Evolution and the Nature of Science: On the Historical Discord and Its Implications for Education

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Abstract: Research in the teaching and learning of evolutionary biology has revealed persistent difficulties in student understanding of fundamental Darwinian concepts. These difficulties may be traced, in part, to science instruction that is based on philosophical conceptions of science that are no longer viewed as adequately characterizing the diverse nature of scientific practice, especially in evolutionary biology. This mismatch between evolution as practiced and the nature of science as perceived by researchers and educators has a long history extending back to the publication of Darwin's theory of natural selection. An examination of how this theory was received by the scientific community of the time may provide insight into some of the difficulties that students have today in learning these important biological concepts. The primary difficulties center around issues of metaphysics and scientific method, aspects of the nature of science too often ignored in science education. Our intent is not to offer a specific course of action to remedy the problems educators currently face, but rather to suggest an alternative path one might take to eventually reach a solution. That path, we argue, should include the use of broader models of science that incorporate these elements of scientific practice to structure teaching and education research in evolution. © 1998 John Wiley & Sons, Inc. J Res Sci Teach 35: 1069–1089, 1998

The importance of evolution to the biological sciences is a point that has been acknowledged in the science education literature. Indeed, the standard practice has been to pay obeisance to its centrality by citing Dobzhansky's (1973) well-known statement regarding the sense-making powers of Charles Darwin's theory in the opening paragraph of articles on the subject. The enthusiasm with which this point is embraced, however, has not been matched by a corresponding increase in scholarly attention. Evolution remains a relatively underresearched topic within the science education community (Cummins, Demastes, & Hafner, 1994). The lamentable fact remains that "large numbers of people reject the theory of evolution, and the science education community has done little to help teachers present evolution in a way that will ame-

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liorate this situation" (Smith, Siegel, & McInerney, 1995, p. 23). This state of affairs presents problems not only for the teaching and learning of evolution, but also for the public perception of science as a whole, of which evolution is clearly the most publicly suspect representative.

Although the field has recently shown signs of life, one of the reasons for its neglect, apart from its factious history in the United States, may stem from the seemingly difficult and amorphous nature of the subject matter itself. It is fairly well established that most students, as well as members of the general public, view the biological world from a kind of pre-Darwinian perspective. This has been documented by researchers in science education and has commonly been taken as the starting point for developing new strategies for teaching evolution in schools (Demastes, Trowbridge, & Cummins, 1992). One approach that has demonstrated promise involves introducing students to the historical precursors of Darwin's theory. The success of this technique, indeed for a good number of the instructional interventions tried so far, has nonetheless been limited (see, for example, Jensen & Finley, 1996). Broad-scale student mastery of evolutionary theory has proven to be quite elusive—a conclusion uniformly reached in the science education literature (Demastes et al., 1992). It has also been reported that even a significant number of science teachers have serious questions when it comes to evolution (Eve & Dunn, 1990). The pervasiveness and persistence of these difficulties suggest, perhaps, that we look for a deeper explanation than any so far considered.

The historical parallels between student experiences in the biology classroom and the experiences of 19th-century scientists are particularly instructive in this regard, though not for the reasons commonly supposed. There existed in Darwin's time a fundamental mismatch between the view of science endorsed by Darwin's contemporaries and the implicit model of science on which he based his theory of evolution by natural selection. The significance here lies not in the similarity between any initial student conceptions and early evolutionary ideas, but rather in the historical longevity of the mismatch between these two views of science. Past characterizations of science, historically derived from physics, internalized a broadly empirical and experimental bias that failed to accommodate key issues evolutionary biology introduced to the scientific community. There has been little done over the past century to reconcile these views, especially in science education, resulting in a situation that continues to impede the development of effective instruction in evolution. The specific difficulties students have understanding evolution are less perplexing when considered in light of the resistance Darwin encountered from the scientific community of his own time. A careful examination of the scientific reception of evolution in the 19th century reveals interesting parallels with current accounts of student learning that suggest positive directions for new work in evolution education research.

The Scientific Reception of Darwinism

There were a variety of responses to the 1859 publication of *On the Origin of Species*. These ranged from solid endorsement to arrant condemnation within the scientific community—to say nothing of the reaction of the general public. Among the critical responses documented, one can find two primary threads of objection. The first and most profound concerned the strong naturalism of Darwin's theory. The scientific community in Victorian England operated within a theistic context that presupposed notions of intelligent design and purpose in the world (Ruse, 1979). Darwin's theory of evolution by natural selection directly challenged the need for such metaphysical commitments and was understandably met with resistance for doing so. The second objection related to apparent methodological irregularities in Darwin's work that for many threw into doubt the validity of his conclusions. Both categories of objection stand out as significant not only historically but, more important for this article, for evolution education today. A brief summary of the historical reception will provide the background necessary for drawing out the implications for science education.

Metaphysical Concerns

The general scientific uproar surrounding the publication of Darwin's *Origin* had surprisingly little to do with the empirical claims on which his theory was based. It was uncommon to find disagreement over the basic assertions Darwin made about the variability of species, the survival rates of young, the plasticity of domestic animals, and the like. These claims and the abundant examples Darwin marshaled in their support were accepted without palpable controversy. Rather, it was his philosophical approach as a whole and its consequences for the place of humans in nature that flew in the face of the prevailing assumptions of the time. Darwin's commitment to a completely naturalistic explanation of the origin and diversity of organisms, now seen as his most significant contribution to biology (Bowler, 1983), was then viewed by many as a dangerous materialism that eliminated divine agency from the history of life on earth. This notion of the divine reinforced deeper philosophical commitments to essentialism and teleology that presented formidable obstacles to the easy acceptance of evolution by natural selection.

Essentialism, the belief in the existence of discrete kinds each with a universal essence, lays claim to the deepest philosophical roots in Western thought (Hull, 1973). Early Aristotelians argued such kinds existed independently in nature, while Platonists believed such universal essences were located only in the realm of ideas. In one form or another this conception of natural kinds, or types, was the foundation of early systems of biological classification in which species were identified and grouped according to their unchanging observable characteristics. Any deviations from the type were viewed as inconsequential developmental aberrations (Mayr, 1991). Such typological thinking was a key component in the anatomical theories of French and English biologists such as Cuvier and Owen in the first half of the 19th century and was also common to the German morphologists of the time (Nyhart, 1995; Russell, 1916).

In Britain throughout the 18th and early 19th centuries significant effort was directed toward understanding biological form as evidence for the work of an active, benevolent deity (Coleman, 1977). William Paley's *Natural Theology* (1802) is the classic work of this kind and represented a broad research program that sought to reconcile the "book" of nature with the Bible; at its heart was a belief in special creation. Natural philosophers in this tradition assumed that the in-depth study of nature, in addition to serving the glory of God, would generate knowledge in harmony with Scripture, since both the Bible and nature were products of the same hand; the possibility of uncovering contradictions was little considered. In his book, Paley described the wondrous adaptations of living organisms and convincingly attributed them to intelligent design. The very existence of organic structures so well suited to their functions, he argued, was one means through which God sought to reveal himself to humanity. This emphasis on designed creations of the deity provided a theological reinforcement to the philosophical disposition toward essentialism. Richard Owen, the highly regarded British comparative anatomist, continued in the essentialist tradition in the second half of the 19th century developing an elaborate theory of anatomy based on idealist archetypes in which he also sought to include, though unsuccessfully, a legitimate role for special creation (Coleman, 1977).

In the wake of Darwin's theory, arguments for the special creation of discrete species gradually disappeared from the scientific community. The commitment to essentialism persisted, however, in the growing debate over the nature and pace of evolutionary change. On one side of the debate was the Darwinian model of gradual accumulation of minor variations, and on the other was the more recent mutation theory of Hugo De Vries, which claimed that speciation resulted from a series of abrupt morphological changes, or saltations. This disagreement over the raw material on which natural selection acted in producing species occupied much of the scientific discussion of evolution in the first decades of the 20th century (Olby, 1988). As philosopher David Hull explained, "from a metaphysical point of view . . . speciation by saltation . . . permit[s] the retention of the discreetness of natural kinds, a tenet central to essentialism" (1973, p. 77). This argument for mutation as the basis for evolution was one of the more common reinterpretations of the original theory and suggests the persistence of essentialist thinking among biologists of the time.

Another frequent alteration of Darwin's theory involved the reintroduction of teleological interpretations to counter the apparently random, nondirected process natural selection inevitably implied. The minimal teleological view ascribed the natural laws governing the evolution of life to divine providence in much the same way Newton accounted for the origin of physical laws in his gravitational theory; that is, although God might not himself intervene in the production of new species, the laws he set down were just as capable of producing them indirectly (Hull, 1973). More strongly teleological changes located the goal directedness with the organisms themselves. Both internal and external forms found expression in the early 19th-century evolutionary theory of the French zoologist Jean Baptiste de Lamarck. Transmutation for Lamarck was the result of two distinct forces acting on the organism: one was an internal progressive force that directed the species to ever more complex forms independently of the surrounding environment, and the other was the more familiar Lamarckian idea of the inheritance of acquired characteristics. According to the latter mechanism, organisms responded to environmental pressures (the external direction) by producing individual adaptations that were then passed on to their offspring (Bowler, 1983).

Although Lamarckism was widely discredited by the scientific community by the mid-19th century, the teleological ideas central to his account of the history of life on earth demonstrated an amazing resiliency. In various forms his ideas made their way into alternative versions of evolutionary theory in the last decades of the century as Darwin's account began to struggle with questions surrounding the specific mechanisms of variation and inheritance (Burkhardt, 1988). One version put forth by biologists of the American School, whose members included Louis Agassiz and Edward Drinker Cope, embraced the idea of an internal, goal-directed force in species that paralleled the regular patterns of embryological development. The paleontological evidence they used to support this theory suggested a much more linear evolution than the branching scheme Darwin described. This linear evolution, or *orthogenesis* as they termed it, was driven by a transmutational force within species which could drive them to nonadaptive forms, even to the point of extinction (Bowler, 1985).

The remarkable structural adaptations throughout the biological world, from the simple whale flipper to the complex mammalian eye, however, were poorly explained by theories of orthogenesis alone. The only alternative aside from natural selection was the rehabilitation of Lamarck's idea of use-inheritance. The 1890s saw a tremendous amount of support for this neo-Lamarckism in Europe. It had the advantage of being able to provide a naturalistic explanation for the evolution of various adaptations while retaining teleological notions of purposeful change—although not directed by any conscious force, variations were elicited to meet the specific environmental needs of the organism (Bowler, 1983). Lacking any better understanding of the generation of variation in organisms, Darwin himself in the sixth edition of the *Origin* allowed use-inheritance a more prominent role, stating clearly that "there can be no doubt that use in our domestic animals has strengthened and enlarged certain parts, and disuse diminished them; and that such modifications are inherited" (1873, p. 108).

The number and nature of the alternative theories offered in place of Darwin's natural selection mechanism demonstrate the strong objection many scientists had to the abandonment of long-held metaphysical commitments to essentialism and teleology in the biological sciences. As a general area of difficulty, obstacles such as these can be found, more or less, across a broad range of practitioners. A second such area in the reception of Darwinism was raised by scientists and philosophers alike regarding the scientific methodology Darwin used.

Methodological Objections

Apart from the fundamental assumptions that made up the content of Darwin's theory was the methodology he employed in their justification—a point with which many of his contemporaries took issue. Although some methodological criticism derived, no doubt, from prior metaphysical objections to evolution, there were also scientists who, although sympathetic to Darwin's conclusions, were sincerely troubled by the means he used to arrive at them. The early 19th century was a time when many eminent natural philosophers in Britain were systematically laying down the foundations of scientific methodology (Hull, 1973). Classics in this field were John Herschel's *Preliminary Discourse on the Study of Natural Philosophy* (1830) and John Stuart Mill's *System of Logic* (1843). These works set the standard against which Darwin's work was judged and, fairly or not, found wanting. The difficulties British scientists had reconciling the explanatory success of evolution by natural selection with its apparent methodological shortcomings reveal a great deal about the gap between the nature of science as practiced and the nature of science as perceived.

The problem, primarily due to an overly restrictive account of science, was compounded by an even less appropriate comparison across disciplines. Evolutionary biology in 1860 was thoroughly grounded in the long tradition of work in the field of natural history, the scope of which included rocks and minerals as well as animals and plants. Confronted with the enormous diversity of specimens in all areas, the field naturalist's first task was careful observation followed by description and systematic classification. Such work produced the great natural histories of the 18th century and continued as important scientific work into the 19th century as well. The essence of such work was descriptive and took nature as found. With descriptive work extending to the intricacies of embryological development and the succession of fossil life forms in rock strata, the importance of historical explanation as the organizing idea in biology took hold (Coleman, 1977). Naturalists looked to the past as the key to understanding the present, searching for patterns and laws of development. During this time, evolutionary ideas surfaced periodically in attempts to understand the history of life on earth, but such ideas had to wait for Darwin to become generally accepted by the scientific community.

In contrast to the diversity of life naturalists struggled to appreciate, describe, and order, physical scientists sought to simplify natural phenomena—stripping the universe down to net forces and point masses. Newtonian mechanics represented the irrefutable success of this approach and provided the model for all science on which the methodologists (Herschel, Mill, and others) based their work. Their collective goal was to account for the tremendous success of science and to abstract from scientific practice methodological rules that would ensure the production of certain knowledge. Following prescriptions laid down earlier by Francis Bacon and Newton himself, the early 19th-century philosophers, thoroughly empiricist in their outlook, sought to elaborate what they saw as the only foolproof path to certain knowledge, reasoning by induction—the slow and stepwise progression from known to unknown. Conjecture and hypothesis were discounted as mere speculation and likely to result in error. In his analysis of their work, Hull (1973) pointed out a great deal of confusion surrounding fundamental philosophical ideas that interfered with the development of any really useful rules of scientific reasoning. The key error of the methodologists, as he explained, was their assumption that certain knowledge could be had, which resulted in a methodological standard that even Newton's work could never hope to meet.

The primary misunderstanding that plagued the philosophers, according to Hull, was their inability to grasp the distinction between demonstrative and nondemonstrative inference. Newton's theory of universal gravitation was a unified theory based upon a limited set of initial definitions of space, time, force, and mass from which one could mathematically deduce observational consequences regarding the behavior of matter. In this manner, physical scientists could demonstrate the validity of their laws by making predictions that could be confirmed by direct experience. This was the model of science confronting Darwin in 1859. His theory of evolution by natural selection, in contrast, was a probabilistic theory based on tendencies in the living world, things such as overproduction of young, differential survival, and so on. Dependent upon the contingencies of the past and the indeterminacy of the future, it had little power to make predictions, much less have any specific prediction borne out by observation. As a historical science, its power lay in its ability to make sense of the disparate facts of the natural world, to unify phenomena across a wide variety of disciplines, and to provide naturalistic answers to questions previously thought unanswerable. The empirical evidence supporting Darwin's theory was overwhelming, but exclusively indirect and, as a result, unable to meet the standard of certainty set by the philosophers of the time.

Methodological questions were ever present throughout the reception of Darwin's work; the scientific community had studied its philosophy well (Ruse, 1979). Scientific societies generally avoided discussion of evolutionary theory following its introduction on the grounds that such speculation was inappropriate in a truly scientific forum. True to the empiricism of the times, though, "scientific papers submitted to the societies could refer to the Darwinian hypothesis provided they presented factual data either in support or in opposition to it" (Burkhardt, 1988, p. 72). Numerous reviews of the *Origin* repeatedly cited its apparent methodological inadequacies. Swiss paleontologist Francois Jules Pictet provided a typical example. In response to the claim that slight changes over time could produce substantial new organic forms, he wrote:

> Before I can accept Mr. Darwin's deduction, I must see for myself a known case of an important organ beginning to form or a modification of some value in essential characters. As long as there is no proof that grave changes can be introduced regularly in the order of direct generation, then I am drawn to the daily observation which leads me to believe the contrary. (Quoted in Hull, 1973, p. 145)

The emphasis in this and other reviews was clearly on the demonstrative model of the physical sciences. An even more explicit comparison was made by mathematician William Hopkins, who, though he encouraged study of the living world, nevertheless insisted that any theories developed display

> the same logical reasoning and the same kind of general evidence as we demand before we yield our assent to more ordinary physical theories. . . . It is impossible . . . to admit laxity of reasoning to the naturalist, while we insist on rigorous proof in the physicist. (Quoted in Hull, 1973, pp. 230–231)

While Darwin's seemingly heterodox methodology proved to be an obstacle for some, the theory's explanatory power and promise as a naturalistic research program into the diversity of life, in the end, tipped the balance in its favor. Well aware of the prevailing empiricism of the period, Darwin worked hard to ground his hypothesis firmly in the preponderance of evidence he and others had collected. However, the very nature of a historical science required a methodological break with the demonstrative model of physics—a break of which Darwin was quite conscious. The standards for the adequacy of his theory, he knew, were different. Commenting on one reviewer's assessment, Darwin wrote:

> He is one of the very few who see that the change of species cannot be directly proved, and that the doctrine must sink or swim according as it groups and explains phenomena. It is really curious how few judge it in this way, which is clearly the right way. (Quoted in Hull, 1973, p. 13)

Although brief, this historical survey illustrates that the evaluation of Darwin's work by the scientific community involved a good deal more than the comparative adequacy of his theory over others with regard to matters of empirical observation. His major contribution was to propose an answer—an explanation, more precisely—for questions not previously asked by Owen's theory of archetypes or Paley's natural theology (Bowler, 1996). It was not primarily a matter of one theory fitting the evidence better than another. As noted above, there were few challenges made to the evidence Darwin adduced to support his claims. The significant issues raised by the scientific community itself centered on the twin tensions between Darwin's materialistic theory and the scientists' deeply held metaphysical beliefs and the conflict over science as prescribed and as practiced.

Reconsidering the Nature of Science

Although the similarities between children's conceptions of natural phenomena and early scientific conceptions, in some cases, have been carefully documented and are at times striking (see Brumby, 1984, for example), there is no reason to expect any necessary similarity between the subsequent path of conceptual development in the student and that in the history of biology. The highly contextual nature of historical and scientific change make any such claims clearly unwarranted. What the history of biology can contribute to educational research, in this case, is a better understanding of the past intellectual conditions that impeded the scientific acceptance of Darwinism—conditions that, for various reasons, have persisted over time and may influence student conceptions in ways that make understanding evolutionary theory difficult today.

Lessons we can take from the reception of Darwin's theory involve recognizing the difficulties that scientists had in making the transition to new conceptions of both the history of life on earth and the best means to be employed in its investigation. In the long view of history, these transitions are relatively recent and not entirely complete, especially outside the field of evolutionary biology; their remnants still pose problems for us even now. What is needed is to uncover the fundamental obstacles, both present and potential, to student understanding of an evolutionary picture of the world and examine current attempts at evolution education in their light. Those obstacles seem well represented in the historical survey above, which suggests that for students to appreciate the import and essence of Darwin's work, a reconceptualization of our view of science within the science education community is necessary. Such a view must include a recognition of both the heterogenous nature of disciplinary practice as well as the importance of nonempirical factors in scientific advancement.

From Physics to Evolutionary Biology

The movement in science studies toward viewing the various disciplines that comprise science as a set of distinct local practices rather than as parts of a unified system, though ongoing since the 1960s, has failed to make significant inroads into the work of the science education community (see Galison & Stump, 1996). Most programs in education research have taken physics as their implicit model for all science without considering the inevitable distortions that result when that research framework is applied to disciplines outside physics. More problematic has been the tendency for science educators to use the physics model in the development of curriculum intended to address general issues concerning the nature of science, thus perpetuating a misunderstanding of scientific method that may foreclose the effective learning of evolutionary biology (Hodson, 1996; Jenkins, 1996).

The situation that exists in science education, not surprisingly, is a consequence of past work in the philosophy of science. Efforts to formalize scientific theories in the 20th century were shaped significantly by the work of the logical positivists (see Joergensen, 1970). These philosophers, just as the early 19th-century methodologists before them, used the unquestioned success of physics as their paradigm for understanding all science (Laudan, 1984). The "received view," as it has been referred to, defines a scientific theory as an axiomatic-deductive system—that is, one begins with a set of axioms, or lawlike statements from which, given some set of initial conditions, one can deduce observable physical consequences (Thompson, 1989). Newtonian mechanics, with its three laws of motion and law of gravitational attraction, is the example most commonly provided. Sciences like this, in which the goal of inquiry is the accurate establishment of laws, or universal mathematical statements, are referred to as *nomothetic* (Sober, 1993). Science so conceived produces theories that lend themselves well to experimental confirmation (or falsification, depending on your philosophical allegiances). While such formalization can be applied profitably in the physical sciences, attempts to cast certain areas of the biological sciences within the nomothetic framework have been problematic.

Philosophers of biology have recently begun to make key distinctions between physics and the foundation of biology, evolutionary theory. One crucial distinction, described by Sober, is that which Darwin implied in the standards he used to judge his own work. Whereas physics concerns itself primarily with the identification of universal laws of matter, evolutionary biology focuses more on the specific patterns and particularities in nature, the plays and outcome of the game rather than the rules, so to speak. This is the domain of the *historical* sciences, which include, in addition to evolutionary biology, disciplines such as geology and paleontology, where the goal is primarily "the reconstruction of genealogical relationships" from the past (Sober, 1993, p. 14; see also Sober, 1988). Models of how historical changes may have occurred have been developed, but such models are far from universal. Instead, they are entirely dependent on the conditions of the local population or phenomena—the current state being dependent on and determined by what came before. Of course, no science can be characterized as completely nomothetical or historical. Diversity of practice within scientific disciplines is common; certain subfields of physics—cosmology for instance—are largely historical. The relative emphasis between physics and evolutionary biology, however, is for the most part distinct.

The nomothetic/historical distinction clearly parallels the confusion Darwin's contemporaries displayed over the difference between demonstrative and nondemonstrative inference. The argument Darwin presented in the *Origin,* historical as it was, was perforce dependent on the wealth of indirect evidence he had accumulated. The expectation that Darwin demonstrate the transformation of some species as one might directly demonstrate Snell's law in geometrical optics was completely unwarranted. This is not to say that certain facets of evolutionary theory are incapable of demonstration—microevolutionary changes in gene frequency are often cited as convincing demonstrations of natural selection. Such instances, however, are hardly universal and remain but minor contributors to the legitimation of the overall theory. The fact that microevolutionary examples need to be marshaled at all merely illustrates the demonstrative bias physical science holds over science in general.

Another important difference concerns the relative complexity of the two sciences. Physics operates at a phenomonological level where, once determined, the laws of matter can always be shown to apply. Biology, specifically subdisciplines like evolutionary biology and ecology, deals with multiple interactions among highly complex systems that are susceptible to easy disruption by study. This fact immediately circumscribes the means by which meaningful data may be collected. As Robert Brandon pointed out, the practice of physics consists for the most part of the direct manipulation of variables, or experimentation, the object of which is to reveal the universal laws of matter. Experimentation is necessary because "nature does not always reliably and repeatedly manifest the conditions we need to observe in order to answer the empirical questions we have posed" (1994, p. 66). Biological systems as they exist in nature are not so easily manipulable. The act of isolating and controlling certain aspects of such a system at the same time removes it from its natural state, which casts doubt on the validity of the conclusions drawn, if those are claimed to apply under natural conditions. For this reason, field studies are the preferred means of collecting data in research into systems that are believed to contain populations undergoing evolutionary changes. Although field studies produce information that is highly relevant, they provide only a limited base from which to generalize, and certainly fail to demonstrate any universal scientific laws. The best that field information provides is an indication of probabilities or tendencies.

Despite these distinct differences between the various aspects of biology and physics, when talk turns to science more generally—specifically the nature of science—it is the physics model with its method of manipulation and control and lawlike structure that is implicitly invoked as the paradigm. The nomothetic emphasis is evident throughout the works of 19th- and 20th-century methodologists and philosophers, and the experimental bias can be traced back well into the 18th century. These mutually reinforcing conceptions have contributed to the creation of the myth of scientific method—a myth that as an instructional objective has been an organizing force in science education since the 19th century (Bauer, 1992; Jenkins, 1996). Student adherence to such a view has been well documented in the research literature (Lederman, 1992). Ryan and Aikenhead (1992), for example, in a report assessing student views on science, technology, and society, found that a significant percentage of students attributed consensus formation in science to the performance of crucial experiments, which they believed had the ability to verify or refute any hypothesis unambiguously (see also Larochelle & Desautels, 1991). Other researchers examining student representations of scientists have found nearly universal the image of the laboratory researcher engaged in physical or chemical manipulations (Boylan, Hill, Wallace, & Wheeler, 1992; Petkova & Boyadjiieva, 1994). In addition, researchers have documented a further tendency among students to conflate technology and science, privileging control and manipulation over explanation and understanding (Ryan & Aikenhead, 1992; Schauble, Klopfer, & Raghavan, 1991).

More troubling than the ubiquity of this distorted view of science among children (and no doubt, in most instances, the general public) is its presence in science education research, in some cases even research related to student understanding of the nature of science itself. In one examination of student understanding of scientific processes, researchers began their analysis by asking students at a science fair "what kinds of things did you consider before you started doing your *experiment*?" [emphasis added], and went on to explore student conceptions of dependent and independent variables without any concern that the very structure of their interview—from the first question—excluded the more observational sciences (Griffiths & Thompson, 1993, p. 18; see also Solomon, Duveen, & Scott, 1996). A recent study exploring the effectiveness of a conceptual change approach to teaching evolution used the evidence of both rats whose tails had been cut off producing tailed young and human circumcision to challenge student "Lamarckian" views—an approach that not only reinforces experimental conceptions of science, but also misrepresents the key evidence that facilitated the transition from a pre-Darwinian to a Darwinian view of evolution (Jensen & Finley, 1995). Other studies have included scientific laws in their discussions of essential concepts regarding the nature of science (Griffiths & Barry, 1993; Meyling, 1997), an assumption clearly in conflict with evolution, a domain in which some philosophers have questioned whether laws can ever be formulated (Brandon, 1994; Mayr, 1985).

One site, perhaps the key one, of the reproduction of this physics-based conception of science is the science classroom itself. Science textbooks have traditionally provided a superficial as well as artificial picture of scientific practice, emphasizing a so-many-step scientific method for generating knowledge and describing how, with repeated investigation, hypotheses become laws. Little attempt has been made to convey the fluid nature of scientific inquiry and the diversity of methods employed by practicing scientists (Hodson, 1996). More influential, we would argue, is the very structure and culture of schooling, which has limited student engagement with science to daily fixed blocks of time—a setting which tends to exclude opportunities for realistic fieldwork, promoting instead the well-regulated laboratory activity. In addition, teacher concerns for efficiency and coverage of material constrain the selection of lab activities to those that serve the pedagogical function of illustrating key scientific concepts (Tobin & Gallagher, 1987; Tobin & McRobbie, 1996; Tyack & Cuban, 1995). Even more efficient for conveying information are teacher demonstrations. In nearly every instance, the emphasis is on the manipulation of apparatus to produce some demonstrable confirmation of a scientific assertion (Driver, Leach, Millar, & Scott, 1996; Hodson, 1993). It is in these school laboratories that most ideas about method are arrived at; distinctions between "school experiments and real scientific research" are rarely made (Hodson, 1988, p. 26). Students come to view *science* and *experiment* in constant conjunction and fully expect that all assertions in science, if valid, should be capable of unambiguous demonstration. This misconception of science has the potential to become an important stumbling block to effective evolution education. A unit on evolution taught in a traditional science classroom may seem to students something of an entirely different kind, consisting of material describing a theory not subject to the usual rigorous tests of scientific accountability.

Although there is no current research that indicates whether this methodological incongruity is an obstacle to student learning in evolution, it seems clear that the distinct methodological issues associated with evolutionary biology should be made the subject of both educational research as well as classroom instruction. Such efforts should be undertaken not only to address what is obviously a potential obstacle to student learning, but, more important, to enable educators to present students with a more complete picture of the nature of evolutionary biology as well as science more generally. In addition, the recent push in science education toward engaging students in authentic scientific inquiry (National Research Council, 1995) cannot fruitfully proceed in the absence of some understanding on the part of students of this key epistemological issue.

Beyond the classroom, where methodological misunderstandings are commonly voiced (Webb, 1994), images of science provide little corrective to the physics model so prevalent among students. Thus, it is not surprising that the public and even significant numbers of science teachers have come to view science in this way (Long & Steinke, 1996; Smith et al., 1995). Difficulties of this nature have been repeatedly found in the community at large, where many echo the objections raised well over 100 years ago. Pictet's demand in Darwin's time to see for himself "a known case . . . of an important organ beginning to form" is matched by creationist textbooks today that adhere to the same narrow conception of science. One such author writes: "If we had a time machine we could observe the kinds of changes that might have occurred in the past. Unfortunately, we do not. . . . Therefore, it does not matter how much evidence is gathered in support of the theory of evolution" (quoted in Smith et al., p. 29). A pamphlet found recently on a kiosk at our university echoed this sentiment, discounting evolutionary theory on the grounds that it attempts to explain "prehistoric processes which are beyond the scope of human observation and verification" (GC Ministries, 1997).

Up from Empiricism

Recognition of evolutionary biology as a science distinct from the generally narrow physics-based model of science is a necessary but not sufficient first step toward a more robust treatment of evolution education and research. The disciplinary myopia described above has been accompanied by a limited philosophical view that has contributed to an overly rational, exclusively empirical view of science, which has handicapped both educational researchers and biology students with respect to evolution. Recent work in the field of science studies, with its emphasis on science as actually practiced, however, provides an initial framework that may be useful in developing a more productive research program in evolution education.

As mentioned previously, the most influential school of philosophy in the 20th century dealing with issues of scientific methodology was that of the logical positivists and their followers. Working from the 1920s to the 1950s, these philosophers attributed the obvious success of science—its cumulative progress in generating knowledge—to a bedrock rationalism applied to objective representations of the physical world. Actual scientific inquiry was, and remains, obviously more complex, being embedded in overlapping social systems and institutions, subject to personal and disciplinary interpretative biases, and the like. Recognizing this, the logical positivists sought to cut through what was irrational and imprecise in practice, to distill out the essence, the logical core. Once properly understood, they believed, this core formalization might be used to develop a normative account of sound scientific practice. The question of whether science could be separated effectively from its practical context is paramount. The positivists believed that as long as science focused on the "immediate observable content" of nature it would be able to "eliminate metaphysical problems and assertions" (Joergensen, 1970, p. 850). This faith in empiricism permeated the inductive prescriptions of the 19th-century methodologists as well. Attempts to establish a certain, empirical base for science, however, began to unravel in the early 1960s with the work of Thomas Kuhn (1970).

With respect to Darwin's theory, as we have seen, there was no easy resolution to the controversy that flared up in the aftermath of its presentation. Key points of debate centered on the adequacy of his method rather than any appeal to empirical evidence. Metaphysical commitments played a central role as well, as scientists either rejected the raw naturalism of the theory in favor of essentialist notions of creation or, more commonly, accepted the evidence of species transmutation while modifying the mechanism of natural selection to include elements of teleology in orthogenesis and Lamarckian use-inheritance. In either case, the historical record reveals the tenacity of these metaphysical ideas in the absence of any significant positive evidence. Issues such as these would be cast as irrational, or nonscientific at least, if one were to accept the empiricist bias of the logical positivist program. However, to ignore this element of scientific debate is to impoverish and misrepresent the nature of theory choice in particular and the progress of science in general.

Recent research in evolution education confirms the primacy of metaphysical issues among biology students as well. In fact, the signal contribution of evolution education research to this point has been the identification of key conceptual difficulties students face in learning evolution. One of the most common conceptions found among children is that of need-driven transformation. This is the notion that an individual organism in nature is able to sense undesirable environmental changes and physically alter itself as a means of compensation, with the changes being passed on to its progeny. It has been shown that teleological reasoning such as this, questionably referred to as "Lamarckian," is predominant among students from middle school through the university level (Clough & Wood-Robinson, 1982; Lawson & Weser, 1990; Settlage, 1994; Tamir & Zohar, 1991). In some cases even after direct instruction in Darwin's theory of natural selection, students continue to apply teleological reasoning to explain cases of adaptation in nature further demonstrating the deep-seated commitment to purposeful change (Brumby, 1984).

Research has also established the pervasiveness of essentialism, or typological thinking, among school students. Halldén discusses the importance of intraspecific variation for the Darwinian model and argues that students' failure to recognize this is "a major stumbling block" in their attempt to explain evolutionary change adequately (1988, p. 542). Bishop and Anderson drew similar conclusions in their 1990 study, claiming that students "viewed evolution as a process that molds or shapes the species as a whole" rather than as a selection process among varied individuals (1990, p. 423; see also Samarapungavan & Wiers, 1997).

The parallels between the metaphysical conceptions students hold today and those displayed by the scientific community of the late 19th century are certainly striking and suggestive of some relationship. The nature of this relationship, however, has yet to be fully explored. What is puzzling is the manner in which some researchers have sought to use this apparent connection in the absence of any detailed explanation for its existence. Some have assumed that since students possess so-called Lamarckian preconceptions, a historical instructional approach will be more effective than traditional instruction (Jensen & Finley, 1995, 1996). Although this might be the case, it would seem important to make some effort to understand the reasons for its effectiveness rather than rely solely on the coarse empirical observation that it works. Others have suggested that past history should be used as a resource to help identify potential alternate conceptions that students come to school with, while denying belief in any sort of recapitulation theory of learning (Brumby, 1984; Wandersee, 1985). Although somewhat appealing, this argument ignores the fact that there are far more conceptions in the history of science that are *not* found in today's students than are, making it a rather hit and miss affair to sift through historical ideas hoping to find some currently held alternate conception. Considering the vast differences in sociohistorical, as well as human developmental contexts, if such parallelisms are found, they are likely to be more superficial than deep.

Students' existing conceptions about evolution are more reasonably understood as a product of their contemporary intellectual environment. Whereas the methodological physics bias described earlier can be traced historically to the influential work of the 19th-century British empiricists, we also see the structure of schooling and teacher ideas about efficiency contributing to its reproduction. Students' essentialistic notions of species, however, are predominantly attributable to the nature of human concept acquisition (Mayr, 1991) rather than to a widespread commitment to theological accounts of special creation, as was the case in the natural theology research program that permeated Victorian science in Darwin's time. Teleological thinking, on the other hand is perhaps more historically transcendent. Notions of progress and purpose have been carried through Western culture since the enlightenment and are pervasive even today. This, combined with the egocentrism and anthropomorphism humans exhibit, makes it unsurprising that students would tend to impute ideas of need and desire to living organisms. In addition, these two metaphysical commitments are mutually reinforcing. Students who willingly attempt to understand evolutionary theory, yet who also retain strong notions of essentialism, will inevitably produce a use-inheritance, teleological explanation of organic change. If all members of a population are seen as identical, the only naturalistic option available is for some or all of the individuals to be physically transformed in a goal-directed way, there being no variation (in the student's mind) on which natural selection might differentially act.

The obvious conclusion to be drawn from this discussion is that metaphysical commitments, whether the product of the student's intellectual environment or, less likely in our view, the surfacing of some atavistic historical conceptions (see Lythcott, 1985), pose a significant barrier to the understanding of Darwinian evolution. Until we begin to use models of science that treat metaphysics as an active part of the sense-making process in science, student difficulties will likely persist. The narrowness of the empiricist view is now almost universally recognized in the science studies community (Nickles, 1995). Outside the history, philosophy, and sociology of science, however, the empirical bias remains strong. This is especially true in traditional research on learning in science education, where, not surprisingly, physics has again provided the model.

Research in both problem solving and conceptual change has invested heavily in the empiricist model—that is, they conceive scientific practice to consist primarily of the evaluation of theory against evidence. Early problem-solving research was most productive analyzing student approaches to solving textbook problems in highly axiomatized subject areas such as physics (Chi, Feltovich, & Glaser, 1981; Larkin, McDermott, Simon, & Simon, 1980). Although problem-solving research programs were later initiated in the biological sciences, researchers never strayed far from its most easily axiomatized areas like genetics (Smith & Good, 1984; Stewart, 1983). Recent research in this field has taken steps toward modeling student problem solving after that done by research scientists, focusing on how students work with and revise scientific models in light of existing and sometimes anomalous empirical data (Stewart & Hafner, 1991). However, even in these very rich instructional environments where students actively simulate scientific research, issues of methodology and metaphysics remain at the level of tacit knowledge and have not yet been addressed; nor, given the construction of the problem situation, has there been any need for students to engage such issues. The focus has remained narrowly empirical.

In the area of conceptual change, the research has been similarly limited in scope. Although based on the postpositivist philosophical work of Kuhn and Lakatos, the conceptual change model retains a good deal of the empiricism of the earlier philosophers—if not in theory, at least in its implementation in educational research. Proponents argue that the process of making the transition from a student's initial conception to an accepted scientific conception is dependent on four factors: dissatisfaction with the existing conception; the intelligibility of the new conception; its plausibility; and its fruitfulness (Posner, Strike, Hewson, & Gertzog, 1982). Instruction that has been designed according to this model almost exclusively confronts initial student conceptions with empirical evidence for which they cannot account and then offers the accepted scientific conception, or theory, in their place (Smith, Blakeslee, & Anderson, 1993).

Posner et al. stated up front their central commitment that "learning is a rational activity" (1982, p. 212). Implicit in this statement is an understanding of science as equally rational, driven by a progressively better fit of theory with evidence—a view contrary to Kuhn himself, who stated that the basis for choosing a new theory "need be neither rational nor ultimately correct" (1970, p. 158). Whereas the conceptual change model does acknowledge that epistemological and metaphysical commitments among students "form the basis on which judgements are made about new knowledge," such issues are seen as beyond the influence of the science curriculum and are marginalized in favor of using anomalous data to induce conceptual shifts in students (Posner et al., 1982, p. 224).

There has been some movement in the teaching and learning research toward a more inclusive account of the nature of science, especially in the area of conceptual change. Posner and Strike acknowledged past overemphasis on the rationalism of the model (1992) and Duschl and Gitomer (1991) argued for a more accurate model of scientific change for use in assessment, one that takes into account the aims and methods of science. Despite these theoretical modifications, the conceptual change model has proven to be somewhat problematic as a guide for instructional practice (Hewson & Thorley, 1989). This is true especially in scientific areas that fall outside the narrow conception of science on which conceptual change was originally based. Recent studies in the context of evolutionary biology—a subject with strong affective and metaphysical elements as we have seen—have demonstrated some of these limitations (Demastes, Good, & Peebles, 1995, 1996).

Toward a Naturalistic Model of Scientific Practice

In the same way that the growing incongruity between the history and philosophy of science in the 1950s sparked the postpositivist shift begun by Kuhn, the inability of current research to address, let alone fruitfully engage, important conceptual difficulties students have with evolution suggests the need for the science education community to reassess its view of the nature of science. Rather than relying on the narrow empiricist, physics-based model of science that has limited our ability to deal effectively with evolution education, we need to examine broader models of science to help guide education research and curriculum development. What is needed is a view of science that not only represents all disciplines with their varied methodological approaches, but also will provide students with a more accurate view of the functional role metaphysical assumptions play in the advancement of science.

The most promising models can be found in the recent work of the science studies community. These have been developed from a close examination of scientific practice, either from firsthand observation or through the scrutiny of a more inclusive historical record (Siegel, 1993; see also Donovan, Laudan, & Laudan, 1988). Older philosophical models, as mentioned previously, sought to formalize the logical structure of science, to isolate its rational essence, in order to distinguish science from less objective fields of inquiry and so that its methods might be propagated more effectively. This attempt at decontextualization, it is now conceded, warped rather than purified. The result was often a scientific model that was, if logically consistent, at odds with reality (Laudan, 1984). Following what has been referred to as the naturalistic turn, philosophers and sociologists of science have recognized the importance of the broad socio-institutional matrix in which scientific practice takes place. Although no unified view of the nature of science has yet emerged, there is much to be found in the rich description of scientific practice that can be used in both evolution education and science education research (Jenkins, 1996).

In the field of science studies, one can trace the emergence of modeling as a central component of scientific practice. Giere described theory development in science as the development of a "population of models consisting of related families of models" that purport to represent the workings of the natural world (1988, p. 143). Drawing on work in cognitive science, he described scientific models as not much different from the mental models people use in their everyday affairs. Kitcher (1993) also saw the articulation of explanatory schemata, or models, as "a crucial part of a scientist's practice." The goal of such practice, he argued, is primarily to increase the adequacy of these models by improving the specificity of their key concepts as well as improving their overall organization. Pickering (1995), in a much more encompassing view of scientific practice, defined modeling as the sole means by which the current state of scientific knowledge is transformed into future states.

The work referred to above is by no means exhaustive, and there would likely be sharp differences of opinion regarding the details of scientific practice as understood by the authors cited here. However, we need not wait for the philosophical minutiae to be settled before we choose to make use of what has been generally agreed upon—especially as it represents a step forward from what has proven to be inadequate so far for the purpose of evolution education. All these authors describe a process in which some representation of the natural world is extended and refined in practice according to criteria determined by the scientific community. The representation can be a theory, which itself can be defined more precisely as a family of models, or an explanatory schemata. For our purposes the general term *model* will suffice and can be defined loosely as an abstract system that represents the workings of the natural world. Such a system is composed of related elements that interact in predefined and predictable, though not necessarily deterministic, ways. Left here—science as the modeling of empirical phenomena—this summary of practice would differ little from the traditional accounts that have been found wanting.

The naturalistic studies of science, however, reveal a much broader understanding of scientific practice, one in which scientific theories, or models, represent only one component of the more complex machinery of inquiry. In addition to theories, Kitcher included language, natural assumptions, methodological views, and canons of good observation and experiment in this multidimensional entity. In a longer view of scientific change over time, Laudan (1984) outlined a triadic network in which theories, methods, and cognitive aims interactively determine the course of scientific advance. None of these operates individually to advance science; theory choice is justified by methodological rules which are themselves subject to revision in light of the cognitive values or aims of the scientific community. These components, Laudan argued, are mutually interdependent; i.e., methodological rules can determine the range of possible theories, new theories can radically alter the nature of previously determined cognitive aims, and so on. Over time, science progresses via a stepwise process in which two components of the triad always provide a stable context for change in the remaining component. Pickering similarly understood the production of knowledge to include theories, disciplinary structures, metaphysical assumptions, and the action of the natural world, adding the social organization of scientists as an important additional component. All of these, he stated, are elements of practice that are interactively stabilized, each contributing in varying degrees to the extension of scientific understanding.

Taken together, these works present a rich picture of the nature of science that is both more complex than past philosophical accounts of science and more authentic. They point to important aspects of practice that have been neglected in science education. In addition, they reveal that it is not enough merely to add to the mix discussions of scientific method, or metaphysics. Science education in various instances has seen calls for the inclusion of methodological discussions, the recognition of the social nature of scientific inquiry, and the acknowledgment of metaphysical points of view. Too often, though, these are viewed as extras to be included as time permits, or in courses designed for the less able to humanize and make the science more appealing. Teaching theories well, even with a detailed look at the empirical evidence that supports them, is not enough, in some cases, for a comprehensive understanding of those theories, or of science as a whole. The growing consensus among scholars is that scientific theories are inseparable from the context of their production and use (see Rouse, 1996). Science, according to these naturalistic studies, is an active process of making sense of the natural world that is dependent upon multiple conceptual and empirical elements—elements that are discipline and even theory specific and that make sense only when taken as a whole—a view that goes well beyond the narrow conceptions of science currently looked to in education.

This last statement, with its reference to the "active process," points out the dual nature of scientific knowledge that, we believe, has important pedagogical implications. What students encounter in the classroom is often presented as a kind of final-form knowledge—a "rhetoric of conclusions," as Schwab referred to it (1962). Even when the tentative nature of knowledge in science is acknowledged, the tendency has been to portray that knowledge as a static body of thought—the most recent final form—subject to change as new empirical evidence comes to light. Educators and researchers have given little attention to the instrumental role that scientific knowledge plays in inquiry and how that role might be conveyed to students.

Clearly scientific theories, as sets of models, contribute to human understanding of the natural world; and that understanding can only be complete if those theories are set in the broader context of the more or less implicit assumptions about the world and the methodologies they entail. This backward-looking view of science, however, is only part of the picture. Scientific theories, with their assumptions and especially their methodological prescriptions, are also, and perhaps more important for the research scientist, instruments used to meet the cognitive goals of the scientific community. These research programs (what might be thought of loosely as Kuhnian paradigms) structure the way one looks at and investigates what remains unexplained in nature; they circumscribe what phenomena can legitimately be made the subject of inquiry and suggest the path that the inquiry might take.

This heuristic value of scientific models has played an important part in the development of more adequate conceptions of scientific practice. For Kitcher, the advancement of science includes not only conceptual progress (more adequate specification of the referents of a model) and explanatory progress (greater unification of phenomena), but also what he termed "erotetic" progress, the ability of a model to suggest a range of interesting and tractable new questions not considered by previous models (1993). In this sense, a model always provides both an explanation for some specific phenomenon, and is itself the starting point for further elaboration, acting in this capacity as a tool for exploring the unknown.

Conclusion

How might these newer views of science help overcome the difficulties science education is confronting in evolutionary biology? To begin with, we have seen in the parallels between the historical reception of Darwin's theory and the conceptual problems of students evidence that the transition from pre-Darwinian ideas concerning the diversity of organic form to Darwin's theory of natural selection was not just a transition to a new theory, but rather a transition from one model of doing science to another. According to Kitcher, Darwin changed the "practice of biology" that included not only recasting what were seen as the primary problems in biology, but also "a methodological thesis about the adequacies of certain kinds of scientific theories" (1993, p. 34). This change entailed the adoption as well of a particular metaphysical world view that proved difficult for some to accept. Darwin's theory of natural selection therefore must be seen as an explanation embedded in a naturalistic world view that derived its logical warrant from its ability to unify and explain a wide range of phenomena within the discipline of biology—a method fundamentally different from that of physics. Darwin's theory cannot be understood properly apart from this context.

A more important difficulty students are likely to encounter in learning evolution, and even science more generally, can be anticipated from the accounts of science described above. Scientific theories, complex as they are with their multiple, interdependent elements, are constructed by the scientific community precisely to fill the dual role of explanation and exploration—to make sense of what is known and to guide future inquiry. Science instruction that ignores the latter function significantly handicaps student understanding. The introduction of Darwin's evolutionary theory not only explained the existing diversity of life on earth, but opened up a new set of questions concerning the living world in a variety of disciplines that had not been considered previously—questions that were both significant and tractable given the Darwinian model as a tool of inquiry. Conceptual understanding comes not from mere knowledge acquisition, but rather from the instrumental use of knowledge as a means to an end. Thus, the validity of Darwin's model cannot be passively demonstrated for students, but can only be fully realized in use. Such use, if it is to be effective in the context of scientific practice, will require students to become familiar with the metaphysical assumptions and methodological process that Darwin laid out. Theoretical context and scientific practice, in this view, are not just interdependent, but really two views of a single entity. It seems clear in this light that instruction or research that fails to address directly such contextual issues in evolution, regardless of other modifications, will continue to be inadequate.

The importance of evolutionary theory to the biological sciences is well established. Despite a recent push in science education research, the development of instruction that ensures student mastery of Darwin's work remains a daunting task. As we have attempted to argue here, we believe that much of the difficulty can be traced to a narrow conception of science rooted in the physics-based empiricism of the 19th century. The historical reception of the *Origin of Species* and the continued difficulty students have with the theory it describes provide compelling evidence for this claim. Problematic for both students and Darwin's contemporaries was and is the conflict between the prevailing metaphysics and that inherent in Darwin's view of organic change—a conflict compounded by an unorthodox methodology that remains poorly understood even today. Drawing on more recent models of science, those that include methodological, metaphysical, and social components as fundamental constituents of practice, allows one to see student alternative conceptions not as impediments to learning, but rather as important aspects of scientific practice to be embraced and engaged in a meaningful way. Perhaps through this broader conception of science, in which metaphysics and methodology can be legitimately and directly addressed, progress can be made in both research and instruction in evolutionary biology.

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