OPINION

TEACHING EVOLUTION EFFECTIVELY: A CENTRAL DILEMMA AND ALTERNATIVE STRATEGIES

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ABSTRACT. We will continue to have a public that is scientifically illiterate until we find ways to get faculty in post-secondary science classes to use effective pedagogical approaches. In this article, I present three scientifically and pedagogically valid strategies for helping students evaluate their initial understandings of evolution and to compare those understandings with more scientifically valid formulations. Adoption of such strategies in post-secondary teaching is central to more adequate preparation of future scientists, opinion leaders, and secondary school teachers.

ENSEIGNER EFFICACEMENT L'ÉVOLUTION : UN DILEMME CENTRAL ET STRATÉGIES PARALLÈLES

RÉSUMÉ. Le grand public continuera à avoir une méconnaissance des notions scientifiques jusqu'à ce que nous trouvions des moyens pour permettre aux professeurs qui enseignent les sciences au niveau postsecondaire d'utiliser des approches pédagogiques efficaces. Dans cet article, je propose trois stratégies scientifiques et pédagogiques pour aider les étudiants à évaluer leur compréhension initiale de l'évolution et à la comparer avec des formulations scientifiquement valables. Il est essentiel d'adopter ces stratégies dans l'enseignement postsecondaire afin de préparer les scientifiques, les leaders d'opinion et les enseignants du secondaire de l'avenir.

The level of discourse on scientific issues in a nation's capital is a measure of the success of that nation's post-secondary science education. In developed nations, politicians and government officials almost universally have at least one post-secondary degree, a degree that usually claimed to teach them scientific ways of thinking. Slow and ineffectual governmental responses to various environmental (global warming) and public health issues (smoking, HIV) suggest suboptimal educational success in science. This reflects both the shortcomings of curricula for science majors and inadequate or ineffective science distribution requirements for non-scientists. In the United States, some of the most egregious examples of educational failure are public and governmental responses to evolution as a central scientific concept, to its inclusion in pre-college science education, and to issues where an evolutionary perspective is central to effective policy (e.g., management of HIV and tuberculosis, response to "bird flu," and crop development and management; see Mindell, 2006).

Scientists frequently attribute public misunderstanding of evolution and other scientifically well-supported but publicly controversial conclusions to resistance based on conservative religious interpretations or dubious political motivations. Whatever the force of these sources of resistance, an additional powerful explanation is available. Post-secondary science teaching, like most of post-secondary education, commonly ignores strong, long-standing evidence on effectiveness (e.g., Michael & Modell 2003; Pascarella & Terenzini, 2005; Smith et al., 2005; Springer et al. 1997; Terenzini & Pascarella, 1994; for evolution: Alters, 2005; Alters & Nelson, 2002; Nelson, 2000). Consequently, most college graduates lack tools for rationally comparing conflicting ideas and deciding which arguments, scientific and otherwise, are well founded (e.g., Baxter Magolda, 2001; Perry 1970). The pervasiveness of the mistaken assumption that all conflicting views deserve equal emphasis without regard to their validity is direct result of this failure. Excessive public acceptance of inadequate views is not simply a result of some facets of popular culture. Rather, it is also and more fundamentally the predictable result of ill-founded pedagogical choices.

A FAILED APPROACH: TEACH THE SCIENCE AND IGNORE STUDENTS' PRIOR BELIEFS

The immense array of biological knowledge means that there never is enough time to cover all of the relevant science in any course. In order to facilitate extensive coverage, traditional pedagogy in science relies mainly on didactic presentations and largely ignores students' prior beliefs. As faculty members' own educations have shown, traditional methods are not totally ineffective. However, "conventional methods are *not* as effective as some other far less frequently used methods…. more effective approaches emphasize small, modularized units of content, student mastery of one unit before moving to the next, immediate and frequent feedback to the students on their progress, and active student involvement in the learning process" (Terenzini & Pascarella, 1994). In physics and biology, alternative approaches increase learning by a factor of two or more (pre-test to post-test gain: e.g., Hake, 1998; Sundberg, 2003; for a meta-analysis see Springer et al. 1997). Further, naïve conceptions in science typically persist despite intensive didactic instruction, as demonstrated by literally thousands of studies (Duit, 2006). However, when students make direct comparisons of their naïve misconceptions with scientifically better-founded schemes, change is frequent. These approaches can lead to greater acceptance of evolution (e.g., Ingram & Nelson, 2005; Scharmann, 2005; Scharmann et al., 2005; Verhey, 2005; Wilson, 2005, 2007; Alters, 2005 reviews earlier work). Thus, naïve views predominate publicly with regard to evolution, perhaps even more than elsewhere in science, at least partly as a predictable consequence of post-secondary pedagogical choices that ignore naïve views and are otherwise sub-optimal.

Suboptimal pedagogies have prevailed for a variety of reasons. They are often attractive to post-secondary teachers who may have had little pedagogical preparation. They are attractive to secondary teachers who often aim to teach science the way academic scientists teach and who frequently lack time to develop lessons that utilize more effective learning strategies (important resources are now available free: Flammer et al. 2006 http://www.indiana.edu/~ensiweb). Importantly, creationist attempts to present religiously motivated, non-scientific views as valid science have made many scientists quite wary of any mention of such ideas in any science classes. As Scott and Branch (2003) emphasize, "it is scientifically inappropriate and pedagogically irresponsible to teach that scientists seriously debate the validity of evolution." Legally, intelligent design and other forms of creationism are religious ideas and are barred from presentation as valid scientific alternatives in United States public schools by the Establishment Clause (*Edwards v. Aguillard*; *Kitzmiller et al. v. Dover Area School District*). Further, direct critical examination of religiously motivated, popular misconceptions may make faculty and students uncomfortable and may be politically unacceptable, especially in communities where any extensive presentation of evolution is already contested.

Thus, the low levels of public understanding of evolution and of science generally are often matched with strong faculty reluctance to use educational approaches that research has shown to be most likely to lead to greater understanding and acceptance. The core to any escape from this dilemma is to recognize the difference between presenting creationist ideas as valid scientific alternatives and presenting them as alternative or misconceptions that need to be critically examined. A critical examination of creationism has been forcefully advocated by a recent president of the US National Academy of Sciences: "intelligent design *should* be taught in science classes, but not as the alternative to Darwinism…. It is through the careful analysis of why intelligent design is *not* science that students can perhaps best come to appreciate the nature of science itself" (Alberts, 2006, p. 741).

AVOIDING AN EVEN WORSE APPROACH: TWO EUAL MODELS

Most secondary and post-secondary teachers of science have not seriously examined the logical and evidential limits of modern creationist theories, including intelligent design creationism (IDC), and of ways commonly advanced for presenting them in science classes. They may lack the knowledge required to help students evaluate creationist arguments or even find a "two equivalent models" approach acceptable. Indeed, a key point against a "teach the controversy" approach is that the teachers most eager to teach a two-models approach and the politicians most eager to require its teaching have been creationists who accept the validity of the science-sounding arguments made by the creationists.

Such a presentation is strongly biased against acceptance of evolution. Evolution is set out as the only area of science for which special treatment is required (by textbook disclaimers most egregiously), thus falsely implying that evolution is weaker than the rest of science. Further, although creationist approaches include explicit, though typically fallacious, statements of supposed problems with evolution, it is tacitly assumed that no criticisms of the creationist position will be presented. It is implicitly assumed that no serious attempt will be made to examine the relative validity of the ideas. Specifically, the presumption is that fairness would require teaching evolution and IDC (or some earlier version of creationism) side-by-side and letting students "make up their own minds." In the absence of detailed examination of the logic and purported evidence, this gives unjustified credence to creationist arguments that are dubious, at best.

Because college education has been so unsuccessful in producing graduates who are competent critical thinkers (Baxter Magolda, 2001; King & Kitchener, 1994), much of the public and many politicians and journalists think that whenever there is a controversy both sides should be presented as equally valid rather than as necessitating a consideration of comparative validity. But whenever alternatives are presented in science classes, we are obliged by the goals of both science and education to teach the students how to compare them on the bases of logic and evidence. A brief summary here of some relevant logical and evidential limits will make clear why any "two equivalent models" is the worst approach.

Some fundamental flaws of presenting creationism as scientifically valid

Behe (e.g., 1996, 2003) has produced the most influential biological arguments for intelligent design. He argues, for example, that the bacterial flagellum and the mammalian blood clotting cascade are so complex that they would be non-functional if less complete and, thus, apparently could not have evolved. He concludes that if it appears that these features could not have evolved they must have been designed by some intelligence. These cases of asserted "irreducible complexity" are the key argument advanced for intelligent design in biology, claims on which the entire argument essentially stands or falls. In a class where IDC is introduced, teachers would have to help students examine closely key examples of "irreducible complexity" and the purported supporting evidence and logic.

Behe's argument has three types of problems. One lies in the nature of the intelligence supposedly inferred. Behe (2001, p. 165; 2003, p. 227) states: "I strongly emphasize that it [IDC] is not an argument for the existence of a benevolent God." Rather, "candidates for the role of designer include: the God of Christianity; an angel – fallen or not; Plato's demiurge; some mystical new-age force; space aliens from Alpha Centauri; time travelers; or some utterly unknown intelligent being." He also notes that the designer may or may not be interested in humans.

The high-school teachers with whom I have worked have tried very hard to respect the religious faiths of their students, often to the point of ignoring or underemphasizing evolution. This respect might be difficult to maintain while dealing with the claim that any unexplained design-like features of organisms might be due to an incompetent, inconsistent and evil alien or a fallen angel. Problems with respect for students' views would extend to their reactions to other students' views. Moreover, even if the teacher were adequately prepared and skilled in managing classroom discussions, the general public and school boards and administrations in many areas may be unlikely to support the examination of the idea that the purported scientific "evidence" for design is as compatible with aliens or fallen angels as with their model of God. But this point is central to the claim by the advocates of IDC that that their argument is not religious and, hence, that a requirement for including it in a publicly funded science class might be considered constitutionally permissible (a claim Judge Jones rejected soundly in his decision in the U.S. federal case of *Kitzmiller et al. v. Dover Area School District*: http://www.pamd.uscourts.gov/kitzmiller/kitzmiller_342.pdf).

A second problem with Behe's argument concerns its basic logic when advanced as science. The appropriate logical conclusion when something appears to have no current scientific explanation is not that God or some other designing intelligence must have intervened. Rather, it is that no scientific explanation is yet apparent and that further study may be warranted. Science has a long and glorious record of finding natural explanations for things that seemed to be inexplicable.

Behe (2003) tries to insulate his argument from critique on empirical grounds. Thus, he claims that any underlying intelligence might have designed only some details leaving others to "the vagaries of nature," i.e., to evolution. Thus, the overwhelming evidence in a wide variety of specific cases (whales, for example) that organisms have evolved can be set aside as irrelevant to less well-analyzed cases. Similarly, claiming that any underlying intelligence might or might not be competent serves to protect any claimed evidence of design against the overwhelming evidence that many aspects are not design-like: adaptation frequently has been severely compromised by historical and developmental constraints. An explicit "two-scientific-models" approach would have to note these flaws in Behe's logic. Protecting a theory from empirical testing takes it decidedly outside the realm of science. Difficulties with teacher preparation, management of discussion to maintain respect, and the local political context apply here, too.

A third problem is the failure of explicit empirical claims. Behe, for example, explicitly claims that particular features (flagella, blood clotting cascades, etc.) would be non-functional if less complete and apparently could not have evolved. Miller (1999, 2003) provides a review of the current state of evidence on Behe's major examples, written at a level that is accessible to undergraduate biology students and to science teachers in all fields. He shows that functionally simpler states do exist as do reasonable hypotheses for how the specific systems can have evolved. Detailed scientific reviews of intelligent design claims and strategies have recently been published in major scientific journals for both the immune system and the bacterial flagellum (Bottaro et al., 2006; Pallen and Matzke, 2006; see Matzke, 2006, for a more accessible summary of the latter). These papers show that the claims made by Behe and others were simply mistaken. Thus, even within Behe's own logic, the core claims are decidedly undermined by current evidence.

Two conclusions follow. First as sketched above, and as many have shown in excruciating detail, there is no reasonable scientific case for intelligent design nor for any other form of creationism as an alternative to biological evolution (e.g., Jones, 2006; Kitcher, 1982; National Academy of Science, 1999; Scott & Branch, 2003; Scott, 2004). Kitcher (1982) provides an unusually lucid introduction to the relevant basic philosophy of science, one written for undergraduates. Strahler (1987) provides an extensive and dispassionate analysis of the empirical claims of pre-IDC versions of creationism. His book should be closely examined by anyone who wants to discuss these issues with students. The emergence of IDC has elicited a veritable flood of additional critiques (for example: Miller, 1999; Perakh, 2003; Scott, 2004; Shanks, 2004; Young & Edis, 2004) and several edited volumes featuring a mix of advocates and critics of ID (e.g., Campbell & Meyer, 2003; Dembski & Ruse, 2004; Pennock, 2001).

Second, the key task is to design effective educational interventions that circumvent the problems posed by a direct two-models approach, especially the psychological robustness of alternative conceptions in science as well as those of under-prepared teachers and a social and political climate that favors confusion on the scientific status of evolution. Further, this must be done in a way that respects, but does not necessarily support, a diverse array of religious beliefs among the students and teachers.

THREE ALTERNATIVE STRATEGIES FOR TEACHING EVOLUTION MORE EFFECTIVELY

There are several alternative strategies for teaching evolution that vary in the extent to which IDC or other creationist schemes are explicitly considered and in their probable effectiveness. The appropriate pedagogies have been alluded to above and discussed well in recent summaries (Alters, 2005; Alters & Nelson, 2002; Ingram & Nelson, 2005; Nelson, 2000; Scharmann, 2005; Scharmann et al., 2005; Verhey, 2005; Wilson, 2005, 2007). For conciseness, I will just sketch the ideas in discussing alternative approaches, leaving implicit the assumption that structured discussion and other effective delivery strategies should be used wherever possible.

Strategy 1: Discuss selected misconceptions with only implicit reference to creationism.

One classroom strategy is to choose a few popular creationist misconceptions and help students reconstruct their understandings without explicitly identifying the misconceptions as creationism. Strahler (1987) provides a detailed summary of most common creationist claims, typically with extensive quotations, and carefully evaluates their merits. Three examples will illustrate strategy one.

THERMODYNAMICS. A common creationist claim has been that since evolution claims that organisms have become more complex through time and the laws of thermodynamics require that things move toward increasing disorder, evolution is prohibited by the underlying physics. I found that most pairs of students in a required senior majors course in evolution could not say what is wrong with this argument, even though most of them had completed courses in physics and chemistry in which key aspects of thermodynamics had been taught. (I invite readers to try this with their own classes.)

The implicit reference approach to this creationist claim might note: "one could think that evolution was prohibited by thermodynamics" and even sketch the typical creationist graph of complexity versus time (see Strahler, 1987). I like to ask students to discuss how the formation of salt crystals from the evaporation of seawater by sunlight is compatible with the second law. This leads to the basic scientific point: the flow of energy towards lower thermodynamic states often drives some other components of the system (the salt in this case) toward more organized states. The basic constraint is that the entire relevant system (here including the sun) must move toward decreased thermodynamic order.

Missing links. Similarly, one might note that for a few decades the earliest fossil birds, whales, and humans seemed so different from their potential relatives that it was not clear which fossil or living groups were most closely related to them. This uncertainty was resolved by the discovery of new fossils in sites quite distant from those that had been studied previously (i.e., from new locations in China, Pakistan, and Africa, respectively) and, in the case of whales and humans, by the development of extensive molecular phylogenies. One can also have students examine models of the skulls of living and fossil hominids in conjunction with molecular phylogenies to illustrate how evolutionary trees can be confirmed from multiple sources while implicitly countering the claim that missing links suggest that humans did not evolve (Nelson & Nickels 2001; Nickels & Nelson, 2005). Again, this can be done without explicit reference to creationist claims that these groups (especially humans) and others without clear fossil antecedents were separately created. (Miller, 2003, notes Behe's early views on whales.)

ORGANS OF EXTREME PERFECTION. As a final example, one might start with Darwin's discussion (often misused by various creationists) of the "problem" for his ideas posed by "organs of extreme perfection" and add newer evidence on the origins of eyes, insect wings, cilia, blood clotting cascades, etc. Again, one can do this without noting the use of these or similar examples by Behe or other creationists and focusing instead on potential difficulties or on gaps in popular knowledge.

LIMITS OF THE IMPLICIT REFERENCE APPROACH. The major apparent advantage of such an implicit approach to helping students develop more scientifically adequate views of evolution is also its weakness. It avoids explicit confrontation. But in so doing, it allows students to conclude that although a few parts of what they thought are wrong, the basic argument for creationism is still strong. It also allows them to seriously underestimate the scientific strength of evolution.

Strategy 2: Make evolution and the nature of science central course themes.

We conducted a series of institutes for high school biology teachers, put teacher-tested lessons and other resources on the web (Flammer et al. 2006) and summarized key aspects of our approaches and their effects (Nickels, Nelson & Beard, 1996; Nelson, Nickels & Beard, 1998; Nelson & Nickels, 2001; Nickels & Nelson, 2005). Our premises, refined by working with the teachers, included:

• A clear understanding of the nature of science is an important outcome both on its own and as a way of understanding and defusing some of the controversy surrounding evolution.

• The nature of science should be a central organizing theme for the entire introductory biology course rather than a separate topic confined to just an introductory chapter or lesson.

• Evolution also should be made a central organizing theme for the entire introductory biology course rather than being largely restricted to one or two chapters or lessons that are easily dropped or condensed due to "lack of time."

• Humans should be used repeatedly as central examples of the evidence for evolution.

This combination helped the teachers understand the strength of the scientific support for evolution and the ways in which evolution was needed to make sense of all of biology. Comfort with their ability to explicitly counter creationist claims, should they arise either in or out of class, was quite important in encouraging many of the participating teachers to emphasize evolution. These points deserve some elaboration.

The nature of science. Science operates mainly at two levels. It summarizes empirical patterns (the planets go around the sun in irregular ellipses) and finds causal explanations that explain why those patterns exist (the orbits are due to the interaction of inertia and warped space). Religion has been of no direct help in choosing among alternative patterns nor in elucidating their particular causes. Indeed, attributing the orbits to God's design fails as an explanation precisely because it would apply to any pattern of planetary movement (hexagons, for example) and thus does not explain any of them. This distinction between explanation in the scientific sense and attribution to a supernatural power helps students understand the nature of science and the limits of religion in thinking about the natural world.

Darwin's *Origin* illustrates a particularly powerful use of empirical patterns in supporting a scientific conclusion: he used confirmation by multiple independent lines of evidence as a central argument for evolution. This idea can be used as a theme or organizing principle to connect many different areas of biology, allowing students to understand simultaneously the nature of scientific argumentation and the role of evolution in explaining biology.

The nature of science can be used to frame each topic in biology. Specifically, I like to ask: What are the key empirical patterns that summarize the biology for this topic? What natural causes are used to explain the patterns? What are the exceptions and can they be explained? How have the patterns and causes been confirmed by testing predictions or finding new independent lines of evidence? How else does this illustrate the nature of science? A few examples will make this clearer.

Linnaeus' patterns and Darwin's explanations. Linnaeus found some important interrelated empirical patterns. Organisms occur in "natural" groups, i.e., congruent groups are defined by a variety of different characters (mammals by hair, milk, three inner ear bones, a single lower jaw bone, etc.). These groups are discrete and usually do not blend together (there are no intermediates between mammals and birds, etc.). The groups are also hierarchically nested into larger and larger groups, each of which is also natural and discrete in the same senses (thus primates and rodents are discrete natural groups which nest into mammals, mammals and birds and turtles are each discrete natural groups that nest into amniotes, etc.). Darwin provided the causal explanation (and used the only illustrations in the *Origin* for it): such groups follow from shared common ancestry. All members of each natural group share a common ancestor from whom the characters that distinguish that group were inherited. More deeply nested groups share more remote common ancestors.

These ideas have been confirmed in multiple ways. Predictions implicit or explicit in these patterns include the idea that new characters will confirm the reality of the groupings and that any intermediates found will not link living groups but rather will link living groups to earlier groups. And, indeed, the amino acid sequences of many proteins support the various natural groups. Spectacularly, the implicit prediction that not only are there no living intermediates anywhere between mammals and birds now but that there never were any has been abundantly confirmed. Fossils link mammals backwards though time into a larger group (Synapsida) and birds link backwards into a group of dinosaurs. Synapsids and dinosaurs in turn link backwards into more primitive groups and not laterally into each other. Similarly, Darwin's causal analysis has been deeply confirmed by DNA. The nested trees from DNA sequences confirm the inherited basis of the similarities and allow us to refine the nested, natural groups (refine in the sense of resolving ambiguities such as which groups of lizards are closest to snakes). Much of the intuitive resistance to evolution centers on human evolution for both for psychological reason ("not me!") and theological reasons including original sin (Nelson, 1986, 2000). Hence, it is especially important to use humans and other primates to illustrate the concepts of discrete natural nested groups (Nelson & Nickels, 2001; Nickels & Nelson, 2005).

Saying, as Linnaeus did, that God created organisms in these particular groups does not explain why the groups are natural (rather than different for each set of characters), nor why they are discrete (rather than laterally merging), nor why they are hierarchically nested (rather than just different). It took Darwin's causal explanations to do that. This is another example of the idea that attributing a natural pattern to God is not a substitute for a scientific explanation of that pattern.

Centers of creation and Darwin's explanations. Darwin observed for himself, especially with rheas and with the fauna of the Galapagos Islands, a previously well-known pattern. Related species tend to occur in geographic proximity as do, to a slightly lesser degree, related genera. Similarly, as Darwin observed for South American fossils related to armadillos (a Neotropical group), current members of a group often occur in geographic areas inhabited earlier by related forms. Before Darwin, these patterns were attributed to God's choice of particular areas as centers of creation. Again, however, attributing a pattern to God actually provides no explanation for the existence of this particular pattern instead of another. Indeed, any other pattern, ten species of kangaroo on each continent, for example, could equally well be attributed to God's whim. Darwin used the descent of similar forms from a shared common ancestor to explain these biogeographic patterns. There are a number of clear exceptions to the patterns. Most are in groups in which long distance dispersal is more likely and, often, has been verified. Humans enter again because Darwin suggested that the fossils linking humans to the great apes were especially likely to be found in Africa where our closest relatives occur. Indeed, such fossils were found in Africa several decades later.

Paley's Watchmaker and Darwin's explanation. Paley (1802) summarized many adaptations and argued that they could not have occurred by chance but were instead evidence of design by a creator (an early version of IDC). Darwin agreed that many features of organisms were adaptive but explained the origin of adaptations by heritable variation and natural selection. He also pointed out that many features of organisms were not directly adaptive but rather were characters inherited from ancestors that now had no adaptive significance or even compromised adaptation. Evolution can explain both the design-like and the design-contrary aspects of structure and function.

Multiple lines of evidence and clear causes. In order to help students understand the full strength of the evidence supporting evolution, it is important to help them understand that evolution is supported by multiple lines of independent evidence, which, in turn, allows evolution to explain multiple facets of biology. That makes it important to set side-by-side Darwin's explanations of Linnaeus' groups, of biogeography and paleo-biogeography as represented by centers of creation, of Paley's list of adaptations and of many of the limits to adaptations, of the groups of fossils that can be expected to have occurred and, more importantly, of the groups we can imagine that never existed (bird-mammal links for example). All of the important fossil links were found after Darwin published the *Origin* in 1859. Even *Archaeopteryx* was only reported in 1861. Much more recently, molecular biology has provided strong confirmation of most of these patterns. Most spectacular has been the discovery that genetic change has been so slow that every organism's genome preserves a record of its affinities that is much more comprehensive and demonstrates far more distant affinities than anything that was possible with morphology and fossils. The very close genetic affinity of chimpanzees and humans confirms our biological roots, as does the mix in humans of adaptive and non-adaptive features.

It is also essential for students to understand how far we have come with causal explanations. Darwin had two key processes: natural selection (he had no clear natural cases) and the tendencies of organisms to both resemble their parents and other ancestors and to vary somewhat from their siblings and other relatives. However, his causal explanations for these resembling tendencies were speculative and inadequate (and included inheritance of acquired characteristics; pangenesis). Biologists subsequently linked resembling tendency first to abstract genes, then to genes on chromosomes and, much later, to DNA sequences. DNA provides a deep causal explanation for why groups of organisms that share a common ancestor *must* resemble each other and *must* differ from groups that do not share that ancestor. DNA also explains many developmental and other inherited limits to the perfection of adaptation (see e.g., Dawkins, 1986). A core kit of developmental genes shared by all animals (and, in part, with plants and fungi) and used in different ways at different developmental times both within an organism and among groups makes evolution both simpler (many fewer total genes have evolved) and more complex (Carroll, 2005). Molecular biology has also allowed the documentation of multiple modes of speciation (Coyne & Orr, 2004).

Newton, Darwin, and Einstein. The nature of science and the significance of Darwin's achievements can be made clearer by comparisons among various scientific breakthroughs. Newton provided a causal explanation (the interactions of inertia and gravity) for a previously well-verified empirical pattern (planetary motion). In a precise parallel, Darwin provided a causal explanation (inheritance from shared common ancestors) for the empirical patterns that Linnaeus had clearly delineated. Similarly, Darwin used inheritance and natural selection to provide a causal explanation for the pattern of extensive adaptation that had been summarized by Paley. In these and other ways, Darwin was the Newton of biology. However, the causal processes that Darwin identified (inheritance from common ancestors, variation and natural selection) turned out to apply to nearly all aspects of biology. These forces united classification, morphology, behaviour, physiology, and geographic and paleo-geographic distributions and applied to all groups of organisms. Darwin thus achieved in biology a general synthesis of the scope and significance that Einstein later achieved in physics. Thus, Einstein was the Darwin of physics.

The strength of the support for evolution can be made even clearer by comparisons with the movement of the planets around the sun. Because so much information has been retained in the fossil record and in genetic sequences and in other data, more independent lines of evidence show that we have evolved from organisms much simpler than fishes than show that the planets go around the sun. Further, the causal bases for evolution are more deeply understood than are those for planetary movement. Newton had "falling tendency" which he quantified and renamed gravitation but was unable to explain. Physicists are still debating the nature of gravitation (i.e., do gravitons really exist?). In a close parallel, Darwin had only a resembling tendency connecting offspring to parents and more distant ancestors with no clear causal understanding of why that happened. However, that resembling tendency has now become a physical necessity. Due to the inheritance of DNA, you *must* resemble your biological ancestors. We know this so firmly that we routinely use DNA to establish paternity and accept its results over all verbal and circumstantial evidence. Hence, if it is a fact that the planets go around the sun, evolution is an equally strongly supported fact. If, instead, evolution were seen as "just" a theory, as the creationists suggest, the idea that the planets go around the sun (and most other major scientific ideas) would also have to be seen as "just" a theory but as one with a less fully understood causal framework. Actually, in science we regard both planetary motion and evolution neither as facts nor as "just theories" but instead see them both as inferences that are so strongly supported empirically and so well understood causally as to be presently beyond all reasonable scientific doubt.

ADVANTAGES AND LIMITS OF STRATEGY 2. This approach makes evolution and the nature of science and the interactions between them central course themes. Much of the same content is taught but each block is now framed within these themes. This makes it easier to prioritize content. The aspects of the nature of science that must be taught are those needed for the larger picture. This means that the scientific method and the nature of "theory" can be ignored unless the teacher is going to use them repeatedly. Similarly, biological content can be partially pruned to emphasize first the aspects that allow the students to understand the larger framework.

Explicit mention of creationism can be minimized or even eliminated with this strategy. Rather, the emphasis is on understanding scientific reasoning and its applications to evolution. Nevertheless, in systematically showing the scope and strength of the science that supports evolution, most common creationist misconceptions can be countered. And an emphasis on scientific explanation *versus* religious attribution cuts to the heart of design arguments.

The literature on scientific misconceptions (Duit, 2006) makes it seem very likely that this approach will be more effective in producing biologically literate public than will any of the approaches discussed earlier, given comparable pedagogies. However, that claim should be treated as an hypothesis in need of empirical verification. Recent empirical studies suggest that more explicit countering of arguments or misconceptions against evolution will be even more successful (Ingram & Nelson, 2005; Scharmann, 2005; Scharmann et al., 2005; Verhey, 2005; Wilson, 2005, 2007). However, empirical studies comparing different strategies are badly needed. Ultimately, biologists should follow Sundberg (2003) and others in a move toward empirical comparisons of alternative strategies for teaching evolution comparable to those summarized by Hake (1998) for physics.

Strategy 3: More direct consideration of creationist claims

This strategy adds several tactics to the approaches of strategy two. These tactics collectively have two main goals. One goal is to make explicit the failure of creationist arguments in the realm of science. The second goal is to make it easier for students to change towards more fully scientific positions by helping them bridge the gap that many of them see between religious creationism and anti-religious evolution. My own classroom approaches to these goals (Ingram & Nelson, 2005; Nelson 1986, 2000) are paralleled in part by those of several others (Alters, 2005; Scharmann, 2005; Scharmann et al., 2005; Verhey, 2005; Wilson, 2005, 2007).

TACTIC 1: UNDERSTANDING BEFORE BELIEF. I found it helpful to frame a course carefully. I noted on the first day and in the syllabus that my main goal was not to get students to accept evolution. Rather, my task was to get them to understand how evolution is central to biological understanding and why most scientists have decided that evolution is a good theory. Further, I wanted them to understand and be able to explain the extent to which evolution is weak science, normal science, or great science. Finally, I asked them to take these same approaches to each important scientific idea. Deciding whether to accept evolution before they understood these things would be premature. More importantly, it would make it harder for them to learn the basic critical thinking processes that scientific reasoning encompasses. Although I used this tactic as part of strategy three, I would suggest that teachers consider using it with any strategy that teaches evolution. I used it with freshman seminars, an introductory biology course, and a majors course on evolution.

TACTIC 2: DIRECT COMPARISONS WITH CREATIONISM. One approach to direct comparisons is to provide creationist readings pertinent to any of the points addressed by strategies two and three. I have used extensive student discussion of two examples that would be easy for others to adopt directly. Gould's (1985) essay, "Adam's navel," includes extensive quotes from a pre-Darwin scientist who argued that the fossil record had been created intact as a necessary part of creating an earth that had the appearance of age. Gould provides a sympathetic refutation. Discussions of this article have been quite successful. Gould's (1993) edited summary of fossil history is distinguished from most similar books in part by extensive descriptions of the key fossil assemblages and of their depositional environments. Discussions of how the differences between the deposits can or cannot be explained on the assumptions of evolution and on those of flood geology help students understand the vacuity of flood geology. Verhey (2005) had students read and discuss selected IDC arguments with critiques thereof. Good choices would be excerpts from Behe (1996, 2003) and Miller (1999, 2003). Wilson's (2005) course extensively and successfully compares evolutionary and non-evolutionary (not just creationist) accounts of such controversial topics as human social behaviour and the functions of religion.

TACTIC 3: NO NECESSARY CONFLICT. Many students believe that religion and evolution must have a fundamental conflict. It is important to show that this is false. Although there are many statements from individual scientists and several official statements from scientific organizations to this effect, the most helpful are from the religious side. Matsumura's (1995) collection of statements in support of evolution includes a number of official statements both from scientific organizations and from religious denominations. Miller (1999) carefully explains both why IDC is specious and how he reconciles evolution with his Christian beliefs without compromising evolution. Student reactions to excerpts have been quite good. Zimmerman (2006) collected signatures from over 10,000 Christian clergy from a wide array of denominations affirming, in part: "the timeless truths of the Bible and the discoveries of modern science may comfortably coexist…. evolution is a foundational scientific truth, one that has stood up to rigorous scrutiny…. To reject this truth or to treat it as 'one theory among others' is to deliberately embrace scientific ignorance and transmit such ignorance to our children." He has also assembled scores of pertinent sermons and articles written by the signatories and lists resources they recommend. Many have direct links to full text.

TACTIC 4: BRIDGE THE DICHOTOMY. Many students see a chasm between Biblical creationism and anti-religious evolution and have never examined any intermediate positions. I have presented and explained a multi-position gradient (young-earth creationist, progressive creationist, theistic evolutionist, non-theistic evolutionist, and atheistic evolutionist) to encourage students to decide what kind of creationist, if any, that they currently are (Nelson, 1986, 2000). Verhey (2005) modified this gradient slightly and used it to construct a survey of student attitudes.

TACTIC 5: BASIC DECISION THEORY. Decisions on which ideas to adopt from among an array of competing positions must take into account the costs and benefits of the ideas as well as their relative probability. I have used a hypothetical rusty hand grenade to illustrate the importance of considering consequences as well as probabilities (Nelson, 1986, 2000). Although evolution is the essential idea for a biological scientist, its value to non-scientists is not immediately apparent to many students, who may see only negative religious costs. Fortunately, the authors of a popular recent evolution textbook (Freeman & Herron, 2003) have greatly increased their emphasis on applied evolution. For example, they open with a chapter on HIV and evolution. Bull (1999) provides a concise overview of applied evolution that is useful in many contexts. Mindell (2006) and Wilson (2007) provide extensive, current treatments.

CLOSING COMMENT

None of the strategies I advocate is a classic "two-models" or "teach the controversy" approach in the sense of treating any creationist models as valid scientifically. As noted in the introduction, I have found no creationist framework that can be rationally treated as equally valid. I hope that even those who are deeply opposed to explicitly presenting IDC or other creationist frameworks in public school science classes will find attractive some variant of the strategy (two) that makes evolution and the nature of science central course themes, ideally one that at least implicitly considers many creationist claims. Most of the high school teachers with whom we worked in summer institutes adopted some variant of this approach. However, I would suggest that teachers of post-secondary biology classes and of intensive, college-preparatory, secondary biology classes should seriously consider using at least some of the tactics summarized under strategy three. Although more evidence is certainly needed, it seems to me that only with these or similar tactics will pre-service teachers and future parents and opinion leaders be adequately prepared to address policy issues concerning evolution. Further, learning to explicitly compare and evaluate positions on controversial issues is a key advance in critical thinking (Baxter Magolda, 2001; Nelson, 1999), one that is important for policy issues and for professional competency well beyond evolution.

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