How Evolutionary Biologists Reconstruct History: Patterns & Processes

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. . . many people who have had but little science come to have too much faith in the facts and laws they have learned, and too much faith that science has all the answers. That unfounded degree of faith then turns out to be a hindrance as they try to make sense of public arguments.

H.H. Bauer, *Scientific Literacy and the Myth of the Scientific Method,* 1992.

No one was present when life first appeared on earth. Therefore, any statement about life's origins should be considered theory [in other words "speculation"], not fact.

1995 Alabama textbook disclaimer quoted in National Academy of Sciences, *Teaching About Evolution and the Nature of Science,* 1998.

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The 1995 Alabama textbook disclaimer, and other attempts to discredit evolution, are symptomatic of the poor understanding of evolution and the nature of science among the general public. According to a 1999 Gallup poll, 47% of Americans reject evolutionary explanations of human origins in favor of the view that God created humans in their present form within the last 10,000 years. In addition, 68% are in favor of teaching both creationism and evolution in public schools (Moore, 1999). Undoubtedly, some of those who reject evolution, or advocate the teaching of creationism alongside evolution, do so on the basis of beliefs that stem from a literal interpretation of Genesis. For these individuals, acceptance or rejection of evolution is not simply a matter of examining the evidence. Their basic beliefs about the nature of the world are in direct conflict with any naturalistic explanation of life's history; consequently, for them the scientific evidence is either irrelevant, or something to be explained away.

However, Alters (1999) argued that it is unlikely that all of those among the 47% who reject evolution are biblical literalists. He found that students who provided nonreligious rationales for rejecting evolution typically cited misconceptions about the nature of science among their reasons. McComas (1998) attributed such misconceptions about the nature of science to inaccurate or simplistic representations of the scientific process in textbooks and classroom discourse. Thus, it would appear that large numbers of students reject one of the central organizing concepts of modern science on the basis of misconceptions developed during instruction. As Bauer (1992) observed, a little knowledge of science acquired from introductory courses can be a hindrance to deeper understanding. Clearly, teachers need to do a better job with students who reject evolution simply because the students misunderstand science.

A major misconception that frequently underlies the rejection of evolution is the belief that we cannot know that evolution happened because no one was there to see it. The goal of this article is to provide teachers with suggestions for presenting to students the historical aspects of science in general, and of evolutionary biology in particular. An accurate understanding of how scientists study the past by interpreting patterns in existing evidence, and by investigating the processes which cause evolution, is a necessary prerequisite for understanding and appreciating the extensive empirical support for the fact that evolution has occurred. The hope is that students who are currently skeptical about evolution on the basis of misconceptions, and who do not have profound religious objections, can be helped to understand and accept evolution as the best explanation for the unity and diversity of life on Earth. This goal is consistent with the call for students to develop an understanding of evolution as a unifying theme of the sciences, and also develop an appreciation of the diverse methods scientists use to carry out investigations of natural phenomena, including those methods used to study the past (American Association for the Advancement of Science [AAAS], 1990, 1993; National Research Council [NRC], 1996).

The Problem

The Alabama disclaimer reflects a widespread and significant public misconception about evolution and the nature of science. Presumably, the Alabama Board of Education is suggesting that it would be necessary to replicate the entire evolutionary history of life under controlled conditions, and also verify one's predictions by direct observation, before any account of that history could be accepted as reliably true. The misconception stems from an "unfounded faith" that scientists possess a powerful and universal scientific method to secure certain knowledge (Bauer, 1992; Kitcher, 1993; McComas, 1998) and that evolutionary biology falls short in terms of the standards of that method (Ruse, 1998).

In contrast to the argument in the Alabama disclaimer (and the mistaken beliefs of the public), there are many scientists whose work addresses questions about the past. These scientists work in fields such as astrophysics, geology, paleontology, phylogeny, biogeography, anthropology, and archeology (Richards, 1992; Mayr, 1997). Scientists who study the past use principles, methods, and patterns of reasoning, some of which were first developed in the 18th and 19th centuries by James Hutton, Charles Lyell, and Charles Darwin (Cooper, 2002a). Building on the work of Hutton and Lyell in geology, Darwin was the first to employ reliable methods for answering questions about the past history of life (Gould, 1986; Kitcher, 1993). The 20th century has seen further advances in methods for investigating the past with the development of cladistics and the use of molecular data (Gould, 1986; Page & Holmes, 1998).

The Source of the Problem

Rudolph and Stewart (1998) traced the origin of current misconceptions about the nature of science to developments in the philosophy of science during the 19th and early 20th centuries. Based on the undeniable success of Newtonian physics, these philosophers mistakenly took physics as the model of how all science should be done. The views of 19th century philosophers reflected a strong bias toward direct observations made during experimental manipulation of nature (Mayr, 1985; Kitcher, 1993; Rudolph & Stewart, 1998). It was mistakenly believed at the time that by using experimental methods (that is, manipulating independent variables and measuring changes in dependent variables), scientific conclusions could be established with absolute certainty. This bias that philosophers had toward Newtonian physics as the model science persisted well into the 20th century, and was reinforced by the development of a school of thought known as logical empiricism (Rudolph & Stewart, 1998).

Rudolph and Stewart (1998) explained that this physics-based view of the nature of science that was emerging in the 19th century presented problems for the acceptance of Darwin's ideas in *On The Origin of Species* (1859/1964). They argued that there are historical parallels between student reservations about evolution as presented in biology classrooms today, and criticisms of Darwin's methodology immediately following the publication of *On The Origin of Species*. Many of Darwin's fellow naturalists found his conclusions in *The Origin* acceptable, but had reservations about his methods for arriving at those conclusions (Rudolph & Stewart, 1998). For example, criticism of Darwin's methods took the form of statements such as the following from paleontologist Francois Jules Pictet: "Before

I can accept Mr. Darwin's deductions, *I must see for myself a known case of an important organ beginning to form* or of a modification of some value in essential characters" (D.L. Hull, *Darwin and His Critics: The Reception of Darwin's Theory of Evolution by the Scientific Community,* 1973, emphasis added). Rudolph and Stewart (1998) argued that, "The difficulties [19th century] 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."

This image of science based on Newtonian physics has provided the basis for the portrayal of science in textbooks and has also been partly responsible for the inaccurate public perception of science (Duschl, 1990; Kitcher, 1993; Toumey, 1996). The result has been the persistence, for many generations, of widespread myths about the nature of science. In short, because of the way science has been presented in textbooks and by teachers in the classroom, the gap between the nature of science as *practiced* and the nature of science as *perceived* persists among students and the general public today.

The Solution to the Problem

Reducing the gap between the perceptions of science and actual scientific practice is essential if there is ever to be widespread understanding and acceptance of evolution. Unfortunately, there is evidence that many biology teachers also hold views that are inconsistent with an accurate understanding of the nature of science and the conclusions of evolutionary biologists (Zimmerman, 1987; Eve & Dunn, 1990; Osif, 1997). The only remedy for the poor understanding of biology teachers is improvement in pre-service and in-service education. Once biology teachers have a better grasp of evolution and the nature of science (and they begin to teach it well), public understanding and acceptance should eventually follow.

Recent efforts designed to improve teacher understanding of evolution have typically taken the approach of combining instruction and activities about the nature of science in general with instruction and activities in evolution (National Academy of Sciences [NAS], 1998). The problem with this approach by itself is that it may reinforce the misconception that there is a single scientific method. Rudolph and Stewart (1998), and Donovan (2001) argued that, in addition to general understanding of the nature of science, a more effective approach to evolution instruction should also convey an understanding of the specific questions asked and the methods employed by evolutionary biologists. According to Donovan (2001), "Knowing something about the questions that are valued in a discipline can provide insight into both the current state of understanding and how phenomena are reduced to data." In addition, he argued that "The alternative, continuing to teach evolution as a rhetoric of conclusions while claiming that evolutionary reasoning is the lynchpin of biological understanding, is at best ineffective and at its worst dogmatic."

The Work of Evolutionary Biologists

There isn't one single scientific method that all scientists use. Like scientists in other disciplines, evolutionary biologists carry out a wide range of different types of empirical investigations to answer a similarly wide range of questions. Brandon (1994) provided a useful framework for categorizing some of the different types of investigations evolutionary biologists conduct (See Figure 1; and Cooper, 2002b). Most of their work can be located somewhere within this framework on the basis of two criteria: whether the investigator makes hypotheses or not, and whether the investigator manipulates variables or not. This framework may prove useful for teachers when discussing with students the variety of methods actually used by scientists.

The closer a study is located to the upper left-hand corner of Figure 1, the more it resembles a controlled

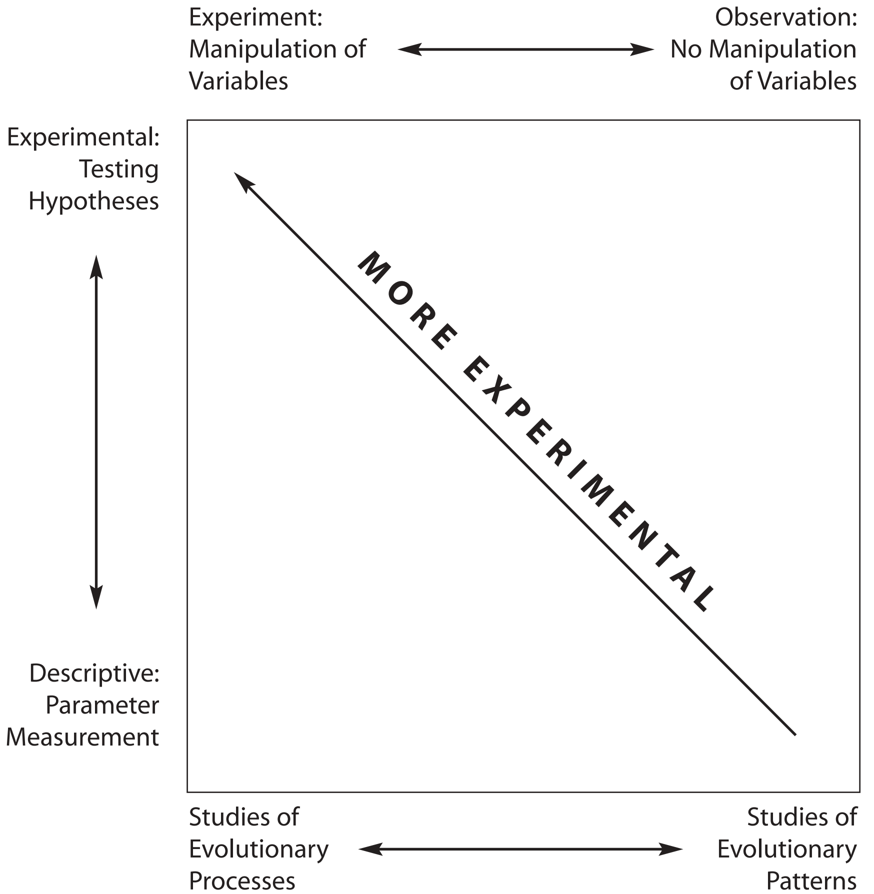

Figure 1.
Brandon's Framework for Classifying the Work of Evolutionary Biologists.
The closer a study is to the top left corner, the more it resembles a textbook-style controlled experiment. Some of the best work in evolutionary biology would be located at top center or top right of the diagram. (Adapted from Brandon, 1994, p.66).

experiment such as that described in most textbooks. Interestingly enough, most of the work done in evolutionary biology cannot be located in this upper left-hand region. Controlled experiments like those described in textbooks, where an independent variable is manipulated and other variables are measured to test hypotheses, may be the least reliable of the methods evolutionary biologists employ (Brandon, 1994; Burian, 1994). "It is simply too easy to create phenomena (in the laboratory) that have no relevance to what is going on in nature" (Brandon, 1994).

Patterns & Processes

For instructional purposes, it may be desirable to place the work of evolutionary biologists, as it is represented on Brandon's diagram, into two broad categories: work intended to analyze the patterns of evolution and work concerned with the processes of evolution. These two broad classes of methods would then correspond to two broad categories of questions identified by Futuyma (1998). These include the questions: *What has been the history of life?* (i.e., the chronology of historical events), and *What are the causes of evolution?* (Futuyma, 1998).

Questions about the history of life are answered by looking at the patterns found in the vestiges of past evolutionary events (e.g., fossils, homologous anatomical structures, or nucleic acid and protein sequences). Empirical studies of evolutionary patterns do not involve the manipulation of variables; therefore, they would be located on the right-hand side of Figure 1. Questions about the causes of evolution are answered by studying the processes that contribute to evolutionary change (e.g., competition, natural selection, genetic drift, etc.). Empirical studies of evolutionary processes frequently do involve the manipulation of variables; therefore, most of these studies would be located on the left-hand side of Figure 1. For the purposes of this article, we will look at specific examples of these two broad categories of questions, and the methods that were used to answer them.

Analyzing Evolutionary Pattern

The first general category of questions of interest to evolutionary biologists involves study of the history of life. How do biologists reconstruct the sequence and timing of events in evolutionary history? Typical questions include: *When did the extinction of the dinosaurs occur? How are the extant forms of fish and amphibians related to known fossil forms of these groups? Which of the extant primates is most closely related to* Homo sapiens? Answering these questions involves searching for patterns, and comparing patterns found in one group of organisms with patterns found in other groups. Comparative methods mainly involve observation, description, and hypothesis testing, but do not require the manipulation of variables. Specifically, answering questions about the history of life requires analysis of the patterns in fossils, morphological and physiological characteristics of living forms, developmental pathways, behavioral patterns, and molecular sequences of nucleic acids and proteins. An important key to answering questions about evolutionary patterns is to correctly identify homologies (similarities between groups of organisms that are the result of common ancestry). Homologies must also be distinguished from analogies. Analogies are similarities between groups of organisms that are the result of functional necessity, but not common ancestry.

As an illustration of comparative methods, let's look at a specific example of a question about the history of life: *Which of the extant primates is most closely related to* Homo sapiens? No one was present to witness the sequence of speciation events that produced all of the hominids and great apes. However, a partial history of those events is recorded in ape and hominid fossils, as well as in the homologous anatomical structures, physiological features, and behavior patterns found in living humans and apes. Evolutionary biologists have analyzed patterns found in the gross phenotypic features of humans and apes to test hypotheses about the relationships between them. In addition, the earliest fossils of ancestral human forms have been compared to both ape and modern human skeletons and found to have marked similarity to apes. More recent hominid fossils, on the other hand, closely resemble modern human forms as they take on more of those characteristics that distinguish modern humans from the other apes. These traits include a larger cranial capacity and a fully opposable thumb (Tattersall, 1995). Early conclusions based on gross phenotypic evidence placed the orangutan as our nearest relative, followed by the gorilla and chimpanzee as second and third respectively; however, this conclusion has since been revised on the basis of molecular evidence (Page & Holmes, 1998).

Since the 1960s, biologists have increasingly used molecular evidence along with other forms of evidence to answer questions about historical patterns. Page & Holmes (1998) explained that "... gene sequences are now recognized as an invaluable document of the history of life on earth." Molecular evidence is often more compelling than comparisons of gross phenotypic features when attempting to answer questions about homology. Gould (1986) explained that "In principle, the recovery of homology only requires a source of information with two properties: sufficiently numerous and sufficiently independent items to preclude, on the grounds of mathematical probability alone, any independent origin in two separate lineages." He argued that morphological features are "too few and too bound in complex webs of developmental correlation to yield this required independence," however, nucleic acids and proteins have the two necessary properties (Gould, 1986).

Although morphological, physiological, and behavioral evidence originally suggested that humans and orangutans were most closely related, the comparisons of immunological cross-reactions of serum proteins by Sarich and Wilson (1967) indicated a closer relationship between humans and chimpanzees. More recently, Goodman, et al. (1990) compared base sequences from noncoding regions of the B-globin gene and reported that the DNA of humans, chimpanzees, and gorillas is more than 98% identical, compared to a slightly less than 97% similarity between humans and orangutans.

Creationists may challenge an evolutionary interpretation of DNA similarity by arguing that such similarities simply reflect the inscrutable wisdom of the designer. However, Max (1998, 2002) explained that humans also share with chimpanzees a number of pseudogenes (nonfunctional copies of functional genes). Since there is clearly no functional necessity for these similarities, they lead "to the logical conclusion that both the human and ape sequences were copied from ancestral sequences that must have arisen in a *common ancestor of humans and apes"* (Max, 1998). Max compared the reasoning that leads to this "logical conclusion" to the precedents in copyright law which state that plagiarism can be detected by finding similar errors in two documents. If two documents were produced independently, it is inconceivable that they would contain similar errors, but if one document had been copied from the other, or both were copied from a common document, similar errors can be explained. These sequence similarities that result from the faithful copying of errors, particularly in nonfunctional regions of the genome, provide strong evidence for the descent of humans and other apes from a common ancestor.

Investigating Evolutionary Processes

Futuyma's (1998) second class of questions focuses on the processes that cause evolution; that is, what are the specific mechanisms that contribute to evolutionary change? This includes questions like: *What factors contribute to the evolution of life-history characteristics in animals? and What causes speciation?* Answering these questions requires the manipulation of variables, or perturbing of systems, and thus more closely resembles the controlled experiments portrayed in textbooks. However, as stated earlier, some of the best work in evolutionary biology is not the most experimental in the sense described by most textbooks (Brandon, 1994). Field experiments and natural experiments are actually more common and more informative. Field and natural experiments have different strengths and limitations than laboratory experiments (Diamond, 1986). For example, the conditions in the field do not permit the degree of control over potentially confounding variables one typically finds in a controlled laboratory experiment; consequently, one may be unable to claim that the independent variables of interest are the sole cause of the phenomena under study. However, an important strength of field experiments is their closeness to the actual phenomena that occur in nature.

An example of a field experiment that tests specific hypotheses about evolutionary processes is the long term study of the differential impact of predation by *Crenicichla alta,* a large cichlid, and *Rivulus hartii,* a small killifish, on the life history characteristics of the guppy, *Poecilia reticulata.* Life history characteristics include traits such as fecundity, and age and size at maturity. In their field study, Reznick, Bryga, and Endler (1990) were able to change the predator of a small population of guppies from the small killifish to the larger cichlid by moving the guppies from a pool where the killifish was their only predator to a new pool where a population of the cichlids had been living with no killifish or guppies. After 11 years of living in the pool with the cichlid that preys predominantly on large, sexually mature fish, the transplanted guppies matured earlier, at a smaller size, and gave birth to smaller, more numerous offspring in each brood than their ancestors had in the presence of the killifish predator. Since the cichlid preyed mainly on larger adults, selection favored those guppies that matured at a younger age and smaller size. The smaller guppies were more likely to survive long enough to reproduce several times, thus making a greater life-long genetic contribution to future generations than their larger cousins. As a result, the numbers of smaller guppies increased in the population.

This work demonstrates that natural selection can produce significant heritable changes in life history characteristics over a period as brief as 11 years (30-60 guppy generations). More recent studies have indicated that significant evolutionary changes can occur in as few as 4 years for male guppies and 7.5 years for females (Reznick, Shaw, Rodd & Shaw, 1997).

Reznick, Bryga, and Endler's (1990) work on the short term evolution of guppy populations provides some understanding of one mechanism that causes change in species and the rate at which it operates under specific circumstances. Gould (1986) explained how Darwin demonstrated in his book, *The Formation of Vegetable Mould, Through the Action of Worms* (Darwin, 1881), that known rates of change can be extrapolated over time to explain large-scale changes that have occurred during the Earth's history. Reznick et al. (1997) employed Darwin's pattern of reasoning from his worm book when they argued that their findings could be extrapolated over time to, perhaps, shed some light on the debate about the relative importance of natural selection versus other processes in explaining the patterns found in the fossil record. Thus, the study of evolutionary process frequently has implications for the understanding of evolutionary patterns. Conversely, studies of pattern may also suggest hypotheses about the processes that shaped past events. Page and Holmes (1998) explained that "... DNA sequences not only contain a record of their phylogenetic relationships and times of divergence, but also the signatures of what evolutionary processes have shaped their history and even the size of past populations."

Recommendations

The patterns of reasoning biologists use to investigate the past are not unique to evolutionary biology. As mentioned above, there are many sciences that focus some, or all, of their investigations on questions about the past. This raises two very important issues for teachers: *How can we convey the message to students that there is a diversity of methods used in all sciences, and that evolutionary biology is not different or unique in its theorizing about the past? How can teachers demonstrate that it is possible for scientists to have a high degree of confidence in their knowledge of the past?*

In order to address the first issue (the diversity of methods), it is essential that teachers move beyond the limited and misleading textbook presentations of a mythical universal scientific method. Brandon's framework may serve as a useful guide for teachers and students as they explore the range of approaches that scientists use to answer questions about nature (Brandon, 1994; Cooper, 2002b). In addition, teachers could present brief descriptions of investigations from other sciences, such as physics and geology, that answer questions about the past (thereby demonstrating that asking and answering questions about the past is not an activity that is unique to evolutionary biology).

In order to address the second issue (getting students to understand that it is possible to have a high degree of confidence in our knowledge of the past), two approaches are recommended. Reasoning about the past based on fossils and DNA evidence may initially seem too esoteric to students. Therefore, they should first be introduced to examples of investigations using these same patterns of reasoning in more familiar contexts. The Modeling for Understanding in Science Education Project presents an activity that requires students to sequence a series of cartoon images and then draws parallels between this activity and interpreting the fossil record (National Center for Mathematics and Science, 2002). This may be a good place to begin.

Another source of activities that presents reasoning about the past in familiar contexts are crime scene investigations. Forensic scientists can reconstruct a crime scene, determine the time and cause of death, and identify possible suspects, all based on patterns in the evidence collected and knowledge of the processes that would produce the patterns of evidence. The Evolution and the Nature of Science Institutes Web site presents a crime scene activity (McNabb, Watts & Willey, 1999) that would be suitable for this purpose. For students who already have some knowledge of molecular biology, there are also simulated crime scene investigations that employ DNA fingerprinting (Rubenstein, Anderson & Hall, 1996; Herreid, 1996).

Once students have experienced these patterns of reasoning about the past in more familiar contexts, they could be introduced to some of the techniques actually employed by evolutionary biologists to reason about the past history of life. For example, Maier (2001) and Singer, Hagen & Sheehy (2001) presented authentic activities that introduce cladistic methods used to determine evolutionary relationships and test hypotheses about the sequence of evolutionary events.

Conclusions

The myth that scientists usually perform controlled laboratory experiments to test hypotheses, and that this experimental work is somehow "more scientific" than historical or comparative studies, is simply incorrect. In addition, the belief that it is impossible to know anything about what happened in the past since no one was there to observe is a serious misconception about the nature of science that hinders the acceptance of evolution. If we allow student understanding of the nature of science to be limited by these widespread myths, then sciences that investigate questions about the past will be found lacking, and widespread understanding and acceptance of evolution will never be achieved.

Rectifying these misunderstandings requires a change in our approach to teaching about sciences, such as evolutionary biology, that have historical aspects. In addition, the national education goal of achieving basic science literacy for America's students requires that we address the diversity of methods found in science, as it is actually practiced (AAAS, 1990, 1993; NRC, 1996). This includes teaching about methods used to study the past. Once students understand how it is possible for scientists to know something about the past they will be able to adequately assess the evidence for evolution and appreciate its central organizing role in biology.

In order for students to achieve this level of understanding, evolution instruction will have to focus on the specific modes of evolutionary inquiry and avoid presenting evolution as a rhetoric of conclusions (Rudolph & Stewart, 1998; Donovan, 2001). Activities on the nature of science in general are necessary (AAAS, 1990, 1993; NRC, 1996; NAS, 1998); however, by themselves, they are not sufficient for improving understanding of evolution. It is also important for students to understand the specific types of questions asked when scientists study the history of life, and the modes of inquiry used to answer those questions (Rudolph & Stewart, 1998; Donovan, 2001).

In cases where individuals are committed to fundamentalist religious beliefs, it is unlikely that any instructional approach will be effective in broadening their views (Ruse, 2001). However, more effective instruction should modify the views of those Alters (1999) identified as rejecting evolutionary explanations on the basis of misconceptions about the nature of science.

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