# EVOLUTION

*INTERNATIONAL JOURNAL OF ORGANIC EVOLUTION*

**PUBLISHED BY**

**THE SOCIETY FOR THE STUDY OF EVOLUTION**

**Vol. 55** **December 2001** **No. 12**

*Evolution*, 55(12), 2001, pp. 2379–2388


# PERSPECTIVE: EVOLUTION'S STRUGGLE FOR EXISTENCE IN AMERICA'S PUBLIC SCHOOLS


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*Abstract.*—The ongoing creation-evolution controversy in North America thrives on the widespread special creationist beliefs of a significant portion of the public. Creation science supports a literal interpretation of the Judeo-Christian Bible, an earth that is no more than 10,000 years old and created ex nihilo in six days by a monotheistic God, with no new kinds arising since the period of creation, and with a single flood of staggering force shaping layers of rocks and trapping the organisms fossilized within them. Despite decisions in numerous court cases that specifically exclude creationism and creation science from primary and secondary biology classes in America's public schools, creationists now work locally to minimize or remove evolution from science teaching standards. The nationally organized movement to resist the teaching of evolution has proven highly effective, influencing state and district school boards in addition to individual teachers and schools. Thus, if teaching about evolution and the nature of science is to survive in America's primary and secondary schools, scientists must likewise work with teachers and reach out to state and local school boards. In this perspective we outline the typical creationist arguments we encounter from students, teachers, school board members, and neighbors. We explain briefly how knowledge of both microevolution and macroevolution is important in medicine, agriculture, and biotechnology. We describe a science education controversy that arose within our own school district, how we responded, and what we learned from it. Finally, we argue that even modest outreach efforts to science teachers will be richly repaid.



*Key words.*—Creation science, education outreach, primary and secondary schools, science education, special creationism.

Received July 17, 2001. Accepted August 15, 2001.


In August of 1999, the Kansas State Board of Education adopted science teaching standards that excluded most requirements for testing knowledge of evolution in its public schools. At the time, one of us (MFA) was visiting the University of Helsinki in Finland, and the incredulous Finns asked ''What is going on over there?'' The answer is complex and highly political. Scientists outside North America are rightly perplexed by a society that juxtaposes stunning scientific achievement with public rejection of the cornerstone of biological science. The ongoing creation-evolution controversy has roots in three aspects of American society: widespread scientific illiteracy, a core value of fairness in public discourse, and the prevalence of religious values in American politics (Kitcher 1982; Numbers 1993; Futuyma 1997; Scott 1997; Pennock 1999; Ruse 1999; Eldridge 2000; Alters and Alters 2001). Most Americans (83%) agree that evolution in some form should be taught in schools, yet fewer than half can correctly identify creationism or evolution (People for the American Way 2000). Of those supporting evolution, some (17%) think both evolution and creation should be taught as scientific theories. Another 16% support excluding evolution and teaching only creationism, which means that one-third of the American public thinks creationism should be part of the science curriculum in our public schools. Alarmingly, the same proportions occur among primary and secondary school teachers, a third of whom either resist or avoid teaching evolution (Weld and McNews 1999). Furthermore, positions have hardened and half of those surveyed state that their minds are ''completely made up'' on the issue (People for the American Way 2000). In America, large numbers of people misunderstand the process of science and therefore fail to understand how evolution fits into mainstream science.

The result is that teaching the science of evolution is endangered in American public schools, despite having survived numerous courtroom challenges. Most aspects of the creation-evolution controversy are not new; discussions about theistic versus materialistic views of nature long pre-

ceded the publication of Darwin's *Origin of Species* in 1859 (Eiseley 1958; Ruse 1999). Although scientists have accepted evolutionary theory for more than a century, challenges to teaching evolution in science classrooms recur with depressing regularity. Creationists exploit widespread misconceptions about evolution to wedge their religious views into local curricula, school board policies, and science teaching standards. Our experiences with university students and teachers in our own school district suggest that most evolutionary biologists in America confront creationist thinking during their professional lives. Evolution's struggle for existence in American public schools continues without prospect of an end, and we call on our fellow evolutionary biologists to reach out beyond their laboratories and classrooms to ensure its survival. What is at stake is more than just evolution; this debate is fundamentally about how science is taught in primary and secondary schools.

Here we have four goals. First, we outline the most common arguments creationists use to attack teaching evolution in public schools. Second, we illustrate how the poor understanding of evolution broadly impacts other areas of biological science. Third, we describe a creation-evolution controversy that arose within our own school district in Colorado, how we responded to it, and what we learned from it. Fourth, we make a number of recommendations for how scientists can become engaged in outreach. We write from the perspective that science and religion provide different ways of viewing the world, but they do not necessarily conflict (see also Matsumura 1995; Gould 1999; Miller 1999; Pennock 1999; Ruse 1999, 2000). Overall, we assert that understanding the creation-evolution controversy and engaging in outreach to primary and secondary education is a responsibility of every practicing scientist.

We start with definitions. In order to discuss science education, we must define what makes up scientific inquiry. We find William Overton's (1982) language in the court decision in the case of McLean versus Arkansas Board of Education (529 F. Supp. 1255 [ED Ark. 1982]) to be clear, concise, and practical:

> Essential characteristics of science: (1) It is guided by natural law; (2) It has to be explanatory by reference to natural law; (3) It is testable against the empirical world; (4) Its conclusions are tentative, that is, are not necessarily the final word; and (5) It is falsifiable.

The same definition was used in the Supreme Court decision in 1987 to put a permanent injunction against so-called equal time laws, which required creation science to be taught if evolution is included in science classrooms (Edwards vs. Aguillard, 482 U.S. 578 [1987]). Overton's five criteria have tremendous heuristic value, although some philosophers of science exclude falsifiability as a necessary criterion (Depew and Weber 1995; Gould 1999; Pennock 1999). Falsifiability cannot be applied to explanations of single historical events like those from paleontology, geology, or astronomy in the same way it is applied to present-day experiments that can be replicated. Even so, individual predictions and hypotheses based on historical explanations can be falsified if they fail to be supported by observations of the natural world. Thus, Overton's definition of scientific inquiry is extremely useful for teaching about the scientific method, the interdependence of experiments and observations, and the limits of the scientific enterprise.

Within that context, we define the theory of evolution as a series of explanations of natural forces that result in descent with modification of living organisms (see also Linhart 1997). A nonexhaustive list of study topics subsumed by the theory of evolution includes: adaptation by natural selection; genetic drift and changes that result from chance events in small populations; mutation and neutral variation within and between populations; rates of change within lineages; rates of divergence between lineages; phylogenetic relationships among populations and species; and analysis of the history of life as recorded by geology, the fossil record, and analysis of DNA. A list of topics addressed by creationists would be much longer because the diversity of opinion on how supernatural forces might shape our world far outstrip the differences among scientists (Numbers 1993; Scott 1997). We define special creationism as the idea that supernatural forces play a direct and leading role in shaping the history of life (Johnson 1993). Within that rubric, creation science refers to the idea of an Earth that is no more than 10,000 years old and was created ex-nihilo in six days by a monotheistic God; on this Earth no new kinds have arisen since the period of creation and that a single flood of staggering force shaped layers of rocks and trapped the organisms that are fossilized within them. Clearly, creation science posits evidence consistent with a literal reading of the Judeo-Christian Bible (Overton 1982); it thereby deviates not only from scientific evolution theory but also from every other creation scenario.

## Creationist Arguments

We repeatedly face creationist challenges. The arguments depend on misunderstandings of science used by creationists to convince the American public that creationism has a place in science education (also see Godfrey 1983; Scott 1997; Alters and Alters 2001). Although creationists cannot agree on the form that creationism should take (e.g., young-earth Biblical literalists vs. day-age creationists), they often agree on how to oppose evolution (Scott 1997). Here we describe commonly repeated challenges to evolution that are used to oppose teaching evolution, and appropriate responses to the challenges.

*Evolution is just a theory.*—In vernacular usage, a theory is an ''educated guess'' or supposition, like a theory of how a crime was committed or why our favorite sports legend failed to score the winning points. In science, we reserve theory for logically consistent statements about Nature that have withstood multiple empirical tests. Creationists exploit the blurred distinction between vernacular and technical usage of theory to cast doubt on the scientific validity of evolution. A typical example is the disclaimer glued into science textbooks in Alabama: ''Evolution is a controversial theory some scientists present as scientific explanation for the origin of living things, such as plants, animals, and humans. No one was present when life first appeared on earth. Therefore, any statement about life's origins should be considered as theory, not fact.'' Denigration of the term ''theory'' is a key strategy

of the creationists, and it is incumbent on us to use it correctly.

*Evolution describes origins of living matter.*—The origin of life remains poorly understood relative to the history of life after its origin. Evidence from geology, astronomy, and physics shows the earth to be about 4.5 billion years old (Zubay 2000). Complex life forms first appeared in the first billion years of earth's history, and the theory of evolution mainly describes events and processes in the following 3.5 billion years. It is possible to synthesize amino acids from mixtures of hydrogen, ammonia, methane, and water, as in the famous Miller-Urey experiments. Other experiments demonstrate the plausibility that most complex biological molecules could have arisen from ''primordial soup.'' Even so, most hypotheses about the origin of life from nonliving matter lie outside the main body of evolution theory. For example, the contents of volume 54 (2000) of *Evolution* comprise 192 primary research articles, but not one that concerns the origins of life. Regardless, creationists commonly point to the relatively modest evidence about the origins of life to bolster their claim that the entire theory of evolution is poorly supported. The disclaimer in Alabama textbooks exemplifies this tactic. Similarly, intelligent design proponent Michael Behe promotes his idea of ''irreducible complexity'' (described below) by defining evolution as ''a process by which life arose from nonliving matter and subsequently developed entirely by natural means'' (Behe 1996, p. xi).

Creationists follow their origins of life argument with so-called improbability analyses to ''prove'' that life must have been specially created (e.g., Behe 1996). The starting point is a truism: Given all possible alternative Universes, each of infinite size, the probability of life arising by chance on this planet at the time it did is infinitesimally small. However, they proceed to argue that an infinitesimally small probability at every point in time and space is equivalent to impossibility across all points in time and space (Robson 2000). Not only is this conclusion false, calculations of the probability of life arising by chance are meaningless. Uncertainty about early earth history (marginal probability) means that no one can assign overall probabilities for the origin of life with any degree of confidence (Bailey 2000; Carrier 2000). While these subtle and perhaps arcane arguments are not discernable to the average citizen, the creationists' conclusion that life is impossible because it is highly improbable is abysmal science.

*Evolution means ''Nature red in tooth and claw.''*—Tennyson's phrase, written ten years before the publication of Darwin's ''Origin of Species,'' decries a cold and cruel world, just as did Thomas Hobbes two centuries before: ''No arts; no letters; no society; and which is worst of all, continual fear and danger of violent death; and the life of man, solitary, poor, nasty, brutish, and short.'' Clearly, the issue of evil in the world preceded Darwin, but to some the idea of natural selection as a mechanism of evolution runs completely counter to notions of a ''peaceable kingdom.'' The prospect of a morally bankrupt universe inferred by creationists from this view of evolution has long provoked opponents of evolution, including William Jennings Bryan in the Scopes' trial (Numbers 1993) and the present-day writings of Philip Johnson (1993). There are two responses to this view. First and most important, the theory of evolution says nothing about nature's purpose or the meaning of life. Evolution is restricted to description and prediction of conditions that promote descent with modification. Second, the natural world contains many examples of cooperation (Kropotkin 1903), and in many cases we can predict that cooperation will evolve from competitive, predatory, or parasitic relationships between species (Hamilton 1964; Dugatkin 1997).

*Evolution means ''survival of the fittest.''*—Herbert Spencer, an economist, coined this unfortunate phrase to encapsulate the idea of natural selection. ''Survival of the fittest'' became a rallying cry of laissez faire capitalists during the 19th century, racists in the 20th century, and others, as an extension of natural law to justify exploiting or exterminating weak and undesirable members of society. The excesses of social Darwinists led to early antievolution laws promoted by William Jennings Bryan (Numbers 1993; Gould 1999). As recently as March 2001, the presumed link between Darwinian theory and social policy was the rationale offered for an antiracism resolution before the Louisiana legislature (H.C.R. 74); fortunately, the resolution passed only after anti-Darwin and antievolution statements were removed. Deciding who in human society is fit and deserves to survive is a social, ethical, and perhaps criminal enterprise that reflects values of human culture at particular times in history. Natural selection is one mechanism of evolution; using it to justify social policies is a perversion of science.

*Evolution is atheism.*—Darwin understood and feared that many people would equate evolutionary theory with the rejection of God, and this claim remains a centerpiece of creationist objections. Philip Johnson, a retired law school professor from Berkeley, in his book *Darwin on Trial* (1993) describes evolution as purely a philosophical ideal, called ''materialistic naturalism.'' Johnson invokes the typical creationist claim that to be an evolutionist one *must* be an atheist, and that materialistic naturalism is the core value that leads evolutionists to reject creationism. Yet many scientists are theists (Miller 1999; Alters and Alters 2001), and most religious and scientific groups recognize that science and faith comprise separate domains (Matsumura 1995; Gould 1999; Ruse 1999, 2000). Science is silent concerning religious and moral issues—at most, the theory of evolution is agnostic. We quote Arthur Shapiro (1987):

> Note that the minimum set of materialistic beliefs [enumerated above] neither denies nor excludes the possibility of the supernatural; it ignores it. Since the supernatural Creator by definition falls outside the realm accessible to scientific method, science per se neither affirms nor denies the existence of God. This was perfectly clear to the liberal Presbyterian theologian James Woodrow when he made his famous defense of Darwinism in 1884, and it is no less clear now. Some individual scientists may have personal quarrels with religion; some may carry their materialistic ideology an additional step and declare their belief that God does not (or cannot) exist. That is their right, but it is not science that compels them to do so.

Recognizing the clearly distinct domains of science and religion characterizes those scientists who are religious and

those religious leaders who accept evolutionary theory as an explanation of the natural world (Gould 1999; Miller 1999; Eldridge 2000; Ruse 2000). Scientists, clerics, and philosophers who conflate science and religion do a disservice to both.

*Only two scientific alternatives exist: evolution and creation science.*—This tactic appeared in the 1960s in *The Genesis Flood,* by John Whitcomb and Henry Morris (1961) which invigorated the creation-science movement. Creation science, which reframes geology and the history of life in light of biblical literalism and a young earth (Numbers 1993), became the primary creationist alternative to evolution after the Supreme Court in 1967 struck down state laws banning the teaching of evolution (including the law in Tennessee that resulted in the 1925 Scopes trial). The result was enactment of equal-time laws that required public schools to teach both creation science and ''evolution science.'' These laws were overturned in the U.S. Courts of Appeals (McLean vs. Arkansas 1982, see Overton 1982) and the U.S. Supreme Court (Edwards vs. Aguillard 1987) as ''serving no secular purpose'' and violating the Establishment Clause of the U.S. Constitution, which prevents governments from either establishing or restraining religion.

Equal time arguments represent an egregious misunderstanding of the scientific enterprise because they posit *only* two alternatives: creationism versus evolution. Creation science claims that evidence for evolution is weak and therefore the alternative, creation, must be correct. This rhetorical trick, used in debates by creationists like Duane Gish, imposes a dualism that is quite simply bad science. Scientific theories do not gain support purely by refutation of other theories. Rather, good scientific theories gain because of internal logic and because of consistency with observations of nature. To achieve primacy, a theory must be superior to numerous alternatives. To be sure, individual experiments contain within them a dual structure (A or B), designed to lead to strong inference from falsification of one alternative. Yet any single experiment is embedded within a network of data collection that includes many plausible and testable alternatives. We could not imagine a college-level course in evolution that considers only two scientific alternatives, nor could we imagine a public school science curriculum that would be constrained in the same way. Scientific honesty requires creation science to produce data that support their theories of biblical literalism and refute *all other* faith-based stories of life's origin—not to mention refuting evolutionary theories.

*Teaching creationism is only fair.*—Fairness is a fundamental value in American society. We have equal-access laws and equal-funding laws, and we strive in our political discourse to allow every voice to be heard. Opponents of evolution have exploited this value. In November 2000, an advertisement for an ''intelligent design'' (ID) conference at Yale University entitled ''Science and Evidence for Design in the Universe,'' began with a call for fairness: ''Scientific inquiry has always included a fundamental openness to new theories and a willingness to explore a wide range of possibilities. A great success of the scientific enterprise is a tribute to this spirit.'' The brochure describes fresh evidence for ID and recent attention paid to it by scholars, implying that it is only fair that the ''new'' ideas be fully considered. Fairness in science, however, is only afforded to competing ideas that are supported by evidence. Discredited scientific ideas are not given equal time! In science classes we do not teach flat-earth theory, the theory of phlogiston, or pure Lamarckian inheritance, except to give students a historical context for understanding modern science.

*Scientific debate is a sign of weakness.*—One of the most enduring (though hardly endearing) aspects of science is that all ideas are continually held up to skepticism, testing, and debate. Creationists often interpret criticism and disagreements among scientists to mean the foundations of evolutionary theory are crumbling away and the slightest push will topple the tower. In the early 1900s, fundamentalists used feuds between Mendelians and Biometricians (see Provine 1971) as a reason for promoting laws that banned the teaching of evolution (Numbers 1993; Gould 1999). Today, creationists use scientific disagreements over tempo and mode of evolution as evidence that evolution theory itself is under dispute, often quoting evolutionary biologists out of context (e.g., Bethel 1985). In reality, disagreements about how to study adaptation, how to define species, or how to interpret the fossil record signal that evolution is healthy science. Debate is intrinsic to the culture of science; ultimately it is how authority in science is decided. Theories that stand up to constant scrutiny and are supported by data are the ones that become authoritative.

*Evolution has never been tested.*—Creationists claim that evolution has never been scientifically tested (e.g., Johnson 1993). In this case, creationists define evolution narrowly as ''Darwinism,'' Darwin's original idea that natural selection acts on relatively minor differences between individuals, leading to gradual changes over long periods of time. But evolution, even Darwinian gradualism, has been compared by scientists to alternatives and has withstood critical testing. In the mid-1800s, scientists accepted the idea of descent with modification by natural selection after alternatives, including Lamarck's inheritance of acquired characters and Owen's archetype, failed to match empirical observations. Darwinian gradualism, however, does not fit all patterns of evolutionary change, and the scientific debates surrounding the details of heredity and speed of phyletic change have emboldened creationists to claim that data do not fit *any* evolutionary scenario. Implying that evolution includes *only* Darwinian gradualism paints a false picture of modern evolutionary biology and ignores advances in theory like genetic drift, neutral evolution, and punctuated equilibrium, to name a few. Post-Darwinian discoveries of multiple tempos and modes of evolution have enriched rather than discredited Darwin's theory of evolution.

*Microevolution and macroevolution define nonoverlapping areas of study.*—In our experience, most people quickly grasp that natural selection can produce changes within species, and creationists generally accept adaptation by natural selection (e.g., Behe 1996; Johnson 1993). Evolution within populations, or microevolution, has been demonstrated experimentally and thus is hard to dispute. In contrast, ideas of common descent among life forms and splitting of lineages into divergent species, or macroevolution, are seen as separate and are rejected by creationists. Creationists dispute evidence for common descent and/or speciation because no

one has done an experiment that directly recreates these aspects of evolution. There are two responses. First, the theory of evolution forms a continuum from small-scale allele frequency changes within populations to large-scale phylogenetic changes between lineages. The creationists assert a false dichotomy between micro- and macroevolution; data supporting any point in the evolutionary continuum reinforce the general theory of descent with modification. Second, the requirement that sound scientific inference is derived *only* from experimental evidence is misleadingly narrow. Entire branches of science (e.g., astronomy, meteorology, and ecosystem science) are conducted primarily outside the context of experiments. These disciplines use historical inference, logical deduction, and observation-based testing of predictions to study natural systems that cannot be manipulated. Creationists equate the scientific method with ''experimentation,'' ignoring that science involves testing of explanations against the natural world, whether the data are collected from experiments or observations of nature. In many cases, scientists conduct ''natural experiments,'' depending on unusual events in nature to test hypotheses. Insisting that ''true science'' only proceeds by controlled experimentation in laboratories represents another fundamental misunderstanding of how science proceeds.

The creationist tactic of falsely separating micro- from macroevolution has led to science teaching standards that include language about adaptation and natural selection while omitting language on common descent. Rejection of common descent and speciation causes creationists to reject concepts like homology. For instance, Behe (1996) never uses the term in *Darwin's Black Box,* but instead refers to the duplicated genes of the hemoglobin gene family as analogous. We describe below how this stance can have profound consequences for the biomedical sciences and agriculture.

*''Intelligent design (ID) theory'' is something new.*—ID deserves special mention because it is the seemingly most recent and seemingly most sophisticated attack on the role of evolution in mainstream science education. Intelligent design has received respectability to the point that the ID textbook *Of Pandas and People* is being considered by school boards for adoption in biology classes. The Discovery Institute, based in Seattle, Washington, promotes ID by attacking evolution by sponsoring academic conferences, public lectures, congressional meetings, publication of critiques of biology textbooks (see Scott 2001), and ''study guides'' for the Public Broadcasting System (PBS) series on evolution that originally aired September 24–28, 2001. However, even a cursory examination of historical tracts on creationism shows that ID is not new—William Paley (of blind watchmaker fame) argued in the early 1800s that complexity in nature is proof of God's existence. The newest twist is from Behe (1996), who claims that cell biology and biochemistry provide rock-solid examples of ''irreducible complexity.'' Structures like flagella and biochemical pathways such as the vertebrate blood clotting mechanism are portrayed as irreducibly complex; Behe argues they could not have arisen through Darwinian natural selection because none of the partially functioning intermediates would be adaptive. The inference is that irreducible complexity of this kind must be the work of some designer.

Intelligent design arguments have been sharply criticized on several grounds (Coyne 1996; Orr 1998). For instance, the logic of irreducible complexity invokes intermediate reductionism: study a problem until it becomes really hard, then appeal to faith for answers. This last stage of ID arguments renders them untestable and moves them outside the realm of science. Irreducible complexity also presumes that adaptations evolve for a specific purpose, from their earliest inception until the ''final'' product. Scientists discarded the concept of directed evolution 150 years ago: the literature is replete with examples of traits in use today that evolved for other purposes, such as feathers on birds that evolved for thermoregulation, not flight. Thus Behe's analogy of a mousetrap as irreducibly complex misses the point that metal bars, springs, and blocks of wood all function for reasons other than killing rodents. The claim that irreducible complexity is a new perspective that arises from recent advances in biochemistry and cell biology is patently false because irreducible complexity can also be found at higher levels of biological organization (e.g., vertebrate hearts, with valves, vessels, and chambers—what good is half a heart?). The old and parallel argument about the evolution of vertebrate eyes was dispatched by Darwin himself. Finally, for ID to gain scientific respectability, Smith (2000) stipulates that it must identify causation (ID has steadfastly refused to name a designer), have internal and external accountability, and generate testable hypotheses. If ID provides detailed theories that remain within the realm of scientific inquiry, scientists will evaluate them accordingly. As currently promoted, ID theory is neither new nor good science.

The most withering criticism of ID theory comes not from scientists, but from philosophers and theologians (Scott 1997; Pennock 1999; Haught 2000; Smith 2000; Oakes 2001a,b). We have modest abilities in these areas, thus we give here only a scientist's-eye summary of the arguments. First, the theology of ID theory looks for directed order in nature, but natural theologians risk losing faith when nature shows its disappointing knack for randomness, capriciousness, and unpleasantness. Second, ID is ''God in the gaps'' theology, using divine explanations for what is not yet understood; this theological position runs the risk of describing a God whose divine power diminishes with every new scientific discovery. Together, these make ID an uncomfortable theology. Perhaps John Henry Newman viewed the problem through the correct end of the microscope when he wrote in 1852 ''I believe in design because I believe in God, not in a God because I see design'' (quoted in Oakes 2001a, p. 52).

## Why Is Specific Training in Evolution Important for Science?

Having described the most common creationist arguments we hear from students and neighbors, we return to the question of why should we be concerned about evolution's current struggle for existence in public schools. If teaching evolution is challenged because of religious objections, how might that hamper individuals who are not taught about evolution or are taught that evolution has no place in science? It is unlikely that such individuals will understand the interplay and differences between the domains of science and the domains of

religion; nor are they likely to appreciate the role of science in social policy. A public increasingly disconnected from general scientific knowledge and skepticism is susceptible to pseudoscientific claims that play on gullibility (e.g., see Shermer 1997). Here we describe how ignorance of evolutionary science has consequences for medicine, traditional agriculture, and use of genetically modified organisms (see also Ehrlich 2000). For each case, we describe how understanding both microevolution and macroevolution could be important.

*Medicine.*—The discovery and use of antimicrobial drugs, which control protists, fungi, bacteria, and viruses, have reduced deaths caused by formerly common maladies like malaria, tuberculosis, and pneumonia, at least in the industrialized parts of the world. Aggressive use of vaccines allowed the World Health Organization to eliminate smallpox in the wild a few years ago. However, extensive use of antimicrobial pharmaceuticals has induced microbes to evolve resistance at an alarming rate (WHO 2000). Overuse and misuse of antibiotics, both in human health and in agriculture, combined with increased world travel and a global food supply, have selected for high levels of resistance in widespread bacteria like *Streptococcus pneumoniae*, *Staphylococcus aureus*, and *Salmonella enterica* in the United States (DHHS 2000). More alarming is the recent understanding that resistance in bacteria and viruses not only arises within populations but is also acquired via horizontal gene transfer between populations and between species. Combating resistance will require exactly the same approaches that evolutionary biologists use to study adaptations in any organism: understanding heritable variation in traits and identifying environmental circumstances that cause individuals with particular traits to survive and reproduce.

The concept of common descent, or macroevolution, also underlies medical protocols. Pharmaceuticals are first tried on mammals such as mice, rats, and dogs; promising candidates may then be tested on primates before clinical trials with human volunteers commence. Thus, biomedical research is directed by the understanding that the species phylogenetically closest to humans have the most similar physiology to humans. In particular, consider organ transplants. Because the number of patients requiring organ transplants generally exceeds the supply of human organs, xenotransplantation (cross-species donation) is an active area of research (Auchincloss and Sachs 1998). One of the best-known cases is Baby Fae, an infant born with an underdeveloped heart who was given the heart of a baboon at Loma Linda University Medical Center (Loma Linda, CA), in 1984 (Bailey et al. 1985). The baboon donor was one of five that had been tested for immunological similarity based on three HLA genes. Three baboons showed relatively low responses to the infant's lymphocytes, and the baboon with the lowest immunological response was chosen as donor. Baby Fae survived for 20 days after surgery with the help of the immunosuppressive drug cyclosporine, but eventually died from rejection of the transplanted heart and other organ failure. The main cause of failure was a mismatch of ABO antigens between the baboon (blood type A) and the infant (type O).

Ethical and procedural questions aside, a troubling aspect of the story is that Leonard Bailey, the lead surgeon for Baby Fae's operation, when interviewed by the Australian Broadcasting Corporation (1985), admitted to being a fundamentalist.* Bailey described how he chose baboons as donors because their hearts were the right size and were available. Furthermore he said, ''The scientists that are keen on the evolutionary concept that we actually developed serially from subhuman primates to humans, with mitochondrial DNA dating and that sort of thing, the differences have to do with millions of years. That boggles my mind somehow. I don't understand it well, and I'm not sure that it means a great deal in terms of tissue homology.'' Further comment seems superfluous, but we note that all subsequent infant transplants by Bailey's group at Loma Linda have used human donors. Research on xenotransplants continues in many laboratories, and we urge all such researchers to include evolutionary rationales in their protocols.

*Agriculture.*—Farmers and breeders have always used principles of selection, and Darwin drew considerable support for his theory of evolution by natural selection by invoking the parallel process of artificial selection used in agriculture. Thus, the development of disease-resistant wheat, high-yield soybean cultivars, and lean beef relies on application of principles of selection. The other face of selection in agriculture is the parallel with microbial resistance to antibiotics: resistance to pesticides and herbicides is a serious problem in agricultural systems (Georgiou and Mellon 1983; NRC 2000). Evolution of resistance occurred rapidly in the latter half of the 20th century after the application of compounds like chlorinated hydrocarbons became common. Currently more than 1000 species of plants, animals, and microbes are resistant to one or more major pesticide or herbicide.

The utility of common descent in agriculture is seen in the quest for the genetic variation needed to increase agronomic yield or tolerance to various pests and pathogens. We can focus our search for new genetic variation by understanding the phylogenetic relationships between domesticated species and their wild relatives. The search is further aided by knowing the historical geographic distributions of domesticated species, and that centers of origin of plant groups usually define where crops have their greatest genetic diversity (Vavilov 1992).

*Biotechnology.*—Plant breeders consistently use the tools of molecular biology to engineer varieties with desirable traits. For example, genes from the bacterium *Bacillus thuringensis* have been inserted into maize and a number of other plant species. These genes cause the maize to express *Cry* proteins that kill several kinds of pests (Lepidoptera and Coleoptera), thereby improving yield and reducing pesticide use. Many in the public fear potential effects on human health, such as allergic reaction, so that transgenic varieties have not been approved for human consumption. A continual risk of growing such engineered crops is horizontal transfer—escape of transferred genes into other natural or cultivated populations. Essentially an evolutionary and ecological problem, horizontal transfer occurs by gene flow when pollen from the engineered plants fertilizes ova in nearby populations. Indeed, the *Cry9C* toxin from Starlink corn has been found in

* The original broadcast was June 3, 1985, during the program Health Report hosted by Dr. Norman Swan.

nearby fields planted with other cultivars, and whether the gene can be removed from the global maize crop is not yet known (*New York Times*, June 10, 2001). The prospect of horizontal transfer is especially frightening if genes designed to prevent losses to pests or bad weather become established in weed populations. The problem of horizontal gene transfer was a surprise to biotechnologists who understood neither the evolutionary history of their crops nor the extent of hybridization between crop species and their wild relatives. Hybridization is less common across animal species, yet does occur in groups like fish. Thus, field experiments on coho salmon engineered to express growth hormone genes originating from arctic char must be carefully controlled to assess the environmental impacts if the growth gene were to be accidentally transferred into natural salmon populations.

Would researchers in these fields (medicine, agriculture, biotechnology) have acted differently if they fully understood the principles of evolution? Surely the above examples illustrate that introducing powerful environmental agents like antibiotics, pesticides, or genetically modified crops can lead to equally powerful evolutionary responses in both target and nontarget species. Given a world economy that now depends on interventions like antibiotics and pesticides, we argue that knowledge of evolutionary biology should be used to develop policies that might circumvent problems such as disease resistance and horizontal transfer. This requires that all biologists, not just those interested in organismal biology, be specifically trained in principles of evolutionary biology. Physicians, agronomists, and policymakers alike should learn how to formulate questions about evolutionary changes in natural and managed populations and how to develop informed hypotheses about possible outcomes.

## A Case Study in Fort Collins, Colorado

It is perhaps not surprising that when Kansas caught the antievolutionary flu in the summer of 1999 (see the Kansas Citizens for Science web page: www.kcfs.org), Colorado soon after caught a cold. In fall 1999 we were contacted by parents whose daughter attended Liberty Common School, a charter school within our local Poudre School District in Fort Collins, Colorado. The charter granted Liberty Common governance by a separate board with extensive parental input, under the promise that Liberty Common would provide an alternative (the Core Knowledge curriculum) enriched in science and mathematics. The concerned parents showed us Liberty's policy on teaching evolution; we present the full text here because it is similar to what could be seen in other school districts:

> Principles for Teaching Evolution
>
> As with other topics, we will adhere to the Core Knowledge Sequence for determining when the theory of evolution is introduced to students (7th grade) and which subtopics should be covered. This subject will not be taught in earlier years.
>
> Human evolution is not listed in the Core Knowledge Sequence or the Colorado Model Standards for Science. Therefore, this will not be a topic of instruction at Liberty Common School.
>
> Discussions of evolutionary theory can lead to discussions of whether or not supernatural forces play a role in the mechanism of evolution or the origin of life. These topics extend beyond the scope of science and will not be taught at Liberty Common School. (See also: Colorado Model Standards for Science 3.4, which states: ''This content standard does not define any student expectations related to the origin of life'').
>
> This policy is not intended to restrict the teaching of evolution as outlined in the Core Knowledge Sequence or limit the scientific discussion of related topics.

This policy, the day-to-day lessons taught in biology, and discussions with the school administrators convinced the parents that Liberty Common School was backing away from a full presentation of evolution. They worried about the overall state of science teaching if evolution were excluded, particularly in a school emphasizing science and math. The parents therefore filed a complaint with the District.

After consulting with the science coordinator of the Poudre School District, we agreed with the parents' concerns and decided to become involved. We and our colleagues wrote letters and editorials to the local newspaper about the Liberty Common evolution policy. Our department hosted a public lecture on creationism and science education by Dr. Eugenie Scott (Executive Director of the National Center for Science Education), to which we invited local science teachers, principals, and members of the School Board. As a result of our visible involvement in the complaint against Liberty Common School, a member of the District School Board asked to meet with University evolutionary biologists, and four of us spent two hours briefing him on evolution, science education, and legal issues surrounding the creation-evolution debate. We went through the Liberty policy line-by-line, pointing out insidious turns of phrase. For example, the policy's second paragraph is correct in pointing out that Colorado science standards do not mention human evolution. The science standards likewise fail to mention the evolution of whales, maize, mushrooms, and bacteria, but specifically excluding them from a science curriculum would be absurd. The third paragraph of the policy uses a twist of words. Although some may prefer to use religious contexts to discuss or understand nature, religious objections cannot be used to exclude teaching scientific evidence for evolution. We pointed out that this twist was reserved specifically for the teaching of evolution. Chemistry, physics, and mathematics also could lead to discussions of the role of the supernatural, yet these areas of science were not excluded.

We believe our time was well spent. Eventually the School Board ruled that the second and third provisions would restrict the teaching of evolution at the school and would violate Liberty Common School's science education charter. The school has now modified its policy, and has a curriculum that specifically includes evolution. How well the new policy is carried out deserves continual attention.

### *What Did We Learn?*

What happened in Kansas in 1999 happened in our back yard a few months later. It is now common for public school officials at all levels to attempt to minimize the teaching of evolution in science curricula. Just like in Kansas, we were successful in defending science education against creationists' incursions in our own schools, but only by becoming directly involved. Attacks on evolution and thus all of science education *can* happen in your state or local school district, even if relatively few individuals push the attack. Creationists are dedicated to their cause and are active in local educational politics. After repeated losses in the courts, their primary strategy is to influence school boards to deemphasize and possibly eliminate evolution in science classes. Defending science-teaching standards now requires local involvement. Confronting individual teachers is difficult, but we scientists can provide expert advice to school boards on science teaching standards, on which textbooks are adopted, and on testing policies (Will there be questions about evolution?). We share these specific lessons:

*Colleges and universities have resources that are extremely helpful in these efforts.*—When we first learned of the Liberty Common School problem, we were at a loss at how to proceed. A few phone calls around campus, however, made us aware of expertise in grades K–12 science education on our own campus. At Colorado State University we have a Center for the Life Sciences, which supports the myriad of life science programs scattered around campus. This Center, funded in part by a grant from the Howard Hughes Medical Institute, includes grades K–12 outreach as part of its mission. The Center staff includes teachers-in-residence who are on leave from the public schools. In addition, Colorado State University supports a Center for Science, Mathematics, and Technology Education with a broader mission to support all K–12 science outreach and a strong connection to the community of teaching professionals. The teachers-in-residence were invaluable sources of advice: they knew how teachers think and work, they knew the state and district science standards, and they knew how to work through the political process to effect curricular changes in the District. We also found considerable help from colleagues in our School of Education. We admit to some hubris in not having made these connections before the local crisis loomed, and we encourage all science faculty to learn about others at their institutions who work on science education and outreach.

*K–12 teachers feel alone.*—Teachers hear consistently from parents who do not think evolution should be taught and less commonly from those who support teaching evolution. Given the multitude of responsibilities teachers have, it is often easiest to give in to the squeaky wheels—a stance reinforced by many administrators in our public schools. Any support we can give to teachers is extremely well received. Examples include volunteering to give presentations in the schools, organizing campus visits for science classes, and working on science teaching standards with local and state school boards.

*Teachers want training on contemporary evolutionary science.*—Many teachers have inadequate backgrounds in evolution and thus do not feel confident in their ability to steer through the creation-evolution morass. An exciting outcome of our local fight was that our Center for the Life Sciences instituted workshops on evolutionary science for teachers. These two-day workshops, offered twice a year, feature presentations by biologists, geologists, physicists, and anthropologists. The topics include the scientific method as employed by evolutionary scientists; how to meet classroom challenges by creationists; and classroom exercises to demonstrate common descent, natural selection, radiocarbon dating, and human evolution. Teachers have incorporated these exercises into their classes, and the Center for Life Sciences will present an ''Evolution Solution'' workshop at the 2001 meeting of the National Association of Biology Teachers. The Center also funds summer internships for teachers, some of whom work in our laboratories. This program allows teachers to do research, which gives them a clearer picture of how we work. In turn, the teachers instruct us about the challenges they face in the classroom and community, in some cases by continuing a correspondence after they return to their schools. To paraphrase radio commentator Garrison Keillor (1987), ''Nothing you do for teachers is ever wasted.''

*School board members and local politicians appreciate overtures from academics.*—We invited members of the school board to Dr. Scott's lecture, and they were most pleased to be given the opportunity to learn more about this complex issue. Since then, we have invited members of our City Council and School Board to attend other high-profile presentations, such as an endowed lecture series that recently brought Paul Ehrlich, a prominent evolutionary biologist from Stanford University, to campus. While many do not attend, they do appreciate being invited—and they tell us so.

*This controversy concerns all scientists.*—We received broad support from colleagues in the physical and social sciences because they understand that an attack on teaching evolution is an attack on all of science education. Strengthening evolution curricula in schools will strengthen teaching of the sciences in general. School teachers tell us of their difficulties teaching how scientific theories are logically structured and how observations relate (or are irrelevant) to theories, and yet these critical thinking skills are central to science. The creation-evolution debate clearly illustrates the limits of science's domain, as well as the power of its methodology.

*Improving science curricula in K-12 need not take a lot of time.*—Every faculty member can make a difference in small ways. Across our department we host approximately 10 visits to departmental research labs from high school classes every year. On average, every laboratory (faculty, postdocs, and graduate students) also makes two to three visits to local schools. Faculty members also blend science education outreach into their courses. For example, honors biology students are required to visit primary schools for presentations. They work with our teachers-in-residence to become familiar with district standards and to draw up lesson plans, which they coordinate with the teacher whose classes they visit. The students initially think this assignment is the easiest part of the course, but they quickly learn otherwise. Not only do they enjoy this assignment, but some also start to consider a career in teaching.

## Recommendations for the Future

Maintaining high standards for science teaching will require constant vigilance, as creationists continue to make inroads onto school boards. The place to begin is to examine the teaching standards for your state (Lerner 2000); next, compare the state standards to those of your school districts and individual schools. Individual states allow varying levels of local control: even if your state and school district have standards that include evolution, they may not be enforced or may be circumvented locally. Teaching standards can be manipulated to remove requirements for teaching all or part of evolution theory, especially ideas of common descent, or to minimize requirements by stipulating that particular parts of evolution theory not appear on statewide examinations. In the state of Colorado, in 1996, standards for evolution were quietly changed to ''not define any student expectations related to the origin of life'' (Standard 34.2). Local efforts, however, may not be enough. Recently, a nonbinding resolution was added to an education bill in the United States Senate by Senator Rick Santorum (R-PA), which declares that ''where biological evolution is taught, the curriculum should help students to understand why this subject generates so much continuing controversy, and should prepare the students to be informed participants in public discussions regarding the subject'' (Holden 2001, p. 2429). The ensuing discussion on the Senate floor made it clear that the intent of the resolution was to include creationism in primary and secondary schools, in accord with the same ''fairness'' and ''macroevolution is not scientifically supported'' arguments described above.

We also must examine our college-level curricula to ask whether we give our students, especially future primary and secondary teachers, an adequate understanding of scientific methods. Research shows that teachers' attitudes toward evolution and creationism echo those of the general public, with approximately one third agreeing that creationist accounts belong in science classrooms (Weld and McNews 1999). This study showed that positive attitudes toward teaching evolution were correlated not with age of the teachers or region of the country, but with adherence to teaching standards, familiarity with philosophy of science, and participation in professional societies. Future teachers must be well trained in the scientific method, and their training in evolutionary science must consistently invoke those methodological principles.

The woeful level of scientific illiteracy in American society is partly our fault, and we recommend three ways that colleges and universities can contribute to creating a science-savvy public. First, we must ensure that science courses for nonmajors include training in critical thinking and scientific methodology. We must also stress the limitations of science's domain; we have found that our students are relieved and comforted to learn that science does not require an atheistic philosophy. Second, we must teach future primary and secondary school teachers the process of science. Just as we require that teachers participate in student teaching to hone their skills, we also must give them opportunities to gain hands-on experience in original research. Third, we must provide continuing education for practicing teachers, including workshops, internships, and teachers in residence programs. These pay quick dividends: a teacher who participated in a summer internship several years ago told us the research experience taught him how much science depends upon attention to small details, in addition to broad theoretical frameworks. When it comes to science and science education, the ongoing creation-evolution debate shows that the devil really is in the details.

## Acknowledgments

Special thanks are due J. Mitton for inviting us to write this article and to the parents whose plea for help jolted us out of complacency. B. Seega of the Australian Broadcasting Corporation provided a taped copy of the Health Report program. T. Wilson, K. Waddell and C. T. Walters provided key references. At Colorado State University, J. Carpenter, V. Jordan, and T. Gorell of the Center for Life Sciences and C. Jones of the Center for Science, Mathematics, and Technology Education have given us the opportunity to directly interact with primary and secondary teachers. We would especially like to thank the teachers in the Center for Life Sciences workshops and summer Research for Teachers program for their enthusiasm and candor. We thank J. Carpenter, T. Gorell, Y. Linhart, E. Scott, M. Viney, and an anonymous reviewer for helpful comments.

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## Appendix

How to keep abreast of the latest developments in the ever-evolving creation-evolution debate:

(1) The National Center for Science Education (Eugenie Scott, President). 420 40th St. Suite 2, Oakland, CA 94609-2509; Phone: (510) 601-7203; Fax: (510) 601-7204; online: www.natcenscied.org. Their publication *Reports of the National Center for Science Education* provides news updates in addition to scholarly writings about the creation/evolution controversy.

(2) The American Institute of Biological Sciences/NCSE List Server Network. List servers have been set up in 47 states and Canada, and include a coordinated list server for managers from each state. Information about the project and instructions for subscribing within each state are available online: www.aibs.org/outreach/evlist.html

(3) Kansas Citizens for Science: www.kcfs.org. This is the group that organized opposition to the famous Kansas State Board of Education ruling in 1999, and provides direct links to a broad variety of online resources for teachers. It also provides detailed analysis of how creationists (from Missouri) influenced the Kansas State Board of Education to circumvent science teaching standards that had been drafted by a committee of 27 teachers and scientists. Science teaching standards that include evolution were reinstated by a newly elected State Board of Education in February 2001.

(4) Other useful online resources, especially for primary and secondary school teachers:

http://www.ucmp.berkeley.edu/history/evolution.html (From the Museum of Paleontology at the University of California: possibly the best coverage of the history of evolutionary thought available anywhere).

http://www.ucmp.berkeley.edu/ncte/resourcematrix.html (Resources for teachers, gathered together after a conference ''National Conference on the Teaching of Evolution,'' October 5–8, 2000).

http://www.talkorigins.org (Where to go for a broad array of writings on the evolution-creation controversy, including debate via online discussion groups).

http://www.aaas.org/spp/dser/evolution/default.htm (American Association for the Advancement of Science web site, with useful resources, especially to the Project 2061curriculum, which provides model standards for science education).

http://www4.nationalacademies.org/opus/evolve.nsf/ (National Academy of Sciences website ''Science and Creationism: Information for Teachers.'' This page links to the excellent books ''Teaching About Evolution and the Nature of Science,'' which is a comprehensive resource for primary and secondary school teachers, and ''Science and Creationism: A View from the National Academy of Sciences,'' which provides a solid and visually compelling description of the evidence for evolution, and answers to common creationist challenges).