitate this is by way of drawing their attention to the various stages given on the lifecycle sheet. Students should isolate each stage and think about various mechanisms.

*Examples may include:*
- *Pesticides which reduce the mosquito population*
- *development of a medicine (i.e. antibiotic) that targets a particular phase*
- *vaccination*
- *changes to the red blood cells*
  - *decreasing the permeability to malaria penetration*
- *reduction in the number of merozoites per red blood cell*
- *reduction in the effectiveness of penetrating the red blood cell by the merozoite*

Following group work, a representative from each group should present the various mechanisms to the class (or ostensibly this class discussion could be done in a very informal format).

One way of further facilitating this discussion is by asking students a direct question about the protozoan:
Why do you think that Plasmodium falciparum goes to so much trouble to “live” and “reproduce” inside the red blood cell? What is unique about the red blood cell?

The ensuing conversation will likely go many directions. Students may propose that the mere fact that red blood cells contain oxygen is why the parasite invades and reproduces inside it. While this is an interesting claim, the instructor should point out that it would be more effective for the parasite to reside inside the lungs if the need for oxygen was the driving force.

The unique component of the red blood cell is the pigment (protein) hemoglobin. What we want students to consider is that there must be a relationship between the fact that the parasite specializes in living inside the red blood cell and the fact that hemoglobin is a very ubiquitous and free-floating protein inside the red blood cell. What we want them to consider is that Plasmodium falciparum eats hemoglobin as a primary source of protein for its own growth and reproduction.

*Note:*

It’s important at the end of this class to provide some closure to the students. It’s possible that students still conflate the mystery disease and malaria. This will lead to confusion in the subsequent classes. Therefore, the instructor should feel comfortable indicating that the mystery disease is not malaria (as supported from conclusions reached following the genetic classes). Rather, malaria is a parasitic disease that is transmitted via a microbial organism and a mosquito vector.

Finally, the instructor should consider setting up the next class by way of indicating to students that in the next class we will consider a holistic exploration of malaria. We will do this by way of examining the frequency of this disease in Uganda (similar to what we did with the frequency of the mystery disease).
Class #6
Evolutionary Analysis ii

In this class, students will examine two sources of observational data derived largely from the work of Anthony C. Allison. Students should attempt to see if the new data has any bearing on their earlier theories for why there are differing pockets of mystery disease carriers (i.e. differing degrees of allele frequencies) in Uganda. The first set of observational data is a map that depicts the prevalence of malaria in Uganda. The second summarizes the degree of malarial infection in children based upon their genotype (either normal or heterozygote) for the mystery disease.

Likely after reviewing the new evidence, students will propose that having the mystery allele in the form of a heterozygote confers some sort of advantage against malaria. After working with the observational data, the instructor is to ask students if they can think of an experiment (as distinct from an observation) that could be done to test their new theory. This will lead into a discussion about Anthony Allison’s experimental work.

The meta goal here is to unpack how scientists analyze data, construct & evaluate theories. In previous classes, we’ve asked students to consider how data (evidence) is used to construct scientific theories. In this class, we will have them consider the general distinctions between data derived from experiments and data derived from observations. This will facilitate several discussions about the nature of science. One such discussion is that scientific knowledge can be created and developed using solely observational evidence as opposed to a more naive view that knowledge progression in science requires scientists to conduct manipulative experiments.

These discussions should further their understanding of how theories change by virtue of having them consider how additional evidence (data) is used to shape our explanations. They should also consider how theories change/develop when certain scientists by virtue of their own experiences make unique insights with existing data (a subjective process)

The class will conclude with a discussion about the frequency of the mystery disease in non-malarial areas (like the contemporary United States) and allow students to consider the ramifications of global warming on the possibility that selection may again favor heterozygotes in the U.S. should endemic malaria return.

Historical Overview
In this section, students will again visit the problem of the anomaly in which the allele frequency for the mystery disease appears to be high (and stable) in certain portions of Africa. From class #4, students explored the possibility that selective
mutation and admixture (and perhaps others) were explanations for the presence of the high incidence of the allele.

In this class, students will have the opportunity to synthesize observational data to construct an alternative theory for the high frequencies of the sickle cell allele. This closely mimics the work done by a rather famous historical medical researcher from the period of roughly 1949 - 1953. Anthony C. Allison, MD, PhD, was a young medical researcher who was interested in human polymorphisms.

In conducting hematological analysis, Dr. Allison noted that there was a strong correlation between tribes that had high levels of the sickle cell allele and the presence of malaria. In locations where malaria existed for a majority of the year (hyper endemic), the native people exhibited higher relative frequencies of the sickle cell trait. Dr. Allison concluded that this polymorphism (the existence of normal “+/+” and carrier “+/−” and very low numbers of “−/−”) was demonstrative that the sickle cell allele afforded some sort of selective advantage such that it was not removed from the population due to natural section.

Some of Allison’s contemporaries suggested that the high frequencies of the allele were due to abnormally high rates of mutation in certain geographical pockets or due to admixture of the allele by way of intermarriage. Others explained the differing levels of the disease with reference to its being largely an endemically-racial phenomenon; that is the disease was correlated with being increasingly black. Dr. Allison refuted the suggestion that the sickle cell allele was maintained through higher levels of selective mutation. He saw no reason to believe that the mutation rate would vary by region (or tribe) and proposed that the extraordinary rates required to offset the removal of the allele due to its inherent deleterious effects would have to have been many times higher than the standard rate of mutations in animals (a number calculated by a famous British geneticist, J.B.S. Haldane).

While serving as a medical physician in Central Uganda, Dr. Allison took time to collect blood samples from various children in an attempt to correlate the severity of the malarial infection with the presence or absence of the sickle cell allele. Allison categorized children on the bases of age, genotype, and presence (or absence) of malaria parasites. His observational data supported his hypothesis that the carrier children developed fewer cases of malarial parasites, and that in those who did have malarial infection, the density of parasites in the blood was significantly lower.

At the same time, to test his theory (again which was heretofore supported by his observational evidence), in 1953, Dr. Allison conducted experiments in which he inoculated tribal men with the Plasmodium falciparum (malarial) parasite. One group of men consisted of sickle cell carriers (heterozygotes) and the other consisted of “normal” genotype (homozygotes). After several days, he noted that the density of malarial parasites in the blood of the carriers was far lower than that found in normal
individuals. This led him to conclude that the trait allele somehow protected an individual from the overwhelming ravages of peripheral parasitemia.

Allison's theory (that a balanced polymorphism was evidence of protection against malaria) was recognized by his contemporaries as representing definitive evidence of natural selection in humans. Variation existed in the form of a polymorphism, and the environment was such that the otherwise deleterious allele in the heterozygote state conferred a fitness advantage to such individuals living in malarial areas.

Dr. Allison postulated that the absence of malaria in the United States explained why the frequency of carriers in U.S. blacks was (is) significantly lower than that found in Africa. Without conferring any selective advantage, the deleterious allele was subject to elimination from the population. Today, there are places in Africa where the allele frequency of the sickle cell allele runs from 20% to as high as 40%. In the United States, the allele frequency remains at roughly 7-8%.

The richness of the population genetic work sheds light on what was (and still is) otherwise regarded as a racial disease. Sickle Cell Anemia has often been characterized as a "black" disease. In fact, the early work of researchers focused on this aspect. Recall that one potential theory resulting from class #4 could have one claim that the more Negroid (black) an individual, the higher the allele frequencies.

That the disease has strong socio-cultural roots is clear. However, understanding the population genetics can lead to interesting discussions about the misconception of identifying the disease simply on the basis of skin color. Discussing the Global Warming Article can be instructive in this manner.

**Day 6 Objectives**
- To engage in open-ended problem solving and discourse to see how a further understanding of evolution impacts learning about the mystery disease.

**Day 6 Materials and Equipment**
- Copies of the two handouts, "Uganda Yearly Malarial Incidence" and "Malarial Rates and Genotypes in Children of Central Africa."
- Handouts of the questions pertaining to the homework readings

**Day 6 Background Reading Materials**
- Be familiar with the historical overview in later in this section of the instructor's manual.

**Set-up Prior to Class**
- Equipment
  - Ensure that the handouts and overheads are ready for use.
• Homework (Posted on the right hand side of the white board):
  Write a daily diary entry based on your experiences in this and previous
classes. Summarize what took place, and consider the diary “seed” questions.
Read "The Structure of Proteins (Hemoglobin)" (pp. 245-246) and "The
Function of Hemoglobin " (pp. 247-248). Complete the "Red Blood
Cell/Hemoglobin Questions" on the readings on p. 249. Create a concept map
of the fourth set of Organismal Biology concepts listed on p. 204 with
reference to these readings and "Anatomy and Physiology of the
Cardiovascular System" (pp. 209-222). Add these to your comprehensive
concept map for the entire unit.

• On Board:
  • Diary “Seed” Questions
    • Inquiry
      Does the ecology/epidemiology of malaria shed light on the
      problem we discovered two classes ago? If so, how?
    • M/R
      Is it enough for a theory to be supported only by observational
data? or does confirming a theory require experimental data? Why
or why not?

• Agenda:
  1. Class Business
     • Turn in diary entry?
  2. Review Uganda Theories
  3. Uganda Problem II / Supplemental Data
  4. General Discussion
  5. Nature of Science Discussions
     a. Observations/Experiments
     b. Innoculation Experiments / Ethics
  6. Uganda Conclusion
     a. Theory Development
  7. African American Issue
  8. Is Global Warming Bad for Health?
  9. Malaria Revisited
  10. Concept Mapping


1. Class Business (~ 5 min)
The instructor should cover any miscellaneous issues related to the course.

2. Student Presentations (~ 30 min)
   • See class #1
   •

3. Review Uganda Theories (~ 5 min)
Announce: Today, we’ll revisit issues regarding population / evolution dynamics.

Note: The instructor may wish to have the overheads of the handouts from class #4 as a reference.

The instructor should spend time reviewing with the class (ask them for their thoughts) what theories they had concluded for the existence of the high alleles in certain parts of Uganda. **Write them on the board.** Some of the possibilities may include (students may have come up with others):

1. “Blackness” is identified as highly correlated with high levels of carriers.
2. Mutations are high enough to offset the removal of the allele(s) from the population.
3. As tribes mixed in Uganda, the higher allele frequency tribes were diluted with the more Europoid (and lower numbers of “-” alleles) tribes.
4. Environmental factors (e.g., something/mutagen in the water)

Revisit Conclusions from Last Class (on Malaria)
The instructor should also remind students:
1. That malaria is a harmful disease that can kill (particularly children)
2. That the mystery disease is a genetically transmitted disease

Note: This will prohibit students from conflating the two (malaria and the mystery disease) and facilitate the discussion following the subsequent Uganda problems.

4. Uganda Problem II (~ 30 min)
The instructor should indicate to the students that during the time when medical researchers were conducting serology tests, they were also noting the prevalence of certain infectious diseases such as Malaria. Thus, in addition to gaining insight into certain subject-specific characteristics, the researchers were able to both qualify and quantify the degree of severity of malaria in regions across Africa.
Students should be broken into groups of three. As a preface to the activity, the instructor should indicate that the students will be given data that provides a pictorial summary of the malarial incidence in Uganda. They should then be instructed to see if the new data can shed any light onto their theories they proposed from class #4 about the high (and heterogeneous) frequency of the mystery disease in certain places of Uganda.

Note: Students will need to use their handouts from class #4. Specifically, they will note (although let them discover this on their own) that by overlaying the new malarial handout onto the allele frequency handout, there is an opportunity to identify patterns with respect to allele frequency and malarial intensity.

The instructor should feel free to wander about the room and answer any questions that the students may have about the malarial data. Here again, this is a very open-ended activity, and it is important to allow students time to study this graphical data. As usual, the instructor should indicate that he/she will expect students to discuss their interpretations in the subsequent group forum.

Note: Students likely will see the correlation between the high frequencies of the mystery disease and the higher frequency of the disease malaria. While interacting with the groups, the instructor should challenge the members to draw conclusions from this striking correlation. That is, does this correlation suggest anything with respect to a causal issue for the high frequencies of carriers of the mystery disease?

Supplemental Data (Dr. Allison's Observations in Uganda Children)

At some point during which students are working in groups on the new malarial data, the instructor should interrupt and provide additional data that relates to specific research regarding children (see second handout). The instructor can preface that Anthony C. Allison was a medical researcher in the early 1950’s who was interested in further examining the apparent correlation between the presence of malaria and the seemingly high frequencies of the mystery disease (as exhibited in the first handout when used in combination with the information from two classes ago). While acting as a traveling medical physician throughout the country, Allison drew blood from Uganda children to use for research purposes on the mystery disease. In the evenings, Allison would analyze the blood for both the genetic make-up of the child (whether they were a carrier for the mystery disease or had normal genotype) and for the potential presence of the malarial parasite, *Plasmodium falciparum* (including its density in the red blood cells).

With regard to the specific table, the instructor should point out the absence of full-blown “/-“ patients (homozygotic recessives). This is due to the fact that the full-blown disease had a high rate of mortality, and therefore there were
relatively few patients from which to sample. Remember, the mystery patient is a full-blown sickle cell anemic (and therefore a recessive homozygote). It may be worthwhile to mention that some children do survive the full blown disease to a state of adulthood so as not to confuse the students regarding the fact that the Mystery Patient is at once a full blown recessive (as proven by his genetic pedigree analysis) and also a surviving “near” adult of 17 years old.

Here again, the students should be encouraged to see if the new information augments, refutes, or has no impact upon their earlier theories from class #4.

While they are grappling with the supplementary data, the groups’ attention should be drawn to the following probing questions that the instructor has placed on the board:

1. Is it troubling to you that you are basing your explanations for the high frequencies on data collected by observational methods, rather than data resulting from conducting a controlled experiment?
2. Do you think experiments are necessary for knowledge to develop in science?
3. Has your theory to explain the frequencies changed? What caused you to change?

In addition to working through the given problem, students should be encouraged to talk about the probing question(s) on the board in relation to their insights gained by examining the historical data. The instructor should emphasize that the class discussions will build off of this initial probing question.

5. General Discussion (~ 5 – 10 min)

The instructor should allow time for students to present their (new) theories concerning how the (new) data about malaria sheds light on their thoughts regarding the high frequencies of mystery carriers in certain locations. Three things should emerge from this work

1. There’s a correlation between high levels of malaria and high levels of carriers.
2. Children with the mystery allele (carriers) seem to contract malaria less frequently and
3. That in children who suffered from malaria and had the mystery trait, their levels of malarial parasites (in terms of density) were much lower.

From this information, students should be able to construct the new theory that the heterozygotes are somehow “protected” against the ravages of the malarial disease and thus have a relatively higher fitness such that the “-“ allele stays high in the population.
6. Nature of Science Discussions (~ 20 – 30 min)

Observations vs. Experiments
The instructor should point out to students that the explanations they initially developed to account for the anomalous frequencies of the mystery disease in Uganda were based on data derived from observational methods. This is true even for Dr. Allison’s collection of blood from the children throughout Uganda. In this regard, Allison did not conduct a controlled manipulative experiment to collect empirical data. A follow up question may help facilitate the discussions:

- Is it troubling to you [students] that you have based your explanations on data collected from observational methods, rather than the results from “experiments”?

- Do you think experiments are necessary for knowledge to develop in science?

The conversation could go many ways. A more naïve view is that knowledge in science (or the progression/development of scientific knowledge) requires data derived from conducting controlled experiments as distinct from data originating from observation (or inference). The more informed view is that inference from observational data is perfectly legitimate in science.

Inoculation Experiments (discussion):
The supplemental data used by students (Allison’s Uganda Children data) was derived from observation. Observation is distinctly different than experimentation. The latter requires an intervention such that a manipulation perturbs the system being studied. Given that students have likely revised their earlier theories to include the notion of heterozygote protection the instructor should ask students if they could think of an experimental test (as distinct from an observation) to test their theory that heterozygotes are protected against malarial ravages.

Students may propose (or the instructor may need to facilitate this) that one way to test the observations would be to inoculate people (whose genetic fingerprint with regard to the mystery disease known beforehand) with the malarial parasite. The thought here is that those individuals with the mystery allele in the form of heterozygotes would be partially protected (have either lower density counts of parasites or lower number of red blood cells infected).

Whether or not the students propose the experiment on their own, the instructor should point out that Anthony C. Allison if fact did perform an
inoculation experiment in an effort to experimentally test his theory for the protection of heterozygotes.

*Ethics and Rational Reconstruction (Values in Science)*

The class should be asked how this experiment (that Allison inoculated tribal men with the malarial parasite) gives us insight into whether or not we believe there to be values in science. The misconception is that science transcends ethical boundaries and remains a tool free from value or ethical scrutiny. The more relevant question is whether or not scientists allow values or ethics to influence their work. On this question, students may respond several ways, and the conversation may take many directions. The bottom line is to instruct students that values are a part of the practice of scientists. Philosophers associated with the post-positivist movement draw our attention to the notion that the value-fact distinction in science advocated by the logical positivists is simplistic. More generally, their claim is that what scientists do is largely influenced by their own theoretical commitments (which themselves are affected by their values). The image of an objective scientist, free from value or ethical positions is an oversimplification.

7. Uganda Conclusion (~ 20 min)

The instructor should help students resolve which of the potential theories students constructed is the “best” (most explanatory) given the data available to them:

1. Increased mutation rate
2. The disease is racial (more black = higher disease frequency)
3. The disease is associated with migration
4. That the disease somehow protects against malaria

- Is there just one model that best explains the allele frequency persistence?

The instructor should realize that the conversation could go several directions. Technically, aspects of several of the theories play into the overall explanation of the heterogeneous (and high) frequencies of the mystery allele in certain parts of Uganda. That the mystery disease was associated with blackness is correct as far as Uganda. The problem here is that this line of thinking could be extrapolated to other areas in Africa (or elsewhere). During the time of 1940’s and 1950’s, some white scientists were too quick to associate the color of skin with disease as if certain dysfunctions were solely predicated on race.

*Theory Development & Tentative Nature of Science*

The instructor may wish to remind students that from their previous analysis (class #4), they proposed introductory theories for why the mystery disease existed in high frequencies in certain locations. From this current class, new evidence and to a large degree new insights with the existing evidence has raised
the question as to whether or not those earlier theories offer the best explanatory power.

What students should be considering is that new evidence (the malarial information – both observational data sets) has caused them to construct a modified theory, heterozygote protection. The point here is that it is normal in science for theories to develop, to gain prominence, and to then be changed (or abandoned) in light of new evidence or insights. This illustrates the tentative nature of science and further supports the tentative NOS discussion from the second genetics class (class 21).

Nature of Science – Subjective Nature of Science

The instructor should call students’ attention to the fact that certain reputable scientists adopted these differing theories for the persistence of the “mystery” allele in certain parts of Africa. Concurrent with the definitive work of Anthony C. Allison, the theories of scientists largely fell into three related camps:

1. The high presence of the mystery allele was due to abnormal mutation rates in certain areas.
2. The disease was correlated with blackness. The blacker an individual’s race, the higher likelihood that there was an increased number of mystery alleles.
3. Migration accounted for the dilution of the allele frequencies.
4. Allison’s Theory – that the high frequencies were a result of a selective advantage against the malarial parasite.

It’s important to consider that all of the scientists who were working on the problem of high all had access to similar data. It was Anthony Allison who linked the disease to protection against endemic malaria by virtue of his ability to synthesize the data into the currently accepted theory.

Perhaps a way to explore this with the students is to question them:

- Why do you think that other scientists were not able to construct the theory that Allison did, particularly when we consider that they had access to the same data?

This conversation could go many ways. It should provide an opportunity to discuss several issues about the subjective nature of science and of the role of insight into theory construction/theory change.

The naïve answer to the question would have us believe that the reason that scientists hold different theories despite the fact that they all have access to the
same data is largely a function of the data itself. That is, a common response is to claim that perhaps some of the scientists just didn’t “see” the entire data set.

The more informed understanding is that scientists adopt different perspectives by virtue of their own subjective perspectives. Scientists are affected by their own theoretical backgrounds (their biases as a result of their own experiences and beliefs). The nature of science aspect represented here is that knowledge construction is affected by subjective factors. Certain scientists pursue (or remain devoted to) incorrect or outdated theories for a number of reasons, from being overly invested (perhaps a life’s work is built on a “wrong” theory) to not being able to make the insights by virtue of the fact that a given scientist is “biased” or influenced in the way they interpret evidence.

8. African American Issue (~ 5 min)

The instructor should mention to the students that the allele frequencies of carriers that exist among the current African American population is approximately 7 - 8%.

- Given that there is no malaria in the U.S., what comments can be made about current African American allele frequencies?

There is no selective advantage to the allele and thus it is free to be removed from the population. Discuss natural selection processes.

The instructor may need to provide additional evidence to the class:

1. African American slaves for the most part came from the Gold Coast of Africa, where allele frequencies (at the time of the late 18th and early 19th centuries) were 22% (the Gold Coast was a relatively high malarial area).
2. There was a high rate of admixture among African American slaves with the Native American (Indian) and White populace.

The example points out that in fact, components of both models do help to explain the issue. Certainly, heterozygote advantage is a driving force for the maintenance of higher allele frequencies in malarial areas. However, admixture is a force that can effectively serve to dilute the population frequencies.

9. Discussion of the Reading: Is Global Warming Bad for Health? (~ 5 min)

The instructor should feel comfortable asking them if they think that global warming may have a future effect on the frequency of the mystery disease in, for example, the United States.

This discussion could also take on many forms. The bottom line is to draw their attention to the idea that should endemic malaria return to the United States (and
assuming that there is no pharmacological protective agent developed against it) we may see a hypothetical increase in the frequency of mystery disease alleles (in the form of carriers). These individuals would have a slightly higher fitness than normal individuals in malarial areas.

Again, the prediction would require some very unlikely constraints, e.g., that people live entirely in malarial areas (i.e. they don’t emigrate to escape), that there’s no drug to provide treatment, etc.

10. Malaria Revisited (~5 min)

Finally, the last thing is to try to figure out “why” carriers are advantageous against malaria. A few questions may get students thinking, but these questions may be a bit too difficult to answer at this stage:

- Can students explain why there is a connection between increased resistance to malaria and the presence of the mutated allele?

- From the data in the table, carriers (heterozygotes) exhibited fewer parasite infiltrations (densities). Can students explain why this may be?

The final question (and fundamental transition) that should be posed relates to the next section:

Students have learned that the heterozygote does not have red-blood cell changes in-vivo (as evidenced by the earlier testing). For all intents and purposes, the blood of that individual behaves normally.

- Why then, do heterozygotes have resistance? What is it in their red-blood cell(s) that confers this?

The answer will relate to an understanding of the molecular biology of hemoglobin.

11. Concept Mapping? (~5 – 10 min)

The instructor should facilitate a discussion with students in which they construct a small concept map from the list of concepts assigned to them last class as practice work:

- malaria
- anemia
- p. falciparum
- heterozygote advantage
- carrier
Note: The example concept map represents just one possible way of properly depicting the relationships between these concepts. It’s conceivable that students will come up with alternatives that are equally acceptable.
Uganda Malaria Incidence

- Normally Malaria-free
- Seasonal Malaria (periods of exposure followed by relief)
- Hyperendemic Malaria (continual exposure)

Uganda Malaria Handout
Malarial Rates and Genotypes in Children of Central Uganda

<table>
<thead>
<tr>
<th>Genetic Disposition</th>
<th>Total Children Examined</th>
<th>% with P. falciparum</th>
<th>Parasite Density Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal (&quot;+/+&quot;)</td>
<td>247</td>
<td>46%</td>
<td>5.9</td>
</tr>
<tr>
<td>Carrier (&quot;+/-&quot;)</td>
<td>43</td>
<td>28%</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: Parasite Density Index = a general measure of the amount of malarial parasites in the red blood cells per volume of blood.

adapted from:
Class #7
A Molecular Perspective

During this class, students will explore the molecular biology of hemoglobin in an effort to understand how changes that occur on the molecular and cellular level explain how resistance is conferred to a heterozygote of the mystery disease.

The questions raised at the end of class #24 provide an appropriate transition to the issues that students will explore in this class. There is an open question, specifically, given that there is no fundamental apparent difference \textit{in-vivo} between the red blood cells of the carrier from that of the normal person (heterozygote vs. homozygote), what does confer the advantage?

In this section, students will revisit that there is a link between the classical genetic notion of the gene and the molecular interpretation of a gene (as a section of DNA that codes for a protein). In the former case, the Mendelian understanding of “gene” refers to whether or not a person possesses a certain phenotype under a model of discontinuous variation. In the latter, the “gene” is a physical entity of DNA that codes for a form of the subunit of hemoglobin.

This class will essentially replicate the historical work of those scientists who sought to extend beyond the classical connotation by identifying the gene in terms of DNA and understanding the actual protein product that was conferred.

**Day 7 Objectives**
During this class, students should learn various concepts and processes associated with a molecular understanding of the mystery disease. This includes how DNA codes for proteins, how proteins have three dimensional structures, and how changes in the DNA via mutations potentially affect the structure and function of the protein. As a result, this class should further students’ understanding of the reductionist perspective in explaining a biological phenomenon.

**Day 7 Materials and Equipment**
- General Overhead of Electrophoresis
- Two Overheads of Mystery Patient Electrophoresis results:
  1. A general interpretation
  2. DNA (mRNA) Sequence Electrophoresis
- Appropriate #s of the handout, “DNA Sequences”
- Appropriate #s of the handouts, “Genetic Code” (or refer students to the coursepak)

**Day 7 Background Reading Materials**
- Be familiar with the coursepack readings and the overheads.
Set-up Prior to Class

- Equipment
  - Have the overheads and appropriate handouts ready before class.

- Homework (Posted on the right hand side of the white board):
  Continue writing a daily diary based on your experiences last class. Summarize what took place, and consider the diary "seed" questions. Finish making a concept map of the Organismal Biology concepts listed on pp. 203-204 with reference to the reading "Anatomy and Physiology of the Cardiovascular System" (pp. 209-222). Come prepared with questions for the review session.

- On Board:
  - Diary "Seed" Questions
    - Inquiry
      How do the molecular biology results from our last class help us to make sense of the strange shape of red blood cells associated with the mystery disease? How do geneticists depict individuals possessing variant forms of hemoglobin in pedigrees? How would cellular biologists account for these variations?
    - M/R
      Comment on how this class affords your understanding of reductionist and holistic perspectives in biology. By itself, does knowing the molecular biology of the mystery disease (i.e. changes in the DNA) capstone our understanding of the mystery disease?

- Agenda:
  1. Class Business
  2. Student Presentations
  3. Concept Mapping
  4. Introduction/Summary Chart
  5. Structure/Function of Proteins/Hemoglobin
  6. Classical Genetics to Molecular Genetics
  7. Electrophoresis
  8. Translation of Hemoglobin
  9. Hemoglobin Structure

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1. Class Business (~ 5 min)
   The instructor should cover any miscellaneous issues related to the course.

2. Student Presentations (~ 30 min)
   • See class #1.

3. Concept Mapping (~ 5 – 10 min)
   The instructor should facilitate a discussion with students in which they construct a small concept map from the list of concepts assigned to them last class as practice work:
   - Recessive allele
   - Normal allele
   - Mutation
   - Deleterious allele

   Note: The example concept map represents just one possible way of properly depicting the relationships between these concepts. It’s conceivable that students will come up with alternatives that are equally acceptable.

4. Introduction/Summary Chart (~ 20 min)
   Announce: Today we’ll examine how molecular biology helps explain or inform our understanding

   It may be best to start with a review using an incomplete concept map (put on board):
   The basic purpose of the review is to get students to think about the distinction between malaria and the mystery disease and yet have them attempt to
hypothesize how being a carrier affords protection from malaria. Have them help you complete the map as a review.

Creation of the Summary Chart

It would be beneficial after the initial concept map to have students help construct a summary chart. The instructor should initiate the discussion by placing the following on the board:

<table>
<thead>
<tr>
<th>Genotype</th>
<th>+/+</th>
<th>+/-</th>
<th>-/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBC Shape?</td>
<td>Donut Shape</td>
<td>Usually Normal</td>
<td>Crescent</td>
</tr>
<tr>
<td>Advantage?</td>
<td>Normal</td>
<td>Malaria Resistant</td>
<td>? (Not sure)</td>
</tr>
<tr>
<td>Disadvantage?</td>
<td>Malaria Susceptible</td>
<td>None to Mild Symptoms</td>
<td>Anemia/Fever/Disease</td>
</tr>
</tbody>
</table>

The instructor can ask students for help in filling in the rest of the chart. Assume that the chart pertains to people living in Uganda. They should be able to assimilate the knowledge they have learned from previous classes and from the readings.

5. Review of Structure/Function of Proteins/Hemoglobin (~ 10 min)

The instructor should probe students for their understanding about the function of the red blood cell. It should be expected that students have a fundamental understanding that the erythrocyte is designed to carry oxygen using hemoglobin.

It’s important that the instructor explains how hemoglobin captures and releases oxygen by discussing the disassociation curve. When concentrations of oxygen are high (as in the capillaries of the lungs), the hemoglobin

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protein has a great affinity for the binding of oxygen. At low concentrations of oxygen, hemoglobin is more likely to give up its oxygen molecules. In the capillaries of the body, a low oxygen (concentration) environment exists. As a result, the hemoglobin in the red blood cell is willing to "give up" its bound oxygen to the interstitial areas of the capillary.

One way of facilitating this discussion is by representing a hypothetical capillary on the board (see diagram). Here, when the red blood cell enters the capillary bed, it is willing to give off its bound oxygen to the environment. As the red blood cell progresses through the capillary, it contains less and less hemoglobin bound oxygen.

At this time, it is worth exploring what students feel is the essential difference between the Red Blood Cells of the Mystery Patient versus those of a normal patient. The instructor should put two concepts on the board, "Red Blood Cell" and "Oxygen." Students should be encouraged to consider how they are related:

In the first case, students should understand that red blood cells transport (or carry) oxygen. The purpose for adding "hemoglobin" in the map is to have students consider how this protein facilitates that transfer.

Students should be instructed to refer to their responses to the homework questions.

1. Both of the types of tests (the earlier *in-vitro* test and the later *in-vivo* test) we’ve discussed in class were designed to measure for the presence of structural changes to the red-blood cell under lower oxygen conditions. Based on your readings, what do you conclude may be affected within the red blood cell such that structural changes occur?

   Given that there is a link between the protein hemoglobin and the carrying of oxygen, it is logical to conclude that there is some defect occurring in the hemoglobin such that under very low oxygen conditions a structural change is induced.

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2. Based on your answer to question 1, what are possible differences between the blood of a normal person, a carrier, and the mystery patient?

The blood of a normal patient has normal hemoglobin. The blood of a carrier has a mixture of normal hemoglobin and mutated hemoglobin. The blood of the mystery patient has fully abnormal hemoglobin.

6. Linking Classical Genetics to Molecular Genetics (~10 min)

The instructor can refer to the chart in which a heterozygote is denoted as "+-". The instructor should point out that while such representations ("+" & "-" ) have been helpful in the sense that inheritance patterns could be analyzed (classical genetics), what do they mean in the context of molecular genetics (i.e., what do "+" and "-" refer to)?

It would be beneficial to draw a sample chromosome pair (in this case, and by no accident, it would be appropriate to use chromosome 11 on which the gene for the beta protein of hemoglobin resides). Through questioning, the instructor should find out if the students understand what is meant by the +/- of classical genetics? The instructor may need to provide explanation regarding the use of "+" as meaning a normal-functioning protein coded by a segment of DNA (molecular gene). Correspondingly, "-" refers to the mutated gene.

At this point, it would also be beneficial to review very basic Central Dogma issues, such that students are familiarized with the DNA to protein relationship. This can be illustrated simply by linking DNA to mRNA to proteins in the context of a concept map drawn on the board.
7. Electrophoresis (~ 20 min)

Given that there are hypothesized differences in hemoglobin between the mystery patient and the normal patient, the instructor should acquaint students with the use of electrophoresis as a test to substantiate any such structural differences. It may be best to use the board to illustrate (see right) the basics of electrophoresis mechanics. Note: It’s up to the individual instructor whether or not to unpack the details of electrophoresis (in terms of making a distinction that the technique analyzes fragments of the protein rather than the whole). From a pedagogical standpoint, it may be more worthwhile to avoid the specifics such that students focus on how electrophoresis is a tool for distinguishing between differing structures (proteins) on a meta-level.

One way of doing this is by using the overhead that simplifies how fragments migrate in an electrophoresis current.

In this illustration, imagine that two fragments (each composed of three amino acids) were placed next to one another in gel wells. When the current is turned on, the fragment that has two positive charges (i.e. two positively charged amino acids) will move further in the current field (i.e. toward the negative pole) than the fragment that has essentially a neutral net charge.

Note: In this example, don’t worry about identifying a sample with a genotype. This (basic) example is to be used simply to get students thinking about the mechanics of electrophoresis.

A way of motivating the electrophoresis work is to point out to students that during the 1950’s (at the same time that Anthony Allison was constructing the theory of heterozygote advantage), another group of researchers was interested in understanding the molecular difference between normal, carrier, and full sufferers of the mystery disease. A rather famous researcher by the name of Linus Pauling proposed using the technique of electrophoresis to see if there were differences between the hemoglobin molecules of these individuals. He chose hemoglobin...
because it was thought to be the most logical thing that would be affected given that the aberrant cell shapes only occurred under conditions of low oxygen.

At this point, the instructor should put up the overhead (general results) of Pauling’s initial test results of running the hemoglobin samples of a “normal” patient, the mystery patient, and a carrier. The instructor may wish to point out that the overhead reflects only the migration of identical fragments and not the entire hemoglobin protein. That is, the hemoglobin for all three types of persons was cut with a restriction endonuclease such that identical fragments were being compared.

Note: Here again, it may be worthwhile to point out that the hemoglobin molecule is very large and composed of hundreds of amino acids. Therefore, to more effectively analyze for possible differences between individuals, it was more appropriate to cut up the molecule into various segments. Therefore, what the students are witnessing on the overhead are “bands” that correspond to multiple copies of identical segments of the DNA.

The instructor should question the class:

- Do the results match the expectations from a classical genetic perspective?

  Yes, one would expect that there would be differences between the homozygote normal and the homozygote recessive. The fact that the heterozygote carrier has two distinct bands is demonstrative that there is a mixture of the normal disease allele and the deleterious allele.

**8. Translation of Hemoglobin Fragment (~ 20 min)**

The next activity has students analyze the DNA sequences that code for the pieces of the hemoglobin beta protein (which are depicted on the overhead/handout of the mystery patient specific DNA). Students should assemble into groups (of 3), and the instructor should pass out a copy of the genetic code to each group.

The instructor should review how the genetic code is read with reference to the mechanics of translation (DNA, codons, mRNA, tRNA, amino acids). Following a basic review, the instructor should pass out a copy of the fragment handout. Groups should be encouraged to examine the structure of the fragments with reference to the amino acid composition(s). Note: The materials they’ve been given will allow them to see (after translation) that there is a fundamental difference in one amino acid between the normal fragment and the mutant fragment. Also, by using the genetic code handout, students can determine that there is a fundamental charge difference.

Following group work, the class should reconvene. The instructor should facilitate a discussion in which volunteer groups present their findings.
Note: Glutamic Acid is the sixth amino acid in the normal fragment. It is replaced by Valine in the mutated fragment. Because Valine is a neutral amino acid (which means that the fragment “lost” a negative charge) the fragment will not migrate as far in the gel. Therefore, the mutated fragment moves less far.

9. Hemoglobin Structure (~ 20 min)

Due to the complexity, the instructor should provide the final link regarding the effect that the amino acid difference in the beta chain has upon function of the hemoglobin molecule as a whole. To facilitate this, the instructor should refer students to the hemoglobin overhead. He/she should then point out to students where the mutated amino acid in question resides (on the outside of the beta chain).

The instructor should also point out to students that having a neutral charge on the outside of the hemoglobin molecule in the beta chain is an unstable state when the hemoglobin molecule is not bound to oxygen. Here again, to minimize complexity, it may be more beneficial from a pedagogical standpoint to mention that in the deoxygenated state, the mutated hemoglobin forms chains (they align next to one another to minimize the instability of the outside valine amino acid).

The sixth amino acid (now the neutral valine as the mutant form) is unstable on the outside of the hemoglobin molecule (in it’s position in the beta chain). It is unstable because it is neutrally charged. This instability is manifested by the fact that the molecule is surrounded in ions (primarily water) such that something neutral is repelled. To minimize this repulsion, the hemoglobin molecules align in rod-like chains where one mutated valine is paired up with another such that the two neutrally-charged amino acids “shield” one another. These chains are relatively rigid, and en masse they are what cause the distortion of the red blood cell!

Hemoglobin Tetramer Tetramer Chains Chains Distorting RBC
At this point, it would be worthwhile to add to the chart on the board a new line regarding the protein phenotype:

<table>
<thead>
<tr>
<th>Genotype</th>
<th>+/+</th>
<th>+/-</th>
<th>-/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenotype</td>
<td>Hb+/Hb+</td>
<td>Hb+/Hb-</td>
<td>Hb-/Hb-</td>
</tr>
<tr>
<td>RBC Shape</td>
<td>Normal</td>
<td>Usually Normal</td>
<td>Crescent</td>
</tr>
<tr>
<td>Advantage?</td>
<td>Normal</td>
<td>Malarial Resistant</td>
<td>Malarial Resistant</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>Malaria - Susceptible</td>
<td>None</td>
<td>Anemia/Fever</td>
</tr>
</tbody>
</table>

This new line illustrates that the classical Mendelian genotype of, for example, "+/-" does correspond to an actual molecular product, two hemoglobin forms: a normal form Hb+ and a mutated form Hb-.

The instructor should question students:

- Do you think that having a genotype of Hb+/Hb- means that half of the red blood cells have the "normal form" of hemoglobin while the other half have the "mutated form"?

  *No. There will be a mixture of each within each red blood cell.*

- So how is a Carrier (heterozygote) “Protected” from Malaria?

Because students may not yet be able to answer the preceding question, perhaps it would be best to follow up with:

- What if the malaria protozoan uses (consumes) hemoglobin once it’s in the red blood cell? Think about it in terms of a normal person and a carrier?

  *In a normal person, who has normal hemoglobin, the consumption of the hemoglobin in the person’s erythrocyte would place a strain on the ability of the individual to transport oxygen. No structural changes would occur other than lowered oxygen transport (less hemoglobin) and anemia from the lysing of the red blood cells following periodic release of the daugther merozoites upon shizogony.*

  *In a heterozygote, half of the hemoglobin in the red blood cell is mutated. If the parasite consumes the hemoglobin, a potentially severe low oxygen state could occur within each red blood cell. This could cause even the*
carrier's red blood cell (with the parasite(s) to change shape, preventing the spread of the parasite.

The instructor can close by indicating that the red blood cells in the carriers in which the parasite has induced a shape change are removed from the circulatory system by the spleen. Because of this, the person's overall blood level of the parasites remains low enough that the person is able to survive a potentially catastrophic attack. It is this survival that allows a person to survive childhood and develop the long-term immune response.
Basics of Electrophoresis

General Electrophoresis Overhead

○ = an amino acid
mRNA (transcribed from the DNA) of sequences of hemoglobin fragments taken from the three individuals:


DNA (mRNA) Sequence Overhead

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Hemoglobin Molecule
2 Alpha and 2 Beta amino acid polypeptides (a tetramer)

Hemoglobin Chain
Chains Effect RBC

Hemoglobin Overhead
During this class, the instructor will reveal the name of the mystery disease as sickle-cell anemia. Students will watch a film which ties together several of the subdisciplinary approaches to examining the disease.

**Day 8 Objectives**

As this is a summary class, the instructor is encouraged to have students revisit the objectives for the third unit to see if they have gained insight into various aspects of the nature of biology and/or the nature of science.

We wanted students to consider how biological phenomena (in our case the mystery disease) can be studied from numerous interrelated subdisciplines. Through examining how various subdisciplines of biology study sickle-cell anemia, we hope students appreciate that the hierarchical levels of biology (e.g. cells, genes, populations, tissues, etc.) are richly connected. In one way, this awareness ties in nicely with the nature of biology that we’ve examined; that both reductionist and holistic perspectives are necessary to genuinely understand a phenomenon. In another way, having students explore the hierarchical nature of biology ties in directly with the goals & objectives of the national standards (Benchmarks for Scientific Literacy). Here, students are encouraged to explore how systems are interrelated by virtue of making connections between them. In many ways this is wonderfully exemplified in the sickle-cell unit.

Finally, in taking an historical approach, students have gained insight into how knowledge develops by way of exploring how theories are constructed and evaluated.

**Day 8 Materials and Equipment**

- A copy of the video, “Blood” ready for showing

**Day 8 Background Reading Materials**

- Be familiar with the movie so that you can facilitate the summary discussions.

**Set-up Prior to Class**

- Equipment
  - Have the VCR hooked up and ready for viewing.
- Homework (Posted on the right hand side of the white board):
  - Study for the Exam. Consolidate your diary entries.

- On Board:
  - Diary “Seed” Questions
Inquiry
How have the experiences in this unit informed your view of the teaching of science?

M/R
Textbooks present science as a process in which knowledge is gradually and uncomplicatedly accumulated. Has your experience in this unit caused you to agree or disagree with this? Why or why not?

Agenda:
1. Class Business
2. Student Presentations
3. Concept Mapping
4. Film – “Blood”
5. Discussions
   a. Reductionism/Holism
   b. Theories/evidence review
6. Review for Exam
1. **Class Business (~ 5 min)**
   The instructor should cover any miscellaneous issues related to the course.

2. **Student Presentations (~ 30 min)**
   - See class #1.

3. **Concept Mapping (~ 5 min)**
   Check to see if any of the students has any questions about the concept maps they are constructing.

4. **Film – “Blood” (~ 25 min)**
   The instructor should preface the movie by indicating that it’s time to reveal the name of the mystery disease. Note: It’s quite possible that by now many if not most of the students have already determined its name. That being said, in keeping with the format, the movie should provide a nice closure.

5. **Discussions (~ 30 - 40 min)**
   This final discussion can examine any outstanding questions that students may have (whether from the unit itself or from issues raised in the movie). The instructor should also spend time wrapping up the philosophy that was adopted throughout the unit; taking a single phenomenon and examining it from multiple, linked perspectives (subdisciplines). Perhaps a couple points would motivate this approach:

   1. Research in cognitive science indicates that “experts” (in problem solving) exhibit an increased proficiency in making links in their cognitive structure. That is, expert’s knowledge structures are richer in how they link up various concepts with one another. Science education researchers contend that one way to improve student learning is by having students create cognitive links, or mental schema.

   2. One aspect of constructivism contends that real learning takes place only when the learner takes what he/she knows and connects it with the material being learned.

   Students should consider these two points when the think about how this third unit was designed.
**Nature of Biology – Reductionism/Holism Review**

Another important aspect that this experience should illustrate to students is that both reductionist and holist perspectives are necessary to fundamentally understand a biological phenomenon.

The instructor would be wise to point out that their understanding of the disease sickle-cell anemia required them to consider its component parts (e.g. red blood cells, hemoglobin, DNA). They should also be reminded that part of their understanding involved thinking about how various component parts had potential ramifications for the functioning of the whole organism. The latter holistic approach requires us to think about, for example, how changes in the red blood cell potentially affect the normal operation of the cardiovascular system. Or, we could consider how changes in the genotype of a person (in this case being a carrier for the disease) has ramifications on how that person survives in certain environments (e.g. malarial), or how selective advantages of certain genotypes affect population genetics, in general.

The instructor should draw the moral here – that any understanding any biological phenomenon (e.g., studying the eye) requires both a consideration of how the eye functions to benefit the whole organism (note that this may be thought of with reference to evolutionary causes – i.e. the eye has evolved to its current state in humans by virtue of how it exists to benefit the operation of the human). Conversely (and as importantly), understanding the “eye” requires us to consider the structure and function of its parts.

Correspondingly, a reductionist understanding of sickle-cell anemia would have us consider the structure and function of it’s (the disease’s) “parts” (e.g., changes in hemoglobin, mutations to the DNA, changes to the Red Blood Cell). A holistic understanding of sickle-cell anemia requires us to consider how the disease contributes to greater wholes of which it is a functioning part. In this manner, we would consider how the disease has contributed to the frequency of the disease allele in the context of population evolution in concert with ecology (malaria).

**Nature of Science – Theories / Evidence Review**

The instructor should also feel comfortable reviewing with students how the historical examination of the sickle-cell disease afforded them several opportunities to construct their own scientific theories. Each subdiscipline had its own set of “problems” that the student were challenged to explain. These explanations became their theories. The strength of these theories was predicated on the supportive data (evidence) that the students used. In this regard, history has been helpful to see how knowledge develops, is evaluated, and (potentially) changes.
6. Review For Exam
   Explain the format & answer any questions.
Appendix F

Daily “Seed” Questions for the Student Journal Entries
Daily Diary Seed Questions

Class # 1 – Physiology & Cellular Perspectives
(Inquiry) "What curious things did you notice about the patient's red blood cells?" "What effect might these features have upon the functioning of the patient's cardiovascular system? "What further research questions do you have about the mystery disease?"

(Meaning and Relevance) "How do your research questions relate to the distinction between reductionistic and holistic approaches in biology?"

Class # 2 – Genetics I
(Inquiry) "What connections did you see between the genetics discussion last time and our exploration of the physiology and anatomy during the first class?" "How could you account for the differences between individuals who seem to have some of the symptoms of the mystery disease, as compared to those like our mystery patient who have the full blown disease?"

(Meaning and Relevance) "Is the theory you developed today a 'good' theory? What makes a theory 'good'?"

Class # 3 – Genetics II
(Inquiry) "Are the results from this class a "better" interpretation of the genetics than the last class? Why or why not?"

(Meaning and Relevance) "Do you think that the results from today 'prove' the genetics of the mystery disease? Why or why not?"

Class # 4 – Evolution I
(Inquiry) "What was the anomaly (problem) we discovered during our last class? Develop a theory that would explain this anomaly and identify the evidence you have in favor of it."

(Meaning and Relevance) "Since 1947, the evidence (e.g. pedigrees) in support of the genetics of the mystery disease favors the theory of (recessive) simple dominance. Suppose in 2002 you collect pedigree information and your data conflicts with the theory. What does this do to the status of that theory?"

Class # 5 – Ecology
(Inquiry) "What similarities and differences exist between malaria and the mystery disease? What reasons do you have for believing or doubting that the mystery patient has malaria?"
(Meaning and Relevance) "Thus far, much of what you've done in the course of this third unit still remains unresolved. How might this teaching approach (a lengthy mystery) enhance or detract from students' experiences in learning about biology?"

Class # 6 – Evolution ii
(Inquiry) "Does the ecology/epidemiology of malaria shed light on the problem we discovered two classes ago? If so, how?"

(Meaning and Relevance) "Is it enough for a theory to be supported only by observational data? Does confirming a theory require experimental data? Why or why not?"

Class # 7 – Molecular Biology
(Inquiry) "How do the molecular biology results from our last class help us to make sense of the strange shape of red blood cells associated with the mystery disease? How do geneticists depict individuals possessing variant forms of hemoglobin in pedigrees? How would cellular biologists account for these variations?"

(Meaning and Relevance) "Comment on how this class affords your understanding of reductionist and holistic perspectives in biology. By itself, does knowing the molecular biology of the mystery disease (i.e. changes in the DNA) capstone our understanding of the mystery disease?"

Class # 8 - Summary
(Inquiry) "How have the experiences in this unit informed your view of the teaching of science?"

(Meaning and Relevance) "Textbooks present science as a process in which knowledge is gradually and uncomplicatedly accumulated. Has your experience in this unit caused you to agree or disagree with this? Why or why not?"
Appendix G

NOS Questions Given During Class Problems
NOS Questions Given During Class Problems

Class # 1 – Physiology & Cellular Perspectives

Class # 2 – Genetics i

- Suppose that another group of students proposes a different theory to explain the genetics of the mystery disease. How would scientists value (determine) which theory is more valid?

Class # 3 – Genetics ii

- Was your theory (simple dominance) that you developed last class based upon the pedigree data from last class (1923 data) “wrong”?
- After today’s problem, do you have a new theory to explain the genetics?
- If yes, what (specifically) led to your new theory?

Class # 4 – Evolution I

- As “scientists” you all have access to similar data for the Uganda Problem. Do you think that you will all come to the same theory to explain the unusually high frequencies? Why or why not?

Class # 5 – Ecology

Class # 6 – Evolution ii

- Is it troubling to you that you are basing your explanations for the high frequencies of the mystery disease on data that was collected from scientists making observations (rather than their having conducted controlled experiments?)
- Do you think experiments are necessary for knowledge to develop in science?
- Has your theory to explain the high frequencies changed? What caused you to change?

Class # 7 – Molecular Biology

Class # 8 - Summary
BIBLIOGRAPHY


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