Students' Perceptions of the Nature of Evolutionary Theory

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ABSTRACT: This study explored how some college students understand the nature of the theory of evolution and how they evaluate its scientific status. We conducted semistructured interviews with 15 college biology seniors in which we asked them to explain why they think evolution assumes the status of a scientific theory, how it compares to other scientific theories, and what criteria do they use to determine if an explanation is scientific or not. Students' responses encompassed five themes that include evidence, certainty, experimentation, method of theory generation, and prediction. Those themes focused on the theory's empirical dimension which seemed to be derived from a generic and simplistic model of physical science theories that valued direct evidence. Demanding that evolutionary theory conform to this model reveals a misunderstanding of its *nature*. This misunderstanding was expressed in relation to aspects of methodology, explanation, and prediction. The findings underscore the need for using explicit discipline- and context-specific approaches to teaching and learning about scientific theories. © 2005 Wiley Periodicals, Inc. *Sci Ed* **89:**378–391, 2005

INTRODUCTION

Science educators have studied the nature of science from a variety of perspectives. Some researchers have focused on the effectiveness of different approaches to teaching the nature of science in the general context of student learning (Abd-El-Khalick & Lederman, 2000a; Bartholomew et al., 2004) or teacher preparation (Abd-El-Khalick & Lederman, 2000b; Khishfe & Abd-El-Khalick, 2002), while others have focused on teaching the nature of science in the context of specific disciplinary frameworks (Abd-El-Khalick, 2001; Brickhouse et al., 2002; Driver et al., 1996; Duschl, 1990; Leach, Hind, & Ryder, 2003; Matthews, 2000; Shipman et al., 2002). Improving students' and teachers' understanding of the nature of science has shifted from being a desirable goal, to being a central one for achieving

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scientific literacy (American Association for the Advancement of Science [AAAS], 1990; National Research Council, 1996).

Research is growing about a core set of nature of science principles appropriate for school science (McComas et al., 1998; Osborne et al., 2003). Although those principles include important ideas, Rudolph (2000) has expressed concern about efforts to incorporate general understanding about the nature of science into the science curriculum due to a (1) mismatch between the simplified conceptions of science and their ability to "inform the specifics of any disciplinary practice" and (2) "growing concern(s) over the validity of universal conceptions altogether" (Rudolph, 2000, p. 407). Attending to those concerns demands refocusing studies of the nature of science within clearly defined disciplinary contexts.

Combining questions pertaining to the nature of science with a disciplinary content, such as the theory of evolution, sharpens the lens with which we examine understanding. Some researchers have focused on students' cognitive understanding of evolutionary theory (Anderson et al., 2002; Bishop & Anderson, 1990; Demastes et al., 1995), while others have examined paracognitive factors that influence student engagement with the content, such as their personal or religious beliefs (Brem, Ranney, & Schindel, 2003; Dagher & BouJaoude, 1997; Fysh & Lucas, 1998; Jackson et al., 1995; Roth & Lucas, 1997). Those studies demonstrate that attending to the conceptual dimension alone in teaching the theory of evolution is not adequate for improving engagement with or understanding of this theory. While it is expected that students possess incoherent or alternative conceptions about almost any science topic, it is documented that students who perceive conflict with their personal or religious beliefs are more likely to express higher resistance to the assumptions and conclusions of the theory of evolution (Sinatra et al., 2003).

Students have expressed their objections to evolutionary theory in terms of one or more of the following types of arguments involving: (1) conceptual difficulties, (2) extrascientific explanations (e.g. Aristotelian ideas), (3) faulty understanding of the nature of science, and (4) interpretation of the nature of religion (Dagher & BouJaoude, 1997). Students' conceptual difficulties and appeal to outdated explanations are generally accompanied by a limited understanding of the nature of science. Addressing students' conceptions of the nature of science then become a necessary, though not sufficient, vehicle for helping them to understand the epistemological foundations of evolutionary theory.

Science educators have long noted the importance of attending to the nature of science when teaching the theory of evolution suggesting specific interventions such as (1) using a nature of science approach to the theory of evolution (e.g. Clough, 1995; National Academy of Sciences, 1998), (2) following a historical approach that enables students to view their own personal controversies in a larger societal perspective (e.g. Solomon et al., 1992), and (3) teaching nature of science via content-specific and embedded inquiry activities (Passmore & Stewart, 2002). While those approaches are promising, we do not have adequate documentation on their comparative success in improving students' understanding of the *nature* of evolutionary theory.

The purpose of this study is to explore how some college biology seniors characterize the nature of evolutionary theory. By focusing on this key idea, we hope to address the role the disciplinary context plays in shaping students' views. The findings can have useful implications for developing and evaluating science curricula and instruction.

THEORETICAL FRAMEWORK

The theory of evolution is a composite of five main theories: nonconstancy of species, common descent, gradualism, speciation, and natural selection. According to Mayr (2001), the first two theories were accepted within a few years of publishing *On the Origin of Species* while the latter three were accepted much later in the 1940s. Because evolutionary theory (ET) is not one theory but a system of theories, Mahner and Bunge (1997) maintain that it can be tested only indirectly by testing its component parts: "What are testable are the bound models of the component theories. Thus, confirmation for the system of theories ET is obtained by what might be called the 'evidential consilience' of the diverse models of its component theories" (p. 363). Thus, a substantive understanding of the nature of evolutionary theory involves an appreciation of the convergence of three types of evidence offered in its support: circumstantial, direct, and historical (see Figure 1).

Scientific theories and laws are two of the most complex constructs in the philosophy of science. Defined as overarching explanations that have been well substantiated, scientific theories are typically contrasted with scientific laws or "descriptive generalization[s] about how some aspect of the natural world behaves under stated circumstances" (National Academy of Sciences, 1998, p. 4). The expectation that laws of nature be empirical and universal generalizations has caused some philosophers to question whether laws of nature exist at all (Cartwright, 1983). One way that philosophers have addressed that is by arguing

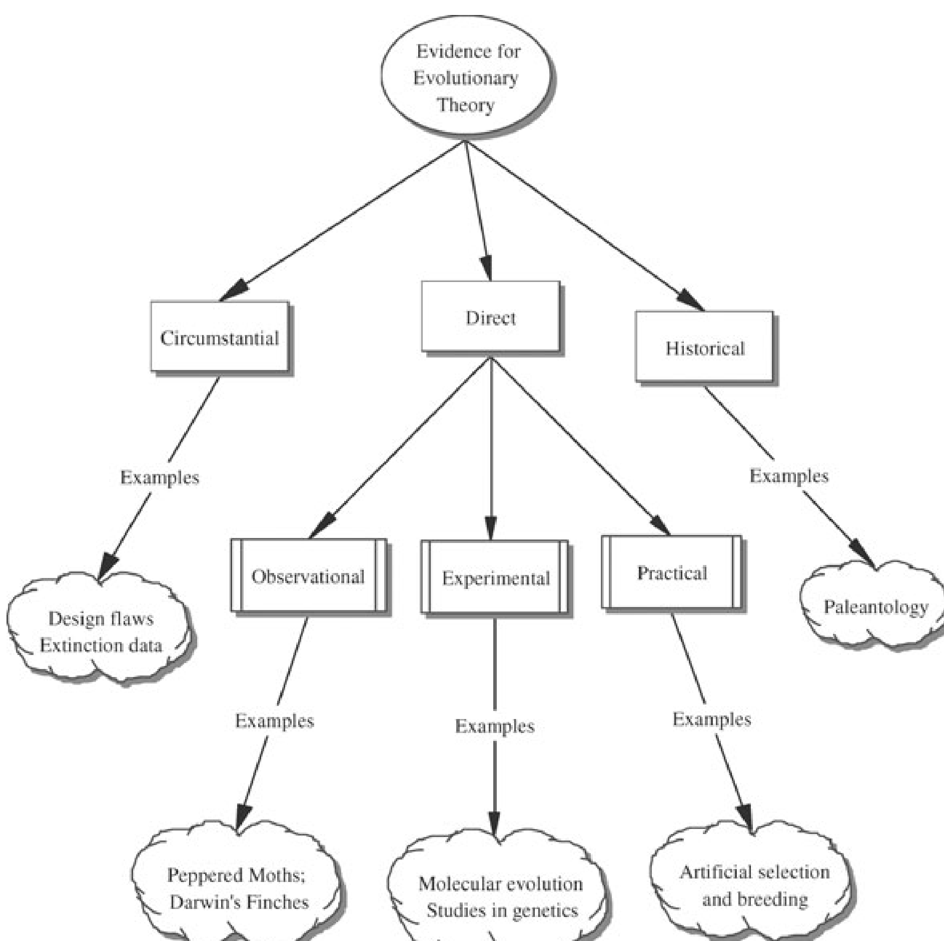

Figure 1. Nature of evidence for evolutionary theory: A description based on Mahner and Bunge (1997, pp. 362–366).

that the *empirical* requirement for laws is too strong given the profusion of *a priori* generalizations in the sciences and therefore should be dropped (Elgin, 2003). Others like Ruse and Hull assume that this problem is common across the sciences, and focus on defending the existence and legitimacy of biological laws.

Mayr believes that "biologists usually organize their generalizations into a framework of concepts" and that progress in biology is a function of the development of those concepts. (Mayr, 1982, p. 43). Sober (1993, p. 15) suggests that "models" is the preferred term for those generalizations. Biological models have "characteristic if/then format that we associate with scientific laws. These mathematical formalisms say what will happen *if* a certain set of conditions is satisfied by a system. They do not say *when* or *where* or *how often* those conditions are satisfied in nature" (p. 15). This is also typical of the laws in physics. Of most concern to several philosophers of biology like Ruse (1988), Sober (1993), and Ghiselin (1997) is treating knowledge claims in biology on the same par of credibility as knowledge claims in physics.

In elaborating differences between the sciences, Sober (1993) distinguishes between the monolithic (lawlike) and the historical (idiographic) sciences emphasizing that this characterization does not imply that "each science is exclusively one or the other" (p. 14). Rather he sees the difference as one of emphasis between means and ends. Sober contrasts the work of a particle physicist who uses descriptions of particular objects as means to the goal of inferring general laws, to the work of an astronomer (both physical science) who uses physical laws to infer the properties of a particular object as a means to arriving at historical particulars about that object. In evolutionary biology, a systematist is concerned about reconstructing genealogical relationships while a paleobiologist identifies which species lived and which others did not. Both aim to arrive at historical reconstructions that explain observations rather than arrive at general laws. The disciplinary distinctions are a function of a variation of emphasis between the goals and means within each subdiscipline.

Sober (1993) suggests that in order to classify a claim as a law or a historical hypothesis in evolutionary biology, it is important to be clear about the specific "proposition" in question. Asking "whether 'natural selection' is a law is meaningless until one specifies which proposition about natural selection is at issue. To say that natural selection is responsible for the fact that human beings have opposable thumbs is to state a historical hypothesis; but to say that natural selection will lead to an even sex ratio . . . is to state a law" (p. 16). Whether the goal is to arrive at laws or to explain historical events, subdisciplines in biology work together to provide coherent explanatory frameworks.

Generally speaking, laws/models deal with regularities while theories embody complex systems of explanations/historical reconstructions that supersede the boundaries of given laws and are of generally unobservable nature. Developing the models or the explanations is never a linear process. According to Sober (1993), Darwin's pattern claim (all terrestrial organisms are related geneologically) and process claim (natural selection is the principle cause of complexity) were not a "straightforward report of what [he] *saw*" (p. 14). This is reminiscent of Galileo's claims about the heliocentric universe which were not derived directly from his observations. The logical and creative relationship between observations, model building, and theory development is a complex one in all the sciences and is perhaps the least understood by lay people.

From an educational perspective, studies on student understanding of the nature of scientific knowledge show that students tend to (1) associate laws with a high level of certainty than theories because they are more directly observable (Dagher et al., 2004; McComas & Olson, 1998); (2) demand direct evidence to be offered as proof of a theory (Dagher et al. 2004); (3) believe that theories are proven hypotheses (Sandoval & Morrison, 2003) that can become laws when they become confirmed (Dagher et al., 2004; Griffiths & Barman, 1995;

McComas & Olson, 1998; Meyling, 1997; Ryan & Aiknhead, 1992). Gibbs and Lawson (1992) analysis of high school biology textbooks show that they promulgate a number of naïve ideas that have been expressed also by students such as describing theory "as hypotheses that have been supported over a long period of time" (p. 137). Also they promote the mistaken notion that theories that are consistently supported by experimentation and observation become accepted as laws.

Given the complex nature of evolutionary theory just described, we were interested in finding out how college biology students characterize the nature of this theory, why they think it is called a theory, and to elicit in the process comparisons with other scientific theories that they choose to discuss. Our goal was to elicit students' characterizations in an open-ended fashion, allowing them to express their own views about evolutionary theory. The focus was not on documenting what students retained of the factual content of the theory as much as on using what they retained from it as a springboard for eliciting their perceptions about the *nature* of evolutionary theory.

METHODOLOGY

This study is an extension of an earlier one in which we explored how students accommodate their understanding of the theory of evolution with their religious beliefs. We chose the 15 participants interviewed in this report from among 62 college biology majors[1] who were enrolled in a senior seminar at a private university in Beirut, Lebanon. We based our purposeful selection of participants on their response to an open-ended questionnaire in which we asked them to disclose their student identification number, age, religion, and answers to the following three questions: (1) List the major principles of the theory of evolution. Use examples to clarify your answer. (2) Do you believe that the theory of evolution presents a conflict between science and religion? Explain in detail. (3) Does the theory of evolution clash with your own beliefs about the physical and biological world? Discuss in detail. The findings of the initial study were reported elsewhere (See Dagher & BouJaoude, 1997). Based on their responses to this questionnaire, we selected students who represented a broad range of views and religious backgrounds. Of the 15 interviewees, 10 were males and 5 were females. Those numbers reflect the ratio of males to females in the original study.

We conducted semistructured interviews with individual students in which we referred to the student's written response as an entry point into discussing why they think evolution assumes the status of a scientific theory, how it compares to other scientific theories, and what criteria do they use to determine if an explanation is scientific or not. Follow-up questions focused on exploring students' reasoning in more detail. The interviews ranged from 30 to 45 min in duration. We transcribed the audiotaped interviews verbatim and analyzed the transcripts seeking to capture the range of views expressed among participants.

We read the transcripts with an open system, that is, we did not use a pre-established guiding scheme for organizing our observations. However, we were aware of the students' general understandings about scientific theories as reported in the literature (Brickhouse et al., 2002; Driver et al., 1996; Jiménez Aleixandre, 1992; Shipman et al., 2002). Using the constant comparative method (Strauss, 1987), we grouped similar characterizations of

[1] Regarding the educational background of the participants at the time of this study, it is important to note that an evolution course is not among the core requirements for completing coursework for a biology degree. Among the general education core requirements for students at this university is a set of four Civilization Sequence courses in which students are exposed to the major schools of western thought. In one of the courses, Darwin's *On the Origin of Species* is read and discussed. Also, students read descriptions of the scientific method by Francis Bacon.

evolutionary theory under the same theme. A new theme qualified as a separate category if it was adequately distinct enough from the others, and if we judged it to carry enough theoretical significance to deserve identification. Some of the initial themes were later collapsed under others, leading to five themes that seemed to capture the range of students' characterizations.

FINDINGS

Our data analysis revealed that the students focused on one or more of the following themes describing the theory of evolution: the nature of evidence underpinning the theory, the degree of certainty, experimentation, method of theory generation, and the ability of the theory to generate predictions that allow reproducibility. Each theme constitutes an umbrella category for a number of descriptive statements about the theory that are expressed differently among students but are directed toward the same big idea.

The issue of overlap across the themes was natural because students do not usually think in terms of "pure" characteristics but typically refer to several in constructing their answers. Those themes are not unrelated, and the majority of students (9 of 15) mentioned more than one. Of the nine students, three referred to three themes and six referred to two. For a characterization to become a theme, it had to be discussed by the student as a focus point, or one of several. For example, it is natural when students refer to experimentation to discuss the nature of evidence expected in an experiment. However, not all students who mentioned direct evidence by observation, referred to the necessity of doing experiments. In what follows, we will illustrate each theme with excerpts from the transcribed interviews.

Nature of Evidence

The majority of students (9 of 15) focused on the nature of evidence given for the theory, mostly expressing the idea that evolutionary theory is deficient in meeting a criterion of "proof" or evidence that was trustworthy. In their view, the evidence is either inadequate because "there are many views concerning this phenomenon [evolution] and . . . no one theory has had enough evidence to support its facts" (S1), or impossible "because [evolution] describes mechanisms that extend over thousands and millions of years that cannot be measured on a human scale" (S2).

One student for instance attacked the validity of evidence: "The evidence is just not clear and valid." For this student, valid evidence is "something that is very certain" such as "the earth is round, the earth is oval, things that are scientific, very scientific things" (S3). Others discussed the importance of direct evidence and explained that it meant observing the process of evolution in person, something they knew to be impossible due to the time frame involved. One student for example explained:

> What is hard about proving evolution for instance is the fact that evolution requires long and long periods of time, thousands or even hundreds of millions of years to take place. Now this is something very hard to prove, for example they cannot wait. If you have to see evolution happening you should for example photograph an animal now and then photograph it later about a million years later this is very hard to prove at the moment but you can depend on certain evidences for example mutation. (S4)

While most students conceded that observational or experimental evidence exists or may be secured for natural selection, the majority found the extrapolations to be unlikely to support the claims of macroevolution.

The majority of students expressed the idea that evolution is considered a theory because it lacks "hard facts": "facts which were unambiguous and incontrovertible in themselves" (Driver et al., 1996). The students do not seem to appreciate that (1) theories, in general, are underrepresented by data, (2) the theory of evolution employs historical explanations for which "direct evidence" as employed in some branches of physical science is impossible to secure, and that (3) creativity and imagination play an important role in the construction of scientific theories. Even though some students expressed awareness of the historical and circumstantial evidential base of evolutionary theory, they were reluctant to regard it with the level of confidence they attributed to direct evidence. Instead of viewing nondirect evidence as corroborative evidence that strengthens the theory, it is treated as soft evidence that weakens it.

Degree of Certainty

There were two main views expressed by students with regards to the degree of certainty: The theory of evolution is certain (two students) and the theory of evolution is not certain (three students). One of the students who espoused the certainty position stated that "Everything is done by research. Starts with a hypothesis then theory. . . . Theory is when we're sure, if nothing has been done it is a hypothesis. [Theories] use observations and experiments" (S5). On the other side of the coin were three students who regarded theories to be uncertain. For instance, one student expressed the view that a theory is a confirmed hypothesis and that when theories become more confirmed they become laws. Previous studies show a similar trend in student thinking (e.g. Bishop & Anderson, 1990; Brickhouse et al., 2002; Demastes, Good, & Peebles, 1995; Ryan & Aikenhead, 1992). In one student's view, the theory of evolution is called a theory because it cannot be proven, otherwise it would be called a law. In another student's view, theories are not scientific enough because: "something is scientific when I don't have doubt in it. A theory is something that may be right and may be wrong" (S3).

Students seemed to differentiate between degrees of confidence in some theories depending on whether they can be proven or not. For example, one student explained the difference between cell theory and evolutionary theory by stating that the first was proven because we can see cells under microscopes, whereas evolution is not proven because we cannot experiment on humans. So for this student some theories are proven and some are not—kinetic theory and Newton's laws have been tested and applied; relativity and evolution are not really scientific in the sense that they do not meet the same rigorous criteria of testing. Another student contrasted the law of gravitation (gravity is there—conflating the law with the phenomenon—also noted in Brickhouse et al., 2002) with the theory of evolution (evolution is postulated). This distinction was an unsuccessful attempt by the student to demonstrate what he perceived to be a critical epistemological difference between laws and theories.

While Mayr (1982) concedes that in some instances it is possible to provide proofs that correspond to assertions, in most cases it is impossible for biologists to provide proofs with absolute certainty. This is also true in physics: "scientists are satisfied to consider as true either that which appear most probable on the basis of the available evidence, or that which is consistent with more, or more compelling, facts than competing hypotheses" (p. 26). In Mayr's judgment, it is inappropriate to expect absolute truth or proof in any branch of science.

Experimentation

Experimentation was considered by one third (5/15) of the students to be the hallmark of science and declared that the theory of evolution falls short of meeting this standard.

The following captures a typical view: "when someone puts some hypothesis, he needs to demonstrate it by an experiment but in evolution we are working on man and on creature, so we can't demonstrate, we can't give a proof. See 1 + 2 gives 3 ok? Or we can't measure by a meter or something" (S6). In this quote the student is describing the impossibility of experimentation given the limitation of the experimental subject.

Another student finds the lack of experimentation to be problematic. Although he admits the existence of nonexperimental evidence, he does not view it as valid enough to elevate evolution to the level of fact, and that's why it remains a theory in his view:

> Due to its mere nature, experimentation is not direct, could not be applied directly to the theory. However there are some evidences which occurred in our century. . . . There is proof that before the industrial revolution these plants have changed in shape and in structure and in biochemical properties to adjust to the new environment. These are some changes which occurred but in nature over a large period of time, it is not subject of direct experimentation in the lab. [It is unlikely to become a fact] unless man unlocks the secret of time so that he can just elapse long period of time in short time. (S7)

The description given by this student and others (see also quotes from S4, nature of evidence subsection earlier, and S9 in the predictability subsection) are reminiscent of Gould's metaphorical Popperian test of evolutionary theory in which one "would need to wind the tape of history back and replay it time and again under a variety of different circumstances—an achievement possible only in certain model test-tube experiments" (see Rose, 1998, p. 47). Despite the fact that some students made reference to legitimate experimental evidence, they wanted that evidence to apply to all propositions including the historical ones.

Method of Theory Generation

Few students (4 of 15) framed their ideas within a linear framework characteristic of the "scientific method," arguing that the theory of evolution missed one or more of the steps. In one student's view, knowledge is considered scientific

> because there are scientific steps or criteria for something to be scientific. Like you need to have observations, make experiments on something and then from observation and experiments you can deduce whether your facts could be right or wrong. So there is a specific method or way to establishing something as scientific or not." (S1)

Another student pointed out that the theory of evolution itself does not follow the scientific method (hypothesis–experiment–theory):

> Usually with the scientific method we start with the hypothesis and we go testing and if the hypothesis is correct if goes into being a theory but I don't know anything about evolution starting as a hypothesis and being tested, you know where was it tested? All we know is that he [Darwin] based it on citing he was in Galapagos Islands if I remember well and there he noticed many things. A theory {hesitant} I don't know if it is a big step or if he made any investigations concerning the thing." (S8)

The expectation that every step in the method ought to be followed in the prescribed order and that following the scientific method is what gives confidence in obtained knowledge are characteristic of students' responses in this category (see an earlier quote by S5 under "Degree of Certainty").

Predictability

Even though this category was expressed only by two students, we retained it as a theme because of its theoretical value. For one of those students, scientists' inability to predict the course of evolution, placed the theory of evolution at a lower level than other theories in biology:

> You see, no scientist can expect what are the plant species that are going to survive one million years from now. No scientist can provide such a prediction. But they can always predict that if you have a human you give them such and such drug this drug would have this effect on this human because clinical trials have been conducted on thousands of people and molecular mechanisms and drug action was completely described very accurately in a way that is no longer controversial. . . . but as far as the theory of evolution every single step in it is very controversial, extremely controversial because it has never been observed in the past. It is not reproducible experimentally." (S9)

One of the difficulties of meeting the predictability expectation in the theory of evolution is that "different genotypes within a single population may respond differently to the same change of the environment. The changes of the environment, likewise, are unpredictable . . . Finally, there are occasionally very drastic changes in the global environment resulting in so-called mass extinctions" (Mayr, 2001, p. 277).

Synthesis

In Table 1 we present the five themes that emerged from student responses. Against their responses, we present our inference of their referent for describing the theoretical status of theory of evolution. Students' reference point capture one or more elements from a simplistic and generic model of theories in physical science. We use the word "generic" in this paper to refer to a set of abstracted qualities or overgeneralized characteristics of theories that students use to describe evolutionary theory. This generic model, seems to be the standard against which students gauged the credibility of the theory of evolution, leading most of them to conclude that it is not truly scientific (in the Popperian vein; see Mahner & Bunge, 1997, p. 362) because it fails to meet one or more of the premises of the generic model.

Very few students in this study referred to the logical, sociological, or historical dimensions of evolutionary theory (Duschl, 1990; Root-Bernstein, 1984). One student for example pointed to a logical contradiction between conservation of genetic code and change in the code for evolution to happen, another referred to a logical contradiction with the principle of biogenesis. One student (S7) correctly noted the logical convergence of evidence: "We have evidences. . . They support it very very logically, not each alone but collectively" (S5). Students' heavy emphasis on the empirical dimension, compounded with many misunderstandings associated with it, such as the necessity of direct observation or experimentation, predisposed most to view the theory as tentative in a rather dismissive way.

Most students in this study viewed evolution as an eventlike property instead of an equilibration process that is "uniform, simultaneous and ongoing; not distinct, sequential or bounded, like an event" (Ferrari & Chi, 1998). This lack of distinction in the ontology of evolutionary concepts was evident in the way students talked about the five different themes depicted in this analysis.

Most students in this study found the theory of evolution to be lacking the hard evidence they typically expect of credible scientific theories. They seemed to have trouble accepting the validity of the three types of evidence (circumstantial, direct, and historical) leading

TABLE 1
Students' Expressed Views About the Theory of Evolution Contrasted with Students' Normative Views of Scientific Theories as Inferred by Authors

Theme	Number of Students Who Expressed This Theme Idea Against Those Who Rejected ET	Students' Expressed Views on the Theory of Evolution	Students' Normative Views of Scientific Theories as Inferred by Authors
Nature of evidence	9:6	Solid evidence cannot be secured. It cannot be proven.	Solid scientific evidence should be direct and visual.
Degree of certainty	5:3	Scientific theories are certain (2). Scientific theories are not certain, they change (3).	Scientific theories can be right and can be wrong. Scientific theories are tentative.
Experimentation	5:2	No direct experimentation is possible especially in relation to macroevolution.	Experimental evidence is necessary for theory generation or validation.
Method of theory generation	4:3	The theory of evolution is missing one or more of the steps of the scientific method.	There are steps to arriving at theories that consist of observation and experimentation.
Prediction	2:2	The theory of evolution cannot predict the course of evolution.	Scientific theories should make predictions.

to a logical convergence of evidence from different fields. Also, their points of reference consisted of "generic" criteria that fit more the profile of mechanical/causal explanations than historical/genetic explanations. This was evident in their insistence on visible proof, certainty, experimentation, and prediction. The circumstantial and historical types of evidence were not seen by most students as trustworthy because they do not conform to the standards students have come to associate with things scientific.

In sum, students seem to develop over their K-16 schooling some model of scientific knowledge. Features of this generic model include a perception that evidence should be direct (specifically: observational or experimental), that theories should always generate testable predictions (regardless of the "size" of their propositions). Demanding that evolutionary theory conform to this model reveals a misunderstanding of its *nature*. This misunderstanding which is most noted in relation to methodology (see types of evidence in Figure 1), explanation, and prediction is not surprising given that students may not be aware that the component theories of evolutionary theory "are general, and general theories only allow for general explanations and predictions" (Mahner & Bunge, 1997, p. 364).

DISCUSSION

This study documents how some students (9 of 15) use their generic understanding of the nature of science as ammunition to dismiss evolutionary theory (see Table 1 for the ratio of students rejecting evolutionary theory under each theme). Although this study focuses on student reasoning about the theory of evolution, we speculate that students' conceptions of other theories may be also tainted with similar generic views to those expressed here. We speculate that this generic model of what a scientific theory is, is tacit in nature, and is not articulated unless a newly encountered theory clashes with some deeply held beliefs (religious or secular). Given these findings and previous studies, we acknowledge that students' generic descriptions about the theory of evolution may have been motivated by affective factors shaped by their religious beliefs, worldviews, or social expectations.

Science education reforms stress the need for an improved understanding of the nature of science for the sake of achieving scientific literacy. One formulation of scientific literacy in this regard (AAAS, 1990, pp. 2–7) emphasizes the importance of understanding the scientific worldview which includes the following assumptions: *The world is understandable, scientific ideas are subject to change, science cannot provide complete answers to all questions*. It also emphasizes understanding scientific inquiry, which includes the following components: *Science demands evidence, science is a blend of logic and imagination, science explains and predicts, scientists try to avoid bias, science is not authoritarian*. But to what extent are the general assumptions underlying this worldview adequate for directing our efforts in reforming students' understanding of science?

From our perspective, components of the "scientific worldview" are too general to capture the subtleties of the nature of different science disciplines. Students in our sample communicated a strong awareness that scientific theories are subject to change and that scientists cannot provide complete answers to all questions. They also recognized the importance of evidence in science, and appreciated the power of scientific explanation and prediction. However, this set of generic understandings was decontextualized. It did not enable most students to appreciate the distinctive *nature* of evidence, explanations, and predictions employed in evolutionary theory. In fact, most students interviewed in this study used their "generic" understandings of evidence, explanations, and predictions to explain why evolutionary theory is defective. For example, students used the view that scientific knowledge changes to reject scientific theories especially if they clash with their religious understandings.[2] In light of their acceptance of religious knowledge as immutable, and their recognition that scientific knowledge is evolving, they find it perfectly logical to favor the former over the latter.

Likewise, the view that scientific theories are backed up by evidence was commonly expressed by the participants in this study. The problem they faced was not one of acknowledging the need for evidence as much as one of understanding and evaluating the nature of that evidence and what makes it valid in the context of evolutionary theory. Most students in this study made skewed judgments about which evidence is valid (direct) and which is not (historical and circumstantial). Furthermore, they seemed to want to subject the historical evidence to "tests" appropriate for direct evidence reflecting a misunderstanding of the nature of those evidences and how they relate to one another.

We firmly believe that generic attributions concerning the nature of science can become vacuous when disconnected from the epistemological foundations of specific theories and practices. The "scientific worldview," or any other set of agreed upon nature of science

[2] Dagher and BouJaoude (1997) found that about one third of the students in the original sample ($n = 62$) rejected evolution on religious basis. These students used two religion-based arguments against the theory of evolution. First, they suggested that organisms created by God were perfect and consequently are not amenable to change. Second, all organisms existing on earth were created as is and thus it is not possible that they evolved from more primitive forms.

principles, ought to be embedded in specific theories. It is only from within the context of a specific theory that it is possible to understand the logical, empirical, sociological, and historical basis of scientific knowledge. The processes of theory choice and validation, as pointed out by many science educators (Duschl, 1990; Norris, 1985; Root-Bernstein, 1984; Rudolph, 2000) are too complicated to be accounted for by generic models of scientific inquiry.

Given the preceding discussion, we believe that the most common approach to teaching the nature of science that takes a starting point a set of nature of science constructs and attempts to infuse them in the content should be reversed. Instead of asking what big ideas about science do we want to embed in the science context, we need to ask what nature of science concepts are integral to the development of the target scientific theory (such as evolutionary theory, plate tectonics), and then design a curriculum that attends to them in context. Much like Passmore and Stewart's (2002) modeling approach to teaching evolutionary biology in high school, similar curricular models can be developed in relation to other topics to promote rich discipline-based understandings of science and scientific inquiry (see also Leach et al., 2003; Stewart & Rudolph, 2001).

When the syntactic nature of science is deeply grounded in the substantive aspects of that knowledge (Schwab, 1962), it is possible to explore the power and limitations of scientific theories with an eye on the ontological and metaphysical assumptions underlying them. This also helps situate scientific knowledge both historically and socially, thus humanizing that knowledge (Lemke, 1990) and making it more appealing to students. This type of teaching and learning about the nature of science is explicitly integrated in ongoing encounters with a diverse set of scientific theories. The understanding is "grounded, with each inquiry, case, or research programme providing the bounds for what science is about in that particular instance, and with each instance building toward a greater understanding of not what science *is*, but rather of what science *includes*" (Rudolph, 2000, p. 417). Consequently, assessment of understanding of the nature of science would not focus on students' ability to construct generalizations that hold true at all times and places, but on their ability to identify the proper cannons of evidence associated with inquiry in specific science (sub)disciplines.

The findings in this study support Rudolph's (2000) poignant argument concerning the futility of teaching nature of science concepts based on some universally abstracted notions even when those have been agreed upon by experts. The cost of cultivating a generic understanding of the nature of science is high: It leads to false conclusions and compromises students' understanding of science as well as the plurality of scientific methods and explanations. We believe that an explicit discipline- and context-specific approach to teaching and learning about scientific theories is a more fruitful pathway for (1) situating students' conceptions about nature of science in rich disciplinary contexts, (2) enhancing the development of students' metacognitive skills, and (3) promoting a stance of inquiry toward both the content and methods of the sciences.

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REFERENCES

Abd-El-Khalick, F. (2001). Embedding nature of science instruction in preservice elementary science courses: Abandoning scientism, but. . . . Journal of Science Teacher Education, 12, 215–233.

Abd-El-Khalick, F., & Lederman, N. (2000a). The influence of history of science courses on students' views of nature of science. Journal of Research in Science Teaching, 37, 1057–1095.

Abd-El-Khalick, F., & Lederman, N. (2000b). Improving science teachers' conceptions of the nature of science: A critical review of the literature. International Journal of Science Education, 22, 665–701.

American Association for the Advancement of Science. (1990). Science for all Americans. New York: Oxford University.

Anderson, D., Fisher, K., & Norman, G. (2002). Development and evaluation of the conceptual inventory of natural selection. Journal of Research in Science Teaching, 39, 952–978.

Bartholomew, H., Osborne, J., & Ratcliffe, M. (2004). Teaching students "ideas-about-science": Five dimensions of effective practice. Science Education, 88, 655–682.

Bishop, B., & Anderson, C. (1990). Student conceptions of natural selection and its role in evolution. Journal of Research in Science Teaching, 27, 415–427.

Brem, S., Ranney, M., & Schindel, J. (2003). Perceived consequences of evolution. College students perceive negative personal and social impact in evolutionary theory. Science Education, 87, 181–206.

Brickhouse, N., Dagher, Z., Letts, W., & Shipman, H. (2002). Evidence and warrants for belief in a college astronomy course. Science and Education, 11, 573–588.

Cartwright, N. (1983). How the laws of physics lie. Oxford: Clarendon.

Clough, M. (1995). Diminish students' resistance to biological evolution. The American Biology Teacher, 5, 401–415.

Dagher, Z., & BouJaoude, S. (1997). Scientific views and religious beliefs of college students: The case of biological evolution. Journal of Research in Science Teaching, 34, 429–445.

Dagher, Z., Brickhouse, N., Shipman, H., & Letts, W. (2004). How some college students represent their understanding of scientific theories. International Journal of Science Education, 26, 735–755.

Demastes, S., Good, R., & Peebles, P. (1995). Students' conceptual ecologies and the process of conceptual change in evolution. Science Education, 79, 637–666.

Driver, R., Leach, J. Millar, R., & Scott, P. (1996). Young people's images of science. Buckingham: Open University Press.

Duschl, R. (1990). Restructuring science education. New York: Teachers College Press.

Elgin, M. (2003). Biology and a priori laws. Philosophy of Science, 70, 1380–1389.

Ferrari, M., & Chi, M. (1998). The nature of naïve explanations of natural selection. International Journal of Science Education, 20, 1231–1256.

Fysh, R., & Lucas, K. (1998). Religious beliefs in science classrooms. Research in Science Education, 28, 399–427.

Ghiselin, M. (1997). Metaphysics and the Origin of Species. Albany, NY: State University of New York Press.

Gibbs, A., & Lawson, A. (1992). The nature of scientific thinking as reflected by the work of biologists and by biology textbooks. American Biology Teacher, 54, 137–152.

Griffiths, A., & Barman, C. (1995). High school students' views about the nature of science: Results from three countries. School Science and Mathematics, 95(5), 248–255.

Jackson, D., Doster, E., Meadows, L., & Wood, T. (1995). Hearts and minds in the science classroom: The education of a confirmed evolutionist. Journal of Research in Science Teaching, 34, 93–95.

Jiménez Aleixandre, M. (1992). Thinking about theories or thinking with theories? A classroom study with natural selection. International Journal of Science Education, 14(1), 51–61.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. Journal of Research in Science Teaching, 39, 551–578.

Leach, J., Hind, A., & Ryder, J. (2003). Designing and evaluating short teaching interventions about the epistemology of science in high school classrooms. Science Education, 87, 831–848.

Lemke, J. (1990). Talking science. Norwood: Ablex.

Mahner, M., & Bunge, M. (1997). Foundations of biophilosophy. Berlin: Springer-Verlag.

Matthews, M. (2000). Time for science education: How teaching the history and philosophy of pendulum motion can contribute to scientific literacy. New York: Plenum-Kluwer.

Mayr, E. (1982). The growth of biological thought: Diversity, evolution, and inheritance. Cambridge, MA: Belknap Press of Harvard University Press.

Mayr, E. (2001). What evolution is. New York: Basic Books.

McComas, W., Clough, M., & Almazroa, H. (1998). The role and character of the nature of science in science education. In McComas, W. (Ed.), The nature of science in science education: Rationales and strategies (p. 3–39). Dordrecht: Kluwer Academic.

McComas, W., & Olson, J. (1998). The nature of science in international science education standards documents. In McComas, W. (Ed.), The nature of science in science education: Rationales and strategies (p. 41–70). Dordrecht: Kluwer Academic.

Meyling, H. (1997). How to change students' conceptions of the epistemology of science. Science & Education, 6, 397–416.

National Academy of Sciences. (1998). Teaching about evolution and the nature of science. Washington, DC: National Academy.

National Research Council. (1996). The national science education standards. Washington, DC: National Academy.
Norris, S. (1985). The philosophical basis of observation in science and science education. Journal of Research in Science Teaching, 22, 817–833.
Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. Journal of Research in Science Teaching, 40, 692–720.
Passmore, C., & Stewart, J. (2002). A modeling approach to teaching evolutionary biology in high schools. Journal of Research in Science Teaching, 39, 185–204.
Root-Bernstein, R. (1984). On defining scientific theory: Creationism considered. In A. Montagu (Ed.), Science and creationism (pp. 64–94). New York: Oxford University Press.
Rose, S. (1998). Lifelines: Biology beyond determinism. Oxford, NY: Oxford University Press.
Roth, M.-W., & Lucas, K. (1997). From "truth" to "inverted reality": A discourse analysis of high school physics students' talk about scientific knowledge. Journal of Research in Science Teaching, 34, 145–179.
Rudolph, J. (2000). Reconsidering the 'nature of science' as a curriculum component. Journal of Curriculum Studies, 32, 403–419.
Ruse, M. (1988). Philosophy of biology today. Albany, NY: State University of New York Press.
Ryan, A. G., & Aikenhead, G. (1992). Students' preconceptions about the epistemology of science. Science Education, 76, 559–580.
Sandoval, W., & Morrison, K. (2003). High school students' ideas about theories and theory change after a biological inquiry unit. Journal of Research in Science Teaching, 40, 369–392.
Schwab, J. (1962). The teaching of science as enquiry. In The teaching of science (pp. 1–103). Cambridge, MA: Harvard University Press.
Shipman, H., Brickhouse, N., Dagher, Z., & Letts, W. (2002). Changes in student views of religion and science in a college astronomy course. Science Education, 86, 526–547.
Sinatra, G., Southerland, S., McConaughy, F., & Demastes, J. (2003). Intentions and beliefs in students' understanding and acceptance of biological evolution. Journal of Research in Science Teaching, 40, 510–528.
Sober, E. (1993). Philosophy of biology. Boulder, CO: Westview Press.
Solomon, J., Duveen, J., Scott, L., & McCarthy, S. (1992). Teaching about the nature of science through history: Action research in the classroom. Journal of Research in Science Teaching, 29, 409–421.
Stewart, J., & Rudolph, J. (2001). Considering the nature of scientific problems when designing science curricula. Science Education, 85, 207–222.
Strauss, A. (1987). Qualitative analysis for social scientists. Cambridge, MA: Cambridge University Press.