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# PERSPECTIVE: TEACHING EVOLUTION IN HIGHER EDUCATION

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*Abstract.*—In the past decade, the academic community has increased considerably its activity concerning the teaching and learning of evolution. Despite such beneficial activity, the state of public understanding of evolution is considered woefully lacking by most researchers and educators. This lack of understanding affects evolution/science literacy, research, and academia in general. Not only does the general public lack an understanding of evolution but so does a considerable proportion of college graduates. However, it is not just evolutionary concepts that students do not retain. In general, college students retain little of what they supposedly have learned. Worse yet, it is not just students who have avoided science and math who fail to retain fundamental science concepts. Students who have had extensive secondary-level and college courses in science have similar deficits. We examine these issues and explore what distinguishes effective pedagogy from ineffective pedagogy in higher education in general and evolution education in particular. The fundamental problem of students' prior conceptions is considered and why prior conceptions often underpin students' misunderstanding of the evolutionary concepts being taught. These conceptions can often be discovered and addressed. We also attend to concerns about coverage of course content and the influence of religious beliefs, and provide helpful strategies to improve college-level teaching of evolution.

*Key words.*—Creationism, evolution, higher education, prior conceptions, religious beliefs, student-centered instruction, teaching.

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> ''Research has taught us a great deal about effective teaching and learning in recent years, and scientists should be no more willing to fly blind in their teaching than they are in scientific research.''—Bruce Alberts, President, National Academy of Sciences (Committee on Undergraduate Science Education 1997, p. v).

When we consider teaching as currently practiced in many postsecondary science courses, we must confront an interesting paradox. Scientists, perhaps more than any other group, insist on solid data and sound theories. However, most science faculty have paid little if any attention to the empirical and theoretical studies that ask what methods of teaching are most effective either generally or for particular groups. Neither is the question of how well one's teaching is working typically seen as meriting much investigation. Rather the tendency is to continue to teach as we were taught, resisting any suggestions that traditional approaches might be less than optimally effective or that they might be biased in favor of particular groups. Typically, any evidence of less than optimal learning is attributed to a lack of student effort or insufficient prior preparation, thereby letting the faculty member off the hook. The effects of this are perhaps most visible for publicly controversial subjects such as evolution, genetics, and environmental policy.

In the past decade, the academic community has increased considerably its activity concerning the teaching and learning of evolution. Some representative events are: (1) the convening of the national Evolution Education Research Conference, which brought together educational researchers to identify and discuss critical issues in evolution education (Good et al. 1992); (2) the establishing of a Society for the Study of Evolution (SSE) Education Committee, which organizes educational symposia at the SSE annual conferences and National Association of Biology Teachers' conventions (Eckstrand 1998); (3) the holding of a recent National Conference on Teaching Evolution (2000; for more information see http://www.ucmp.berkeley.edu/ncte) attended by representatives from 41 professional scientific and educational societies; (4) the issuing of new statements and materials supporting evolution education by many science and science education organizations (e.g., National Association of Biology Teachers 1995; National Science Teachers Association 1997; National Academy of Sciences 1998, 1999; American Association for the Advancement of Science 1999; American Geological Institute and The Paleontological Society 2001); (5) the creation of a new center to study the teaching and learning of evolution (Evolution Education Research Centre, McGill University, Montréal, Québec, Canada); and (6) the production of a white paper on the science of evolution prepared by delegates representing eight scientific societies, with the purpose of serving ''as a statement of the nature and importance of the field for use by policymakers, educators, and scientists alike'' (Futuyma 1999, p. 44; for an executive summary see Meagher 1999). The representing societies were the Society for the Study of Evolution, American Society of Naturalists, Society for Molecular Biology and Evolution, Ecological Society of America, Society of Systematic Biologists, Genetics Society of America, American Behavior Society, and Paleontological Society.

Despite these and numerous other beneficial activities, public understanding of evolution is considered woefully lacking by most researchers and educators. This lack of understanding affects evolution/science literacy, research, and academia in general. Moreover, there is an intentional undermining of evolution education by antievolution organizations (probably over 100 worldwide) with some of the most influential groups headquartered in North America (Institute for Creation Research 2000; R. Numbers, pers. comm.; Alters and Alters 2001; Antolin and Herbers 2001). Such ''opposition to evolution is so vocal in the United States that it has threatened federal funding of evolutionary research'' (Futuyma 1999, p. 43).

## Rudimentary Public Understanding of Evolution

In a recent national Gallup poll concerning evolution, 45% of Americans chose the responses ''God created human beings pretty much in their present form at one time within the last 10,000 years or so'' (Brooks 2001). Only 35% of all respondents thought ''the theory of evolution is supported by evidence.'' Yet, in the same poll, 80% of respondents considered themselves to be ''very informed'' or ''somewhat informed'' about evolution. Similar results from a National Science Board (National Science Foundation) countrywide quiz revealed that only about half the respondents answered ''false'' to the statement ''The earliest humans lived at the same time as the dinosaurs.'' A mere 45% responded ''true'' to ''Human beings, as we know them today, developed from earlier species of animals'' (National Science Board 2000, p. A-549).

Regardless of whether people think humans developed from earlier species of animals, many don't seem to know what the term evolution means. For example, another national poll reports that of those who recall ever having heard the term evolution, only 50% chose the correct layman's definition (People for the American Way Foundation 2000, p. 38). The poll also reports confusion with the term ''theory'' and confusion about, or rejection of, the factuality of evolution. With regard to theory, 74% agreed that ''evolution is commonly referred to as the *theory* of evolution because it has not yet been proven scientifically'' (p. 41). On another question, only 29% felt that evolution was ''completely accurate'' or ''mostly accurate,'' while the remaining 71% responded ''mostly not accurate,'' ''completely not accurate,'' ''not sure,'' or ''might or might not be accurate, you can never know for sure'' (p. 40).

Such a lack of even a rudimentary understanding of evolution by the general public is often blamed on the way the media communicates evolution and antievolution. However, a communication analysis of *Time*, *Newsweek*, and *U.S. News and World Report* revealed that these periodicals accurately portrayed evolution as ''the school of thought'' (Pullum 1993, p. 10). (These three periodicals reportedly are read by more people than the combined daily audiences of the three major network television news programs.) Nevertheless, the analysis also pointed out that the magazines typically mentioned the possibility of supernatural causality in the same articles. Such juxtaposition of science and supernatural causation in articles about biological evolution may lead to confusion among casual readers. This concurrence is prevalent in newspaper articles, such as in the recent *New York Times* article: ''Darwin vs. Design: Evolutionists' New Battle.'' In this article about intelligent design advocates' newest attacks against evolution, the public read that ''Leaders of the design movement also look for flaws in evolutionist thinking and its presentation, and have scored heavily by publicizing embarrassing mistakes in prominent biology textbooks'' (Glanz 2001, p. 18). (For a response to such accusations see Coyne 2001; National Center for Science Education 2001; Pigliucci 2001; Scott 2001.)

Whether the media portrays the science of evolution accurately to the general public probably affects peoples' understanding of evolution. Nevertheless, most teachers and professors hope that in-class education has a greater effect on learning evolution than does the media. However, classroom evolution education typically is not effective enough. A recent U.S. state-by-state evaluation of the treatment of evolution in science standards determined that ''more than one-third of all states do not do a satisfactory job''; and, astonishingly, ''ten [states] never use the 'E-word''' (Lerner 2000, p. xii). The last formal science course students generally take is high school biology. When students reach college, the effect of being underprepared follows them, whether or not they take any biology.

## Does Education Currently Make Much Difference?

Research results show that there may be surprisingly little difference in performance between majors and nonmajor introductory biology students. For example, in an ecology and evolutionary biology pretest of 1200 students, biology majors scored only 6% higher than nonmajors. When the same students were posttested on the first day of the following semester, the researchers concluded ''that majors, who received a much more rigorous treatment of the material, came through the semester with the same degree of understanding as the nonmajors!'' (Sundberg and Dini 1993, p. 301).

A large proportion of college graduates (baccalaureate) hold elementary evolution misconceptions. For example, 35% think that ''the earliest humans lived at the same time as the dinosaurs'' and 42% indicated that they don't think ''human beings, as we know them today, developed from earlier species of animals,'' a figure that is scarcely distinguishable from that for the public at large (National Science Board 2000, p. A-549).

This overall lack of even the most rudimentary evolution understanding has prompted the editor of the *American Biology Teacher* to conclude that:

> When you combine the lack of emphasis on evolution in kindergarten through 12th grade, with the immense popularity of creationism among the public, and the industry discrediting evolution, it's easy to see why half of the population believes humans were created 10,000 years ago and lived with dinosaurs. It is by far the biggest failure of science education from top to bottom. (Christensen 1998, p. D3)

However, it is not just evolutionary concepts that students do not retain. In general, college students retain little of what they supposedly have learned. Although a very few studies report exceptionally high values, such as students retaining 50% of the course content, studies more commonly report a retention of 20% or less (Gardiner 1998). For example, fewer than 38% of college graduates (baccalaureate) could correctly respond in their own words to the questions, ''what is a molecule?'' and ''what is the Internet?'' Only 53% could answer the question ''what is DNA?'' In addition, 35% thought lasers work by focusing sound waves, 26% thought that radioactive milk can be made safe by boiling it, 30% did not know how long it takes for the Earth to go around the Sun, and only 44% thought the universe began with a huge explosion (National Science Board 2000).

Worse yet, it is not just students who have avoided science and math who fail to retain fundamental science concepts. Students who have had extensive secondary-level and college courses in science have similar deficits. Illustrative of this fact are documentary films produced by the science education department at the Harvard-Smithsonian Center for Astrophysics, which show the inability of graduating Harvard seniors to explain why it is hot in the summer and cold in the winter (Schneps and Sadler 1988). (The students primarily thought the seasons were caused by the relative proximity of the Earth to the Sun, not mentioning the tilt of the Earth.) In another film, the same researchers documented the extreme difficulty shown by students graduating from MIT in completing a simple DC circuit when given a flashlight battery (D-cell), light bulb, and a piece of wire (Schneps and Sadler 1997).

Many such concepts are so basic that their understanding is essential to the understanding of other concepts being taught. The troubling question is this: If students don't understand even fundamental concepts, how can they understand more advanced concepts built upon these fundamentals?

These results appear even more dismal when contrasted to our aspirations as faculty. Most science faculty want students to be capable of far more than just recalling facts and repeating basic concepts. The Society for College Science Teachers' position statement on introductory college-level science courses states that, ''at a minimum, every student should know and be able to do the following:. . . Solve and evaluate problems. . . . [Design] meaningful experiments . . . . Evaluate critically. . . . Explain scientifically related knowledge claims. . . . Ask meaningful questions about real world scientific issues'' (Society for College Science Teachers 1993, p. 31). Most instructors would maintain that such knowledge and ability should be the minimum expected from any college science course, yet even the most fundamental science concepts are often ''taught'' but not learned. Certainly, fundamental concepts are presented, so why are students not learning what instructors think they should? Many educators would argue that if students have not learned, then true teaching has not occurred.

### *Traditional Pedagogy—The Relatively Ineffective Kind*

What distinguishes effective pedagogy from ineffective pedagogy? Most instructors teach as they were taught (Tobin et al. 1994). In general, most college teaching styles, at least in science, appear to focus on instructor-centered teaching (contrasted with more student-centered teaching discussed in the next section). In instructor-centered teaching, the instructor solely determines, primarily from tradition and disciplinary content, exactly what is to be taught and how it should be taught—most often presenting content to students as if it were capable of being merely transferred (or downloaded). Instructors who espouse this pedagogy believe that ''strong'' students may figure out how to accommodate the information, thus truly learning, while the others may not, thus not learning. It is the ''sink or swim'' approach to teaching. Problems with such instruction become evident when student retention and understanding of even the most fundamental concepts in the course is shockingly limited, as reflected in the low levels of scientific literacy even among college graduates, discussed previously.

Thus, these traditional methods may not be the best to promote student learning. In a review of the past three decades of research literature in higher education, a zoologist at Rutgers University (Gardiner 1998) summarized some important aspects of what hampers student learning with regard to lectures, critical thinking, testing, and curriculum:

*Lectures.*—Many students are strikingly limited in their ability to reason with abstractions. Therefore, they have significant difficulty understanding many college lectures that instructors perceive to be straightforward and level-appropriate. In addition, student attention begins drifting after only 10 to 20 minutes. Students are rarely involved in frequent student-faculty interaction during class; in many classes students are asked and respond to questions for less than 10% of the class time. This paucity of time for interaction with and among students is especially noteworthy given that there is an inverse relationship between lecture listening time and critical thinking. In addition, there is a positive association between lecture listening time and rote memorization. Even when professors do ask questions of students in classes, approximately 90% are recall of merely memorizable facts, with just a few percent requiring evaluation skills.

*Critical thinking.*—Most faculty want students to be critical thinkers. However, many students are epistemological dualists, viewing the academic world in terms of true or false, right or wrong, credit or no credit. Instead of analyzing evidence that contradicts their erroneous conceptions, students often just passively receive knowledge from authorities—professors. To become active learners, students need professors to use methods that involve them in grasping important concepts, but only 10–30% of professors use methods other than traditional lectures as their primary pedagogy.

*Testing.*—The attempt to engender higher-level thinking skills in students is often thwarted by the very way instructors evaluate student work. The knowledge-level tests that are typically administered in university science classes reinforce dualistic epistemologies, concrete thinking, and mere surface approaches to learning. Additionally, the validity and reliability of many such tests can be called into question. Moreover, assessment is often infrequent, which diminishes effective educational experiences. In short, even for instructors of large lecture-hall courses, it is not appropriate to administer typical easy-to-construct multiple-choice tests.

Rather, there are ways to design reliable and powerful multiple-choice tests that have distractor options (i.e., wrong answers) that closely match student misconceptions. When this is done the ''distractor-driven multiple choice tests combine the richness of qualitative research with the power of quantitative assessment, measuring conceptual change along a single uniform dimension'' (see Sadler 1998 for a research-based account and explanation of developing appropriate quantitative tests, p. 265). The use of such questions as part of an interactive teaching approach has been quite important in demonstrating the relative ineffectiveness of traditional pedagogy in college physics (Hake 1998).

*Curriculum.*—A professor's pedagogy and how the students approach general education is far more important in student learning than is the curriculum. For a partial review of college science generally, see Springer et al. (1997).

### *A Fundamental Problem: Prior Conceptions*

Research involving student learning in high school biology suggests that there is a complicated synergism affecting the learning of evolution. For example, the following can be very influential in the process of student conceptual change: the learner's prior conceptions related to evolution, scientific epistemology, view of the biological world, religious orientation, acceptance of evolutionary theory, and scientific orientation (i.e., ''the degree to which the participant organized her/his life around scientific activities, understood the natural world through physical causation, and interpreted natural events through a scientific lens'' [Demastes et al. 1995, p. 658]). Such facets of the conceptual ecology of evolution are difficult to uncover at the college level, where typically the beginning-level undergraduate class size is far too large for personal instructor-student interaction. However, one important set of predictable difficulties can be addressed (but usually is not) even in very large classes. Students' prior conceptions are a major factor affecting how and if students learn, and these conceptions can be uncovered and addressed. The National Research Council's Committee on Learning Research and Educational Practice has highlighted this as a ''key finding'':

> Students come to the classroom with preconceptions about how the world works. If their initial understanding is not engaged, they may fail to grasp the new concepts and information that are taught, or they may learn them for purposes of the test but revert to their preconceptions outside the classroom. (Bransford et al. 2000, pp. 14–15)

Such prior conceptions often underpin students' misunderstanding of the evolutionary concepts being taught. Some of these underpinning misconceptions may not fall directly within the discipline of evolutionary biology but may be fundamental to, or have bearing on, learning evolutionary concepts. Other misconceptions may directly involve evolutionary concepts to be learned, since many students have had ample formal and informal educational opportunities to misunderstand evolution, and have had significant time (often years) to make ''sense'' of their intuitive views.

In a study involving 322 university sophomores' (education majors) understanding of natural selection, the researcher concluded that there is a logic to students' misunderstandings. ''There seems to be a structure of misunderstandings which allows one to logically trace the origin of the misunderstandings to mistaken assumptions'' (Greene 1990, p. 883).

There are many types of misconceptions and mistaken assumptions on which those misconceptions are based (Committee on Undergraduate Science Education 1997). Five groups are especially pertinent here:

*From-experience misconceptions* are those that students surmise (consciously or unconsciously) from their everyday experiences. One from-experience misconception is that mutations are always detrimental to fitness.

*Self-constructed misconceptions* occur when information that students see or hear conflicts with what they already ''know'' (their misconception) but, rather than change their misconception, they accommodate the new knowledge in the framework of an old misconception. For example, students who have a long-held impression that evolution is predictably progressive, with the end goal being humans, will incorporate natural selection into that type of determinism. A deterministic perspective does not appear to be relegated exclusively to undergraduates or to nonbiology graduate students. In a study of 15 biology students at the master's degree level, the researchers noted a trend for students to propose deterministic-type explanations of evolutionary processes (Zaïm-Idrissi et al. 1993).

*Taught-and-learned misconceptions* are unscientific ''facts'' that have been taught informally by parents and others (and sometimes formally by school teachers) or unconsciously learned from fiction. For example, previous to college, numerous undergraduates have been told the Lamarckian idea of inheritance of acquired characteristics. Also, many repeatedly have seen dinosaurs and humans coexisting in print and visual materials such as films, books, and cartoons.

*Vernacular misconceptions* arise from the difference between the scientific use of a word and its everyday use, and the consequent misunderstanding of the distinction. More explanation and examples are given shortly, but one of the most prevalent examples of a vernacular misconception is evolution's status of being ''only'' a theory.

*Religious and myth-based misconceptions* are concepts in religious and mythical teachings that, when transferred into science education, become factually inaccurate. Two such misconceptions are that organisms do not have common descent and that the Earth is too young for evolution (and most geological processes) to have occurred.

There are several studies of students' specific misconceptions concerning evolution. For example, in a survey of 392 university students, nearly 43% thought ''evolution involved a purposeful striving toward higher forms (that it is steady progress from microbes to man).'' Seniors were less likely to embrace this idea than other levels of students. Over 12% of freshman thought ''Man evolved either from the gorilla or chimpanzee in Africa.'' About 32% of students answered ''no'' when asked ''Do you think that the modern theory of evolution has a valid scientific foundation?'' Two primary reasons for these answers were that ''we can never be sure about the past,'' and ''because evolutionary science is principally based on speculation, and not on 'hard' scientific fact'' (Lord and Marino 1993, p. 354).

The subjects of another study comprised nonmajors taking introductory biology courses, most in their junior or senior year of college. This study was designed to develop a more complete and systematic description of student conceptions about evolution. The results revealed three major ways in which college nonscience majors' conceptions about evolution differed from the ''population thinking'' (Mayr 1982) based conceptions widely held by scientists.

(1) *Students thought that the environment itself (rather than genetic mutation, sexual recombination of genes, and natural selection) causes traits to change over time.* They failed to distinguish between the separate processes responsible for the appearance of traits in a population (which originate by random changes in genetic material, e.g., mutation and sexual recombination) and the survival of such traits in the population over time (natural selection). Students had difficulty understanding the key idea that the environment affects the survival of traits *after* their appearance in the population. Instead, students thought that change was due to environmental forces alone, which acted on organisms to produce change, and held various conceptions about how the environment exerts its influence.

Some held teleological/Lamarckian conceptions; that is, students attributed evolutionary change to need. For example, students thought that if cheetahs needed to run fast for food, nature would allow them to develop faster running skills. Some held other Lamarckian views, attributing evolutionary change to use and disuse. For example, students thought that if cave salamanders did not use their eyes for many generations, their eyes would become nonfunctional. Also, a number of students attributed evolutionary change to organisms' ability to change in response to environmental ''demands.'' For example, students thought that polar bears adapted to their environment by slowly changing their coats to white.

(2) *Students did not view genetic variation as important to evolution, even though such variation is essential to evolution taking place.* Students viewed evolution as a process that acts on the species as a whole, not recognizing that it is variation among individuals within a population that constitutes evolution's raw material. They did not understand that the process of natural selection is dependent on differences in genetic traits and in reproductive success among individual members of a population.

(3) *Students viewed evolutionary change as gradual and progressive changes in traits, rather than as a changing proportion of individuals with discrete traits.* Students did not recognize that traits become gradually established in a population as the proportion of individuals possessing those traits grows with each succeeding generation. They believed that all individuals change slowly over time. For example, students thought that if salamanders living in caves did not need sight, then they would pass down genes conferring less and less ability to see until the salamander populations were blind (Bishop and Anderson 1986, 1990). Similar results were found in a study of underprepared college students enrolled in a biology course (Jensen and Finley 1996).

Research results also indicate that nonmajor biology students reinforce their naive conceptions by confusing the scientific terms ''adapt,'' ''adaptation'' and ''fitness'' with the everyday terms (Bishop and Anderson 1986, 1990). The prevalence of vernacular misconceptions is certainly not surprising, since many scientific words are used in day-to-day language but carry meanings that are quite different from their meanings in the context of evolution. Unless the meaning students hold for this word is examined and compared to the scientific meaning in an evolutionary context, and unless students replace their intuitive conception with a scientifically correct conception of a word, they will construct new knowledge with this faulty concept. The learning that results may not coincide with what instructors expect to happen.

For example, in an evolutionary context, the meanings of ''adapt'' and ''fitness'' are quite different from students' everyday senses of these words. For many students, the term ''adapt'' refers to individuals changing their physical, behavioral, or other attributes in response to an environmental condition. The change is called an ''adaptation'' (as it sometimes is even in science courses). For example, a night owl student adapts to getting up early for an 8:00 A.M. class. This confusion of terms reinforces the misconception that the environment somehow acts upon individual organisms to force them to change certain characteristics or perish. Similar problems occur with the term ''fitness''. In its everyday sense, fitness refers to an organism's health, strength, or intelligence. For example, individuals are considered ''fit'' if they eat a balanced diet, are an appropriate weight for their height, and exercise.

In another example, many students believe the difference between a theory and a law is that a theory is merely a hypothesis that possibly has been tested a few times, and that a law is nearly (or is) a scientific fact because it has been successfully tested many times. Using these meanings, students often consider that evolution is not a law but ''only'' a theory, therefore setting evolution into a supposedly inferior category than if it were a law. This characterization of the scientific use of the words ''theory'' and ''law'' has led students to believe that if scientific theories had enough evidence and were tested sufficiently with resulting supporting outcomes, then scientific theories would become scientific laws. Such misconceptions of the meanings of the words ''theory'' and ''law'' are reinforced by the vernacular meaning of the word ''theory'' as something that is not factual—merely a guess without any or with very little supporting evidence. This use of the word is so ingrained in our culture that even many scientists, when casually speaking, will use the term ''theory'' in the same way that the general public uses the word.

Students traditionally considered high achievers in science also enter university or medical school with troublesome evolutionary misconceptions. One researcher studied 150 first-year medical students in Australia (where students enter medical school immediately after grade 12) who had strong backgrounds in science, a quality necessary for Australian medical school entrance. This cohort of students was given qualitative problems based on the concept of natural selection and was probed for explanations. For example, students were asked: ''When they were first sold, aerosol insecticides were highly effective in killing flies and mosquitoes. Today, some 20 years later, a much smaller proportion of these insects die when sprayed. Explain why you think this may be so'' (Brumby 1984, p. 501). Results of the overall analyses of multiple natural selection problems such as this revealed results similar to those discussed previously with nonmajor introductory biology students. The results showed that the majority of students believed that evolutionary change occurs as a result of need and that acquired characteristics were heritable. They, too, held vernacular misconceptions, confusing the scientific and everyday meanings of the word ''adaptation.'' Students understood that individuals could adapt to change over their lifetimes and then applied this everyday understanding to the natural selection problems. Therefore, students thought that insects became more immune to insecticides over generations, rather than understanding that more organisms within a population became immune to insecticides over generations.

In many cases it is possible that the very textbooks instructors use to help correct student misconceptions about evolution are problematic. A study of 50 major college-level textbooks in the fields of evolution, biology, ecology, genetics, paleontology, and systematics yielded ''disappointing'' results in even the baseline definition of evolution. Overall, the researcher concluded that many textbooks do not present evolution concepts accurately (Linhart 1997, p. 387).

## A Key Improvement: A Constructivist Approach

Clearly, students bring a variety of misconceptions about evolution to the courses they take, including misconceptions about ideas that underpin and are essential to an accurate understanding of evolution. The important decision for instructors is what to do about these conceptions, if anything. Many instructors present the material to be learned irrespective of what conceptions the students bring with them. Contrarily, the National Research Council's Committee on Undergraduate Science Education reports that ''recent research on students' conceptual misunderstandings of natural phenomena indicates that new concepts cannot be learned if alternative models that explain a phenomenon already exist in the learner's mind'' (Committee on Undergraduate Science Education 1997, p. 28). To grasp the magnitude of the implications for teaching evolution that this implies, recall the array of misunderstandings discussed previously.

The learning theory (or educational theory) advocated most often to facilitate such conceptual change is known as *constructivism.* ''From a constructivist perspective, learning is a social process of making sense of experience in terms of extant knowledge. Persons interact with objects and events through their senses, which are inextricably associated with extant knowledge that includes beliefs and images'' (Tobin et al. 1994, p. 47).

To facilitate a constructivist approach in the classroom, an instructor should provide situations in which students examine the adequacy of their prior conceptions, allowing them to argue about and test them. The contradictions students may face during this testing process can provide the opportunity for them to acquire more scientifically appropriate concepts. As students practice this process, they also become increasingly skilled in the procedures used in concept acquisition. According to Lawson (1994) these *essential elements of constructivist instruction* are:

> (1) Questions should be raised or problems should be posed that require students to act on the basis of prior beliefs (concepts and conceptual systems) or prior procedures. (2) Those actions should lead to results that are ambiguous or can be challenged or contradicted. This forces students to reflect back on the prior beliefs or procedures used to generate the results. (3) Alternative beliefs or more effective procedures should be proposed by students and the teacher. (4) Alternative beliefs or the more effective procedures should now be utilized to generate new predictions or new data to allow either the change of old beliefs or the acquisition of a new belief (concept). (Lawson 1994, p. 166)

For example, in teaching population genetics: (1) Present a set of initial parameters (fitness of both homozygotes equal that of the heterozygote, $p = 0.3$ $q = 0.7$, large population). Ask the students to predict: ''What will happen through time? Will there be an equilibrium or fixed end point? If so at what frequency?'' Then ask them to graph their predictions (as allelic frequency vs. time). In this case, some usually will predict that the ''dominant'' (AA) will quickly prevail—because it is ''dominant'' in the vernacular sense. (2 and 3) Present a computer simulation that graphs an allelic frequency versus time for several populations (or, less excitingly, present the graph as an overhead). When a series of conditions and predictions are examined, the simulations will contradict some of the predictions for many groups of students. This allows them to find their prior misconceptions and revise their mental models. (4) After each round, the new ideas can be tested against new sets of conditions embodying the same genetic concepts until the predictions match the new (subsequently produced) results.

Note that such series of constructivist steps can be used in teaching much of science. Also note that this process of proposing alternatives and then using more neutral criteria to compare among them presents science as a process to be understood rather than as a set of conclusions to be memorized (even though the content is still taught, indeed, taught better). Alternatively stated, it presents science as a process of critical thinking that provides a model for critical thinking elsewhere in the student's life.

This effect on critical thinking is crucial. Inherent in most or all development of an understanding of evolution is the factor of students' present reasoning abilities. Results of a study involving introductory nonmajor college biology students revealed that those who were less skilled in reasoning were more likely to hold nonscientific beliefs than were students more skilled in reasoning. They noted that nonscientific beliefs held by less-skilled reasoners are not easily altered by instruction, ''thus instruction should focus on ways of improving student reasoning skills as well as teaching scientific conceptions'' (Lawson and Weser 1990, p. 605). Others suggest that evolution and other controversial issues provide a context that helps motivate students to learn to critically think more effectively (Nelson 2000).

Most biology educators maintain that teleological and anthropomorphic explanations are inappropriate and contribute to engendering misconceptions. However, some contend they should not be avoided in class explanations. Rather, they advocate that teleological/anthropomorphic formulations be brought up in class because (1) such formulations are constantly encountered by students in more popular science books and movies, (2) philosophers and biologists have no universal rejection of such formulations, (3) research results in one study indicate that acceptance of such formulations does not necessarily imply similar reasoning, and (4) students' reflections on such formulations have heuristic value. They suggest that we ought ''to bring these issues up front whenever they emerge from the specific biological topics being taught, to engage students in explicit discussions about the significance of such formulations, to specify their meanings, and perhaps to emphasize what they do not mean.. . . At the same time, suggest drawing generalizations from the specific incidents, applying the terms 'anthropomorphism' and 'teleology,' and discussing their meaning in general terms'' (Zohar and Ginossar 1998, p. 695).

Many additional examples of activities designed for teaching various aspects of evolution can be found in the literature. These activities range from lessons simulating natural selection using playing cards to using casts of hominid fossil skulls as a central feature in teaching about human evolution (Gipps 1991; Knapp and Thompson 1994; Alters and Alters 2001; Flammer et al. 2001).

### *An Essential Focus: Student-Student Discussion*

Involving students in activities generally increases the amount of student-centered discussion. The advantages of student-centered discussions include increased problem-solving ability, retention, and transfer of knowledge to other situations (McKeachie 1994). Additionally, there is a strong relationship between effective learning and students' active involvement in their learning. For example, interactive engagement approximately doubles the amount of physics students learn when compared to standard lectures and laboratories (Hake 1998). More generally, Springer et al. (1997) performed a meta-analysis of the research on ''the effects of small-group learning on undergraduates in science, mathematics, engineering and technology.'' They found that average effect size ''would move a student from the 50th percentile to the 70th'' on content and that there were similarly large effects on retention and attitude. Further, in-class student involvement with high-level cognitive responses to questions is positively correlated with critical thinking skills (Gardiner 1998).

There are many good summaries of how to use student-student learning in college teaching (including: Whitman 1988; Gabelnick et al. 1990; Johnson et al. 1991; Goodsell et al. 1992; Meyers and Jones 1993; Millis and Cottell 1998). An important factor in the success of student-student interaction is for instructors to take responsibility for three aspects that they often ignore (see Nelson 1994 for elaboration). First, faculty should make sure that each student is prepared for discussion. This can be done, for example, by presenting material in class or by having each student prepare a short assignment and bring it to class. Second, instructors should focus the discussion by, for example, giving appropriate questions so that students work together on matters that are difficult for them. Frequently this means focusing the discussion in part on the students' own conceptions and misconceptions. Finally, faculty are responsible for structuring the discussion so that all students participate productively in their groups.

### *A Helpful Tool: Concept Maps*

A reduction in course content alone will make more student contact time available during class, but does not automatically aid the instructor in identifying students' conceptual difficulties that arise during the course. Some researchers advocate incorporating student-produced concept maps of lecture material into homework assignments (e.g., Mintzes et al. 1999). Studies have shown that analyzing these maps help instructors identify students' conceptual difficulties. In a study of a college course on evolution, the key findings were as follows:

> (a) critical junctures in learning evolution can be identified by monitoring the degree of concordance of superordinate concepts appearing on the class set of concept maps submitted after each of the course lectures; (b) students who made concept maps reported spending an average of 37% more study time on this college biology course than on their previous biology courses; and (c) the use of ''seed concepts,'' ''micro-mapping,'' a standard concept map format, and a standard concept map checklist made the strategy feasible for the instructor to implement and the student to adopt. (Trowbridge and Wandersee 1994, p. 459)

In another related study, the same researchers found a positive correlation between concept map scores and the number of instructor-used graphics during lectures. They recommend that students embed icons from instructor-generated graphics into their own concept maps, ''thus integrating the visual and the verbal'' (Trowbridge and Wandersee 1996, p. 57).

### *Another Helpful Tool: Historically Rich Presentations*

Other researchers recommend including a historically rich curriculum in teaching evolution. In one study involving a college biology survey course, significant student gains in understanding evolutionary concepts were achieved when historical materials in conjunction with conceptual change strategies were implemented. ''It appears that if instruction recapitulates events in the development of the Darwinian theory of evolution by natural selection in a way that meets the conditions for conceptual change, then students replace their initial conceptions with a more Darwinian conception'' (Jensen and Finley 1995, p. 164). A constructivist approach is easy to combine with a historically enriched perspective.

For example, one can ask the students to pretend that it is the 1840s in England, a time when the order from oldest to youngest in the geological record is just being established. Consequently, scientists do not yet know what pattern of changes of kinds of organisms through time will be found. What alternative patterns should they have predicted and on what grounds? This utilizes the first step of the constructivist approach, raising a question that requires a prediction based on the students' own prior conceptions of the more feasible alternatives. The list they come up with (which will include all species present initially and other extrapolations from their existing conceptions) can be enriched historically.

In the present example, two facets of historical enrichment are key. First, the list of alternatives can be enriched alternatives that usually don't occur to the students. Options include cycles of dominance (Lyell) and episodes of total extinction and recreation (Sedgewick). Emphasize that there was no reason other than evolution to expect an ''evolutionary'' sequence. Second, it is important to help students remember or understand that evolution was not really an option yet (except for the young Darwin). Indeed, even in 1859 Darwin still listed the fossil record as a problem for his theory rather than a support. Darwin proposed evolution despite, rather than because of, the fossil record. Consequently, the sequence of fossils that we find in the record is a test not just of their own views but also of Darwin's ideas. Fortunately, Darwin did predict that, if evolution is correct, life must have started with only one or a few very simple forms.

An examination of the patterns of change through time (by readings, lectures, videos, etc.) then corresponds to the constructivist step of testing the array of hypotheses (including Darwin's and the students' and historical alternatives). The conclusion, that Darwin's predictions match the results far better than do the alternatives, then allows students to see how scientists constructed their present understanding of the fossil record as showing evolution and disconfirming the alternatives. Further predictions regarding links or molecular similarities can then be developed by the students and tested with additional datasets, thus continuing in the set of constructivist cycles.

### *Major Complication 1: But What about Content?*

Many instructors who contemplate the active learning steps of constructivist teaching, student-student discussion, concept maps, and historically rich context question how they will have time to incorporate such elements in their teaching and still cover the content they want to teach. There are two general answers to this. The first is that once constructivist processes are worked out by the instructor, a great deal of content can be incorporated into these processes and into outside-of-class assignments. Many faculty make little effective use of textbooks or use class time for lectures that highlight key points in the text. Emphasizing what is important in the text can be accomplished better by giving the students the potential exam questions over the text to use as they read. This will produce content learning (''summarize the nature of the Green River fossil beds and the fauna they contain'') and, given appropriate questions, stimulate a constructivist reexamination of the students' prior conceptions (''how would the deposits differ if they had been deposited in a year-long global flood?'').

The second general answer to the conflict between constructivist teaching and coverage of content is to decrease content. Research indicates that it is far better to decrease the content in order to increase long-term understanding—a ''less is more'' philosophy. In this regard, one pair of researchers found that the increased content of courses for biology majors, compared to the reduced content of biology courses for nonmajors, may not be as beneficial as most instructors would think. The results suggest that ''the nonmajors probably UNDERSTAND basic biological concepts as well as the majors, who are exposed to significantly more detail in the majors' course. The majors simply may be overloaded with details which they do not learn well, and which may even interfere with what they do know'' (Sundberg and Dini 1993, p. 304). Even medical school students appear to benefit from a 30% to 40% reduction in information density, which allows them to better understand the points that are ''essential to know'' (Russell et al. 1984, p. 881). Briefly put, reducing coverage often appreciably increases learning.

### *Major Complication 2: Influence of Religious Beliefs*

Unlike most other concepts in science, student understanding of evolution and much geology appears to be markedly affected by religious beliefs. Numerous studies of college-level students have explored the interaction of science and religious beliefs in teaching and learning science.

In a study involving college zoology students' beliefs about evolution and religion, student religious ''beliefs were shown to interfere with the ability to objectively view scientific evidence'' (Sinclair et al. 1997, p. 118; Sinclair and Pendarvis 1998). The more deeply ingrained the religious teachings, the more the evidence was viewed through lenses different from those of students without contradictory religious beliefs. The researchers consider that due to lack of time and varied helpful experiences to process information in evolution courses, ''for many [students], it is simply overwhelming academically, emotionally, and spiritually'' (Sinclair et al. 1997, p. 124).

Researchers studying biology majors' learning conclude that ''efforts are not likely to affect major cognitive differences in students without actively engaging—neither ignoring nor fighting—other factors [such as religion] that underlie their resistance to the ideas about evolution'' (Dagher and BouJaoude 1997, p. 441). One study found that openly discussing religion in a college-level science course engendered modest growth in students' views concerning the scientific enterprise and ''practically none were offended by how it was treated'' (Brickhouse et al. 2000, p. 354). However, the researchers do not make an unqualified recommendation for this approach because some instructors may have religious beliefs (or antireligious sentiments) that may interfere with a respectful, thus effective, intervention.

In a case study undertaken to examine constructivist transformations in preservice biology teacher views about evolution, the researcher concluded that ''exposing their [preservice teachers'] attitudes, beliefs and values to the light of critical inquiry builds teachers who have a sense of learning—and how students learn'' (Pankratius 1993, p. 7). Another strategy in learning evolution centers on reading a provocative essay on the science-religion topic (including reading some related essays with views differing from the primary essay), with subsequent student writing and discussion about the differing positions. Researchers report that using this technique with science education graduate students resulted in ''conceptual change or improved mental state'' for most students (Loving and Foster 2000, p. 445).

Several other strategies may help. For example, it is important to distinguish between those parts of science that are exceedingly well established (the planets go around the sun in ellipses; humans had invertebrate animals as part of their ancestry) from those that are presently still fairly speculative (how to get a universe or a tRNA mediated genetic system running). This, again, is just part of framing the science we teach within an explicit nature of science context. One advocate suggests using the controversies, and he provides 21 criterion-based comparisons between creationist ideas and normal science. A key research question would ask the extent to which such comparisons actually succeed in getting students to understand and accept the science of evolution (Nelson 2000). A second important question would ask how many such comparisons are needed. Are 20 more effective than 10, and if so, by how much and for what level classes?

Given that about 90% of Americans say they believe in a God, many students will be trying to come to a quasi-coherent integration of their ideas of scientific and religious origins. In our opinion, even those scientists who are inclined towards a purely naturalistic worldview should exercise some caution here. Further, although scientific evidence cannot (at least in our view) support a supernatural worldview, neither can it decisively refute such a worldview (as testified to by numerous theologians and philosophers, within whose realm of expertise this question falls). Some suggest that we provide students with tools that help bridge the dichotomy many of them feel between a scientific and a religious worldview (e.g., Nelson 2000; Alters and Alters 2001).

A warning to faculty is in order. There appear to be some college students who do not increase their understanding of evolution because of their strong antagonism towards its teaching despite instructors incorporating advocated pedagogical practice. Apparently a growing number of these students are well versed in the professional antievolution literature and practices (e.g., creation science, intelligent design theory, scientific creationism, abrupt appearance theory, progressive creationism, and others). More often than not they see the instructor as spreading dangerous falsehoods that have deleterious effects on peoples' lives and afterlives. Their mission is often not to learn evolution but rather to obtain credit for the course without disruption or attempt to persuade the professor and fellow students to realize that the evolution being taught is scientifically, philosophically, and/or religiously insupportable.

## Summary and Suggestions for Further Research

*Active learning.*—Uninterrupted lecturing for 50 minutes (or more) is typically a very inefficient way of facilitating learning. The incorporation of even brief episodes of carefully structured student-student interaction appreciably increases the amount of science students understand and retain. However, current economics and accepted practice in much lower level science teaching favors large lecture classes. Crucial research questions would address how the benefits of active learning can better be realized in such settings. Work in physics education provides a model worth close study as it uses multiple-choice questions as a focus for interaction during frequent pauses in a lecture setting (Mazur 1996). Other approaches worth evaluating initially would include asking small groups to address a series of questions about a graph or table or short reading passage.

*Misconceptions.*—Unless students actively examine their initial conceptions and compare them to standard formulations, the initial conceptions are likely to remain unchanged and may often even distort any related new material that is learned. One key to the success of active learning in physics has been the systematic use of common misconceptions as alternatives in student discussions. In the case of evolution, we hypothesize that failure to actively compare young-earth, fixed-species ''creationist'' misconceptions to standard science is a major factor in the persistence of these misconceptions even among students who have had two or more biology courses. More generally, the questions of what student misconceptions are important and how to effectively help students overcome them merits considerably more research in all areas of biology and geology. (For some of these misconceptions see Nelson 2000; Alters and Alters 2001; Antolin and Herbers 2001.)

*Critical thinking and nature of science.*—Most of the research on learning science has focused on individual concepts that can be seen as right or wrong. In many cases, however, an adequate understanding of science requires the integration of several levels of understanding (e.g., from wobble pairing to population genetics and species conservation). With current pedagogy, undergraduates infrequently reach levels of cognitive understanding that allow such integration to occur spontaneously. Even when we present quick integrative overviews, students typically fail to retain them. Application of scientific concepts to real world problems in contexts such as medical decision-making, genetic policy or counseling, or environmental policy requires further advances in sophistication (Bull and Wichman 2001). In particular, these contexts often involve the requirement to assess the relevance and weight of various trade-offs and values. Most students probably see the interrelation of evolution and religion as requiring just such trade-offs. Several studies provide a background against which hypotheses of how to support the development of critical thinking can be developed for specific classes (Belenky et al. 1986; Baxter Magolda 1992; King and

Kitchner 1994; Baxter Magolda 1999). Nelson (1986, 2000) provides some suggestions for teaching evolution and science generally: making sure that students are explicitly comparing alternative ideas, building the criteria for making the comparisons explicit, and asking about consequences and their relative value. Empirical studies that ask how these higher levels of critical thinking can be better elicited in college science courses are urgently needed.

*Religious complications.*—Because the vast majority of Americans believe in a God, many students will seek some form of compatibility between their ideas of religious and scientific origins. A few studies have shown that religious beliefs appear to interfere with the understanding or acceptance of scientific views, especially for evolution (Lawson and Weser 1990). However, an important research question would ask the extent to which various strategies for addressing religious- and worldview-based obstacles actually succeed in getting students to understand and to accept the science of evolution.

In considering this entire set of issues it is important to ask ourselves whether we wish to produce an understanding of evolution (including its acceptance as the best scientific theory) or the acceptance of unmitigated naturalism as the preferable worldview. We argued previously against the latter. There has been some progress in ways to assess our successes in fostering the acceptance of evolution. For example, an instrument was developed recently to assess high school biology teachers' overall acceptance of evolutionary theory (the Measure of Acceptance of the Theory of Evolution, a 20-item Likert scale). The researchers who constructed the instrument also report the development, validation, and reliability of the instrument. ''The instrument is homogenous, assessing a single construct, which allows for clear interpretation of the results generated from its administration'' (Rutledge and Warden 1999, p. 16). While these researchers warn that it may not be valid and reliable with nonbiology teacher populations, they look forward to possible applicability to other populations. This is a very interesting line of research. However, care must be taken, as difficulty exists with many instruments and polls attempting to measure acceptance of evolution due to the great variety of differing religious beliefs. (For a discussion of these difficulties see Alters and Alters 2001.)

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