Effective Strategies
for Teaching Evolution
and Other
Controversial Topics

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As scientists and science teachers, we find ourselves in a paradoxical situation. The economy—and with it most people’s income directly or indirectly—increasingly depends on the products of science. At the same time, much of the public either rejects or does not understand the central theories of science. We find this especially puzzling for those ideas such as evolution, for which the scientific support is both quite strong and quite easily understood.

A fundamental question for science education in the United States today is: How can we produce a scientifically literate society, especially in areas that are publicly controversial? I will discuss four groups of issues and problems that are central to our efforts to produce a scientifically literate society. I will also suggest some strategies that are important for addressing each of the issues and problems. My examination here of this question arrives at six central conclusions.

1. Active learning is even more important for controversial topics than for the rest of science.

2. One major source of our problems, and not just for publicly controversial issues, is that we too often teach science as a set of conclusions. We should instead teach science as a set of processes for thinking critically about alternatives.

3. We have good ways to judge the levels of strength of support for scientific theories and other criteria for comparing them. Helping students understand these ways of judging is integral to teaching science as critical thinking. It also allows us to show that a publicly controversial theory is not necessarily a scientifically weak or scientifically controversial theory.

4. Although evolution often is seen as an anomaly, it is scientifically as strong or stronger than any other major scientific theory. Interestingly, most other major
scientific theories probably are even less well understood by the public. They would be less well accepted than evolution if they were understood.

5. Public controversies usually rest on disagreements about consequences. Hence, the parties can rationally disagree on how strong the evidence must be to justify a particular decision. If students are to understand why topics such as evolution are controversial, we must help them understand the different views of consequences. Only then can they really make an intelligent decision among the options.

6. Students have strong expectations of what should happen in science classes. These expectations flow in part from their levels of intellectual development. Both the expectations and the levels must be taken into account in the ways we structure our approaches, especially for controversial issues.

Although evolution is my central example, several of the problems and strategies apply widely to many publicly controversial issues. I hope the juxtaposition of strategies with issues and problems will help you devise additional teaching strategies and applications of the ones I discuss. Table 1 lists both the issues and problems and the strategies and the key metaphors I use throughout this article. Table 2 emphasizes the heterogeneity of religious views that underlie the origins controversy. Table 3 explores the interplay of uncertainty, scientific knowledge, and religious views, thus providing a map of many of the most important features of the origins controversy.

### Problems That Arise from Traditional Pedagogy in Science

Studies of science education, and of teaching generally, repeatedly conclude that major changes are needed at all educational levels. Several recent reviews show us how teaching can be made much more effective, both in science and generally.1

A key finding is that didactic pedagogy and passive learning lead to much more limited and temporary understandings of science than can be produced with alternative, more active pedagogies. Because of the way college science is traditionally taught, it sometimes seems that active learning is less important in more advanced classes, even in secondary school. However, much of the most stunning recent evidence for the superiority of active learning has emerged at the college level.

Let me quite briefly summarize four key examples.

1. Hake’s review2 found that structured, student–student interaction approximately doubled the amount of Newtonian physics mastered in introductory physics courses—a conclusion that held across a wide array of institutions from high schools to Harvard. Most impressively, no lecturer matched the average gain achieved by courses that included interaction.

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**Key Consequent Misconception:** Evolution is scientifically weak. | **Strategy:** Emphasize the distinction between fundamental empirical patterns and the causes that account for them.  
**Strategy:** Use history to compare disparate scientific accomplishments.  
**Key Comparison:** Darwin as the Newton of Biology  
**Strategy:** Use criteria to compare great scientific ideas.  
**Key Comparison 1:** Einstein as the Darwin of Physics  
**Key Comparison 2:** Evolution is as good as science gets! |

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**Key Example:** If it is a fact that the planets orbit the Sun, then evolution is a stronger fact. |

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| **Problem:** Students often want us to just tell them what to memorize. | **Strategy:** Teach the “game” of science.  
**Strategy:** Draw a clear distinction between what science does and what religion does.  
**Strategy:** Focus on humans. |
2. Springer and others recently reviewed "the effects of small group learning on undergraduates in science, mathematics, engineering, and technology." The average effect on achievement "would move a student from the 50th percentile to the 70th percentile on a standardized test." They also found strong effects on persistence and on students' attitudes toward science.

3. Angelo and Cross report a calculus course in which writing and structured discussion were able to eliminate the grade of F completely, with no reduction in standards. An economist reported similar results to me—no F's in three years—with the students assessed against nine other sections using common mid-term and final exams.

4. Treisman found that he could reduce the D and F rate for African-Americans in calculus from about 60 percent to about 4 percent with structured active learning. Again, this gain was achieved with no reduction in standards.

Like these examples, the literature on the effects of structured student-student interaction and other forms of active learning usually shows large, positive effects on student learning, especially in science and math courses. These effects are so strong that to teach without using at least an admixture of active approaches is to knowingly sacrifice learning. The first problem and strategy flow from this.

**Problem: Didactic pedagogy and passive learning lead to limited and temporary understanding of science.**

Active learning is especially important for issues that the students see as controversial. There are at least two fundamental reasons.

First, these issues often involve a series of alternative conceptions or non-scientific misconceptions. The use of active learning is especially important when such conceptions are already in place.

Second, dealing with controversies effectively requires that students learn to think in more complex ways. Active learning is a key tool here, too. This leads to the first global strategy for improving the effectiveness of science education, especially for controversial issues.

**Strategy: Emphasize active learning.**

I have placed this strategy first to emphasize its fundamental role. Each of the other strategies will be more effective when implemented using extensive applications of active learning.

However, a key issue in using active learning is deciding what goals we will use it toward. The rest of this article is designed to help teachers define these goals and to help them understand the intellectual steps that students must attain to move toward the selected goals. Within this area, I suggest just a few of the many key ways to apply active learning.
For both evolution and the nature of science, my colleagues and I work extensively with high school teachers to develop active learning lessons. We have made many of these available on the Internet, together with links to other sites containing similar lessons. Further explorations of the ties I see between the use of active learning strategies, especially collaborative learning, and fostering critical thinking are available elsewhere.

**Problems That Arise from Traditional Content and Curricula in Science**

A second thrust in the literature on improving learning in science courses complements the earlier focus on active learning. This second thrust emphasizes that traditional curricular and content also need to be reconsidered. The four problems in this group are self-inflicted. That is, they are the predictable results of the traditional ways of addressing the content of science and of organizing curricula.

This is encouraging. Just as we as teachers have the power to alter our pedagogy to make learning more active, so we have the power to alter the content of our courses. We can increase the extent to which we focus on the underlying processes of reasoning and comparison. This will make understanding the nature of science the route to a deeper and more genuine understanding of science itself.

**Problem: We often appear to present all topics in science as equally well supported.**

As scientists and science teachers, we are charmed by the patterns of nature and their explanations, and we want to share as many of these as possible with our students. In the process, we often present them as simply factual and don't take time to help our students understand the radically different degrees of evidence and other support for different scientific ideas. This problem is amplified both by cultural images of scientific knowledge as absolute and by students' limited sophistication.

**Strategy: Emphasize the wide variation in strength of support among different scientific ideas.**

**Key Metaphor: Big-Mac.**

The first solution is to help students identify and understand the wide variation in the strengths of support for different scientific ideas. This is especially easy for questions of origins (of the universe, of life, of consciousness), as the strength of support is so radically different from that for normal science. These differences are summarized by a "Big-Mac" (apologies to McDonald's) metaphor for the history of the natural world (illustration p. 24 and Table 3 p. 38).
In a McDonald's Big-Mac sandwich, the three layers of bun, like much American white bread, are airy and very soft and compressible. These three layers can be matched with the three origins questions, on which there currently are no solid scientific answers, only somewhat-informed, somewhatairy speculation.

1. Let the bottom layer of bun correspond with our somewhat airy answers to the question of how the universe got started (see illustration below).

2. The middle layer of bun then corresponds with our answers to the question of how a genetic system evolved (with tRNA in the middle of a largely arbitrary translation system being a special difficulty).

3. The top layer of bun, in turn, represents the answers, airy once again, to the question of how consciousness arises out of molecular reactions.

Between these three layers of metaphorical bun, there are two big layers of meaty science (illustration below and Table 3 p. 38). Specifically, we have comparatively solid answers for how and often why the physical universe changed from when big bang was well underway on through the formation of elements, organic molecules, solar systems, and planets. Similarly, once a functioning genetic system is in place, we have strong answers for how and often why organisms changed.

An expanded version of each of these layers is provided in Table 3.
Emphasizing these differences in strength of support between airy and meaty realms in science leads naturally to the next question. How do scientists distinguish speculation from solid knowledge?

**Problem:** In “covering the material,” we often present just the conclusions, leaving out the underlying critical thinking.

Several major studies have emphasized that science teachers at all levels overemphasize content and pay too little attention to helping students understand the processes of scientific critical thinking. Although the essence of science is evidence-based critical thinking, in a rush to “cover the material” we often present just the conclusions. This reduces science to memorization and hides the underlying analytical processes.

**Strategy: Emphasize science as a process of critical thinking.**

What is critical thinking in science? Let’s start with a basic model. Scientists first develop alternative patterns or explanations. They then use evidence and other appropriate criteria to distinguish the better from the weaker.

For example, in the 1880s three hypotheses on Earth’s age were popular:

1. A few thousand years old (from biblical genealogies)
2. A maximum of 20–100 million years old (Lord Kelvin, from cooling rates)
3. Several hundreds of millions of years old (geologists, from rates of erosion, etc.).

Fair tests of these three alternatives were needed.

**Fair tests of alternatives.** A fair test is based on a line of evidence different from those on which the alternatives were proposed. Ideally, this new line of evidence could turn out to have supported any of these alternatives. Radioactive dating provided just such a test for the age of the Earth. None of the alternatives had used it as a foundation, and, it could have shown that Earth’s rocks were all less than 20,000 years old or less than 100 million years old. Instead, it showed the oldest are four billion years old. Many other lines of physical evidence provide similar fair tests, and their results uniformly support an age for Earth of billions of years. This, therefore, is a very strong conclusion.

As a second example, suppose you were living in the 1840s in Great Britain when the geological column was first put in order. What changes, if any, should we have expected in fossils from the oldest to the youngest? Alternative hypotheses supported by ideas other than evolution included all kinds of organisms in the oldest rocks (with or without subsequent extinction); cycles among dominant groups; and successive independent elaborations and extinctions. Thus, Darwin proposed evolution despite, not because of, the fossil record. In *On the Origin of Species* he had to treat the fossil record as a major problem. The oldest marine fossil
beds then known contained most of the modern marine phyla. Darwin predicted that, if his theory were true, life had to have begun with a few very simple forms. The record itself provided a fair test of this and the alternative hypotheses. Our discoveries of much older fossils confirmed Darwin’s prediction and showed that the alternatives were largely wrong.

Most science should be taught in this way. We should start first by helping the students explore alternative patterns or processes, and only later help them examine the evidence and other criteria that allow a choice among the alternatives. The ideal settings for the development of such understanding are authentic laboratory or field problems where students develop hypotheses, design experimental treatments and controls, gather and analyze the data, and defend their conclusions.

This comparative approach emphatically does not mean that all of the ideas should be treated as equivalent in quality. On the contrary, learning should be structured so that students deeply understand the processes of science. Then, their mastery of fair tests and other evidence and criteria will allow them to understand which ideas are strong, which are suggestive, and which are not defensible. The strongest ideas in science are those, like an old Earth and evolution, that repeatedly emerge as better when challenged with multiple empirical questions as fair tests.

Problem: Often, we do not help students learn to compare the strengths of disparate scientific ideas. This leaves them free to think that publicly controversial ideas are somehow weaker than “good” science.

Typically we do not help students understand how scientists decide which accomplishments are great science and which are routine. We usually offer the major sciences in separate courses. Even when we integrate them, we frequently ask the students to make few, if any, comparisons among them. This leaves students free to think that publicly controversial ideas such as evolution are somehow weaker than scientific ideas that are not as controversial (e.g., gravitational theory).

How can we compare the ideas of, say, Newton and Darwin? History can be of considerable help, especially when coupled with a distinction between patterns and processes.

Two strategies: Emphasize the distinction between fundamental empirical patterns and the causes that account for them, and use history to compare disparate scientific accomplishments.

The distinction between major empirical patterns (e.g., planetary orbits) and the causes (e.g., inertia and gravity, warped space) that account for them is crucial in understanding science. But we often fail to keep this distinction clear. For example, we use the term “evolution” to mean the empirical patterns that show how we and other eukaryotes evolved from simpler forms. We also use it to mean the processes...
that explain those patterns, especially heredity and selection. Let's examine the
distinction between patterns and processes a bit further.

**Patterns.** Scientists ask what inferred patterns the data support. For example,
the planets orbit the Sun in irregular ellipses. This pattern had to be inferred: No
one ever saw a planet (except, arguably, Mercury) orbit the Sun, and the outer
planets move so slowly that some have not orbited the Sun even once since they
were discovered. We had to infer the patterns from the regularities in the data. This
was, in part, Copernicus’ contribution.

**Processes.** Science seeks a set of empirically validated processes that explain
why particular patterns occur and, consequently, why other patterns do not. The
distinction between patterns and processes allows us to draw important historical
parallels between the development of our explanations for the motion of the planets
around the Sun and the development of our explanations for the evolution of life on
Earth.

Newton's key contribution was to show that the planets orbit the Sun in irregu-
lar ellipses due to the interactions of inertia and gravitation. Newton thus explained
Copernicus’ planetary patterns. Similarly, Darwin explained patterns summarized
earlier by Linnaeus and Paley (Table 3).

Further, Newton showed the ellipses have to be imperfect (distorted) where the
planets affect each other's orbits. Similarly, Darwin showed that while natural
selection could explain Paley’s adaptations, evolutionary history could explain
“whole great classes” of nonadaptive features.

In these fundamental and very important ways, Darwin was the Newton of
biology. He used inheritance and natural selection to explain patterns discovered
earlier. Such comparisons help students (and us) understand why only some very
strongly supported ideas are truly great.

Again, active pedagogy matters. These ideas will more powerfully shape stu-
dents’ scientific world-views when they “discover” them, wrestle with them in a
collaborative setting, and consolidate the meaning through the facilitated develop-
ment of a group consensus.

**Strategy: Use criteria to compare great scientific ideas.**

The previous strategies allow us to use historical perspectives to compare, for ex-
ample, Darwin's accomplishments with those of Newton. A complimentary strategy
is to ask how we determine the comparative strength of major contemporary sci-
tific theories.

Is evolutionary theory currently much weaker than, about as strong as, or much
stronger than other major scientific theories such as relativity? Because major theo-
ries address quite different things, data and fair tests do not allow a direct compari-
don. We need a different set of criteria. Here are eight criteria for comparing major
scientific theories.

1. **How many lines of independent evidence support the theory?**

   Relativity, for example, is supported by only a few lines of independent evidence.
Several more lines support both evolution (Table 3) and plate tectonics (earthquake distributions, sea-floor spreading, ages of oceanic islands, etc.). Because each of these theories has very strong empirical support, we would need an alternative theory with approximately equal empirical support before we would consider rejecting it.

2. How many previously unconnected areas of knowledge did a theory tie together? Bronowski provides another criterion for comparing scientific accomplishments. He suggests we examine the historical significance of the multiple lines of evidence. Newton’s accomplishment, he explains, lay in connecting two things that everyone knew to be different: the motions of celestial bodies (moons) and those of terrestrial objects (cannonballs and apples). Einstein, of course, made even more connections. However, his synthesis followed Darwin’s equally spectacular connection of evolutionary history with the Linnaean hierarchy, with differences in the distribution of organisms, the patterns of compromises in adaptation, and many more facets of biology (Table 3). In this sense, connecting several fundamentally different groups of natural phenomena, Einstein was the Darwin of physics.

3. Does the theory make precise predictions? Major scientific theories make many predictions, both basic and applied. For evolution, my favorite predictions include two from Darwin: that life had to have begun with a few quite simple forms and that fossils connecting humans to chimpanzees and gorillas would be found in Africa. Predicting the development of resistance to pesticides and antibiotics is also straightforward given basic evolutionary theory.

One of the most important kinds of predictions in science is the prediction of what we will not find (i.e., of what is not possible). Triangular planetary orbits are an example of a phenomenon that is impossible under our physical theories. Darwin’s explanation of classification lets us make similarly strong predictions. For example, because mammals and birds originated from very separate and disparate taxa of reptiles, we can predict that no intermediates between bats (or other mammals) and birds will ever be found in the fossil record. Similarly, most of the organisms you might imagine by combining traits (snakes with feathered wings, for example) cannot have existed, as they combine traits from separate evolutionary lineages. Thus, they will never be found either in the jungle or in the fossil record.

4. How clear are the causal mechanisms? Newton renamed “falling tendency” as “gravity” without explaining how it acts causally. This is still unexplained, leading to current searches for gravity waves. Besides natural selection, the major causal agent in Darwin’s theory was the tendency of organisms to resemble their parents and more remote ancestors. As with falling tendency, the causal basis of this resembling tendency was then unknown.

Now, however, resemblance to ancestors is clearly a physical necessity. Each organism’s DNA is a copy of that of its parents and, in turn, of more remote ancestors. The causal basis of evolution is more deeply understood than is the causal basis of relativity (and than that of plate tectonics). Thus, on this criterion evolution is the stronger theory.
5. Does the theory adequately explain the ultimate origin of the systems it describes and explains? Workers with all theories sometimes attempt to examine the origins of the systems they study. Neither relativity nor quantum mechanics adequately explains the ultimate origin of the physical universe. Plate tectonics does not explain the origin of Earth. Thus, the fact that evolution does not adequately explain the origin of life does not make it any weaker than other major scientific theories.

6. Is the theory scientifically controversial, or only publicly or politically controversial? Each major theory discussed has essentially universal scientific acceptance. Most surprising was the rapid acceptance of plate tectonics in the late 1960s, once sea-floor spreading was verified.15

Controversies within science that address major, well-supported theories usually address what the public would see as quite minor points. For example, there have been heated debates in biology in the last couple of decades over classification. Thus: Should we maintain reptiles as a separate, intact group now that it is clear that some reptiles (crocodiles and dinosaurs) are more closely related to birds than they are to other reptiles (turtles)? These current controversies within evolution address the details of evolutionary history and the details of causal mechanisms. None of them question the occurrence or extent of evolution itself.

7. Is the theory fundamental to many practical benefits embraced by our economic system? Each major theory has important economic benefits. Evolution is of growing importance in the development of medical treatments. Examples include the identification of the sources of particular HIV strains and even individual infections (thus facilitating control); the use of geographic and taxonomic regularities in the search for natural compounds that yield new medicines; and the recent emergence of "Darwinian medicine."17

8. Is the theory widely understood and accepted by the general public? It appears that no major theory is widely understood and accepted by the general public. Plate tectonics requires an acceptance of an old Earth. Yet, polls repeatedly show that a plurality of American adults believe in a young Earth. Relativity requires that we understand, among other things, that the faster we move the slower time actually runs. This effect is large enough to affect our ability to control artificial satellites.18 Quantum mechanics is even weirder. Does the general public understand and accept that when you smash your finger between a nail and a hammer, all three "objects" are almost pure space? Or that Earth itself is almost empty space. The entire Earth, if placed in the gravitational field at the surface of a neutron star, would fit inside a large stadium!

In summary, according to each of these eight criteria, evolution is as good as or better than the other major scientific theories. Evolution is as good as great science gets! Because evolution is sometimes portrayed as scientifically marginal, some may be surprised (as I initially was) by my conclusion that evolution is as strong as any other major scientific idea. Committees formed by the National Academy of Science have twice addressed this issue and have reached similar conclusions.19 My conclu-
sion that none of the major theories of science are understood and accepted by the general public underlies my urging that all of science, not just the controversial parts, should be taught in ways like those illustrated here for evolution.

**Problem:** We often use words in ways that are contradictory to common usage and even in ways that are inconsistent among various sciences.

Again, the problem here is of our own making. In science, we often use words in ways that are directly contradictory to common usage and even in ways that are inconsistent among various sciences. Theory and fact provide an important example.

In general conversation, "theory" often is used to mean "unsupported speculations." But in science, "theory" is used only for ideas that have exceptionally strong support. Similarly, in general conversation, "fact" typically means a direct observation, one that is absolutely beyond doubt. For example: You are reading this sentence right now. "Fact" in science typically refers to a very strongly supported conclusion derived from a group of observations. Typically, such conclusions are not absolutely beyond doubt and, occasionally, scientific facts have turned out to be wrong. Birds and dinosaurs were placed in quite different groups. This "fact" has had to be revised as it became apparent that birds are the direct descendants either of dinosaurs or of their close allies.

These inconsistencies in the way we use words become especially problematical for issues that the public regards as controversial. For these, they allow anyone who dislikes a scientific idea to refer to it as "just a theory."

**Strategy:** Use students' language to bypass the theory versus fact confusion.

The fact versus theory confusion becomes manageable once we have made a clear distinction between patterns and processes and know how to compare the strength of ideas about disparate areas of science. More numerous, strong, distinct lines of evidence show that large scale evolution has occurred (Table 3) than show that the planets orbit the Sun. Therefore, if it is a "fact" that the planets go around the Sun, then evolution is a stronger fact. Alternatively, if evolution is a "theory," then the idea that the planets go around the Sun is a theory also, but a weaker one. Best, both can be considered (like the rest of the core of science) as very strongly supported, inferred facts.

**Two Problems That Arise from Outside Traditional Pedagogy and Content**

We have thus far considered a set of problems that arise from within science education, specifically the ways we traditionally teach science and its content and the ways in which we organize science curricula.
The strategies already presented will allow us to appreciably increase the extent to which students understand the sciences, their comparative strengths, and the nature of science.

We are ready to look at two additional dimensions of public controversies involving science and strategies for addressing the new dimensions. The first additional problem follows from the contrast between the consequences emphasized in basic science and those that must be considered for real-world decisions. It is thus a consequence of how we usually think about science rather than a direct consequence of conscious pedagogical choices. It thereby contrasts with the preceding set of problems. The second problem in this group is a consequence of the need for further intellectual growth by our students.

These two problems let us design additional strategies to teach publicly controversial issues more effectively. They may even broaden our view of the kinds of material that are legitimately included in science courses. Alternatively, when we lack effective teaching strategies for these elements, we may omit or underemphasize the pertinent science.

**Problem: Public controversies usually rest on disagreements about consequences. Hence, the parties can rationally disagree on how strong the evidence must be to justify a particular decision.**

If a theory is strong scientifically, does that mean one rationally must—or even should—accept it? The controversies surrounding the teaching of evolution can help us understand additional reasons why much of the public is skeptical of science and, specifically, of evolution. The core of the problem here is that real-world decisions explicitly involve consequences and values and that different groups will see different sets of consequences as fundamentally important.

Within basic science, the acceptance of a new hypothesis is based largely on the strength with which the supporting data allow a rejection of the null hypothesis. The null hypothesis is, roughly, the best alternative to the hypothesis being examined. Conventionally, acceptance of a new hypothesis follows whenever the chance that the null hypothesis can account for the differences between two sets of data drops below 5 percent (less than 1 chance in 20).

Again, within basic science, we seldom need to remember the underlying tradeoffs, but they are still there. For example, if we used 10 percent instead as our standard for rejecting the null, two consequences would follow. Research would be cheaper and quicker, as smaller sample sizes would suffice. The tradeoff would be an increase in the proportion of published studies that were based on spurious results. With 1 percent, alternatively, the proportion of spurious published studies would decrease, but then research would be more expensive and take longer, as greater replication would be needed.
Five percent is a somewhat arbitrary compromise among these tradeoffs. If, however, real-world consequences are important, an arbitrary acceptance of 5 percent will almost never be appropriate. The level of support—strength of data—that is adequate for one to reasonably accept an idea depends on tradeoffs. Specifically it depends on tradeoffs between the benefits that follow if the hypothesis turns out to be correct versus the consequences that follow if we accept the hypothesis and it turns out to be wrong. The difference between basic and applied science is that real-world consequences are conventionally ignored in basic science but often not ignored in applied science. Further, public controversies involving scientific issues almost always involve conflicting perceptions of consequences and their value. For any publicly controversial area of science, a key strategy is to help students understand and discuss these differences in perceived consequences.

**Strategy:** Explicitly examine the alternative views of consequences and tradeoffs as seen by the various parties.

The various parties in public controversies involving scientific issues often disagree about the consequences and their relative importance, as in the controversies over evolution. They then may rationally disagree on how strong the evidence must be to justify a particular decision. A discussion focused simply on the strength of data and other scientific support can be largely irrelevant. Put bluntly, the data aren't the only thing that should determine what ideas we accept. This is so contrary to the usual mind-set in science that we must start with a concrete metaphor.

**Key Metaphor:** Rusty Hand-Grenade.

Consider, for example, an intact but quite rusty hand-grenade one finds from an old military storehouse. With it on the table between us, we agree that it is so rusty that the chances of it exploding if we pull the pin are slim—decidedly less than one in 10 thousand. Let us further say that one of us has sufficient munitions expertise that the one in 10 thousand is an informed judgment, not just a wild guess. Shall we pull the pin?

The most probable hypothesis, by far, is that the grenade will not explode. When presented with this thought experiment, however, most people conclude that we should not pull the pin. Why not? Because, if the most probable hypothesis is wrong and the grenade does go off, the results are likely to be "inconvenient," especially for those testing the hypothesis. It is important, too, that a demonstration that the grenade is too rusty to explode has negligible benefits. Thus, it is totally rational to reject even a very probable hypothesis when the benefits of acceptance, were it true, are small, and the consequences of being wrong are large.

**Differing Views of Consequence.** Scientists and science teachers typically understand that the evidence supporting evolution is exceedingly strong (Table 3), so that it is very probably correct in its broad conclusions. Within the set of consequences usually considered by basic science, any rejection seems quite irrational.
Many fundamentalist Christians, Jews, and Muslims bring a quite different framework to bear. A central difference is in the answer to the question: What are the consequences of accepting evolution, should it ultimately be false? Evolution by far is currently the best-supported scientific hypothesis. Hence, the answer, within the framework of science, is that the consequences are negligible—we know that ideas in science have to be modified through time, sometimes radically.

However, within the framework used by many religious fundamentalists, premature acceptance of evolution, should it be false, is a serious mistake. Through its perceived conflict with Genesis, it increases the risk of rejecting the truth of scripture and, thus, the chance of eternal damnation. Given the fundamentalists’ assumptions, the rejection of evolution, despite otherwise overwhelming evidence is as rational as our refusal to pull the pin on a rusty grenade.

This perspective first became clear to me as I sought to understand the controversies surrounding nuclear power. Most public controversies, including those in which scientific issues play a role, have contrasting views of consequences at their core.

**More on Consequences?** Getting students in a science class to consider consequences is a major advance. It makes clear that the core issues are not scientific but center on consequences and how we value them. Some would say that we should leave further analysis to social science or, even, religious studies classes. Science teachers who are uncomfortable with some of the following (or preceding) approaches he or she certainly should not use these approaches.

However, if a teacher is comfortable exploring contrasts in consequences just a bit deeper, three major advantages can accrue. The rusty hand-grenade analogy leaves science contrasted with religion. This apparent contrast misrepresents most religious thinking in the United States. Further, such a dichotomous choice leaves students with little room to develop, and may cause them to reject science altogether. Rejection of science is clearly not the best outcome if we want to increase public understanding of science. Finally, to leave the students with a choice between science or religion is to abandon the task of teaching critical thinking at exactly the point where real progress is possible. This is especially unfortunate as evolution provides a topic where student interest will often sustain the hard work necessary for intellectual development.

The following approaches help us achieve these deeper goals. They focus on ways to help students attain a richer understanding of the alternatives and of the benefits and consequences of accepting and rejecting them. Such an understanding of intermediate positions typically requires looking further at differing opinions about the consequences outside of science. I carefully emphasize, both here and with my students, that what I am doing is sociological description. I also carefully avoid arguing for any particular set of such consequences, or for any particular underlying set of religious beliefs. Analogues to this set of approaches can also be applied widely to understanding—and teaching about—other publicly controversial aspects of science.
**Strategy: Bridge false dichotomies.**

Most public controversies rapidly become inappropriately polarized. Casting the issue as religious creationism versus atheistic science is a common example. Since this false distinction serves the political interests of young-Earth creationists, it has received much public press. Consequently, even many college students think that most U.S. churches oppose evolution and are quite surprised to learn otherwise. Thus, one effective response to false dichotomies is to help students understand that intermediate positions are held by many respectable people. This approach is greatly facilitated when we provide opportunities for sale, reasoned, discussions.

**Table 2. Evolution and Creation: From a Dichotomy to a Gradient**

<table>
<thead>
<tr>
<th><strong>Non-Theistic Evolution</strong></th>
<th>The Basic Stance of Science</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accepts:</strong></td>
<td>Old Earth, normal geology and evolution.</td>
</tr>
<tr>
<td></td>
<td>Scientific questions should be decided independently of religious assumptions: Religion has been of no help in deciding either patterns (e.g., shape of orbits) or their causes. Similarly, arguments either for or against God that use natural patterns or processes as evidence are also logically flawed.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Gradual Creation (Theistic Evolution)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accepts:</strong> Old Earth, normal geology and evolution.</td>
</tr>
<tr>
<td>Evolution is God's way of making diverse organisms (just as gravitation is God's way of controlling planetary motion).</td>
</tr>
<tr>
<td>Creation is the ultimate origin of the universe and continues at each moment in its maintenance.</td>
</tr>
<tr>
<td>Some versions emphasize the independent creation of life or of souls. Others also suggest that evidence of intelligent design can be seen in particular features of life or of the universe.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Progressive Creation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accepts:</strong> Old earth and normal geology but only limited evolution.</td>
</tr>
<tr>
<td>Like gradual creation, except that it accepts only evolution within groups.</td>
</tr>
<tr>
<td>New groups (especially humans) were newly created at approximately the time when they first appear in fossil record. The diversity and complexity of new forms when created increases progressively through time.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Quick Creation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The Earth is only a few thousand years old. The geological record was largely formed in a year-long global flood. Some adaptive variation has occurred, but only within &quot;kind.&quot;</td>
</tr>
<tr>
<td>This position rejects or misinterprets much of the physical and biological sciences.</td>
</tr>
<tr>
<td>Quick creation is often mislabeled as creationism or scientific creationism. Gradual and progressive creation are both decidedly more scientific and are equally dependent on a Creator.</td>
</tr>
</tbody>
</table>
I will briefly list four tools for bridging dichotomies in the case of creation and evolution. Each can be used as a focus for such discussions.

1. The article by Skehan in this volume is an excellent tool for helping us understand the legitimacy and importance of intermediate positions. Anyone who feels that science and religion cannot be reconciled should give his article a very careful read. I also recommend it as a tool for talking with troubled students.

2. A powerful tool for moderating the students’ tendency to think that the only options are the polarized ones is to give students a list of positions in the controversy or, better but more time consuming, to ask students to develop such a list. For options surrounding evolution, listing several creationist positions (Table 2) allows small group discussion focused on “if you are a creationist, what type of creationist are you and why?”

3. To briefly emphasize the legitimacy of such intermediate positions, teachers might find it fruitful to ask students to familiarize themselves with the list of plaintiffs who opposed an Arkansas law that “public schools within this state shall give balanced treatment to creation-science and to evolution-science.” Judge Overton’s decision declared the law unconstitutional and listed the plaintiffs:

The individual plaintiffs [who ask that the law be overturned] include the resident Arkansas Bishops of the United Methodist, Episcopal, Roman Catholic and African Methodist Episcopal Churches, the principal official of the Presbyterian Churches in Arkansas, other United Methodist, Southern Baptist, and Presbyterian clergy... 

I use this case after I share the parallel between rusty grenades and the position of many fundamentalists on evolution. This example makes it easy to ask why so many churches would oppose the Arkansas law.

4. What opposing tradeoff might balance the risk to salvation that the fundamentalists emphasize? Full statements of various American Churches in support of evolution have been compiled and are readily accessible either for class use or as a resource for troubled students. These are a good complement to Skehan’s article.

My favorite statement, and one of the most succinct and ancient, is from Saint Augustine’s On the Literal Meaning of Genesis:

Usually, even a non-Christian knows something about the Earth, the heavens, and the other elements of this world... Now, it is a disgraceful and dangerous thing for an infidel to hear a Christian, presumably giving the meaning of Holy Scripture, talking...
nonsense on these topics; and we should take all means to prevent such an embarrassing situation. The shame is... that people outside the household of faith think our sacred writers held such opinions... If they find a Christian mistaken in a field which they themselves know well and hear him maintaining his foolish opinions about our books, how are they going to believe those books in matters concerning the resurrection of the dead, the hope of eternal life, and the kingdom of heaven...

It was evident at least as early as 400 A.D. that there is a risk to faith from denying strongly supported ideas about the natural world. And Augustine emphasizes that this risk can partially or wholly counterbalance any risk from questioning particular interpretations of Genesis. This counterbalancing risk adds a strong religious justification to the already strong scientific justification for rejecting the young-Earth and flood geology interpretations.

**Problem: Students often want us to just tell them what to memorize.**

As emphasized earlier, a central goal in teaching science should be to help students understand how scientists decide which ideas are better and which are weaker. A contrasting preference for dichotomies reflects many students' (and adults') level of cognitive development. Students' prior school experience often has conditioned them to prefer dichotomies and "truth." They ache for us to just tell them what to memorize. Often, they are impatient with our attempts to focus on the underlying reasoning. Further, they are likely to think that if no perfect truth is available, then all answers are really just equivalent opinions. This problem is compounded when students consider nonscientific consequences important. One strategy addresses both aspects.

**Strategy: Teach the "game" of science.**

Ask students to understand and explain which scientists accept and on the basis of what criteria—whether or not that is what the students themselves think. For example, ask them to investigate and explain why evolution is good science. The key addition to the previous strategies is to say explicitly that the task is not to believe or accept the science, but rather to understand the "game" of science. This only seems fair. Students should understand clearly why scientists accept an idea before deciding whether to accept it themselves.

The students often feel that if one has to compare ideas, then all alternatives must be equally valid. Asking them to understand the "game" of science challenges this stance but seems not to be so threatening. Asking them to understand alternative views of consequences promotes the development of further sophistication. Doing so also helps them acquire sympathetic insight into others' perspectives. Such insight is key to the kinds of intellectual development that should happen in learning science, but typically do not. The sympathetic insight also fosters a more

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civilized class by helping students who accept one point of view (such as evolution or quick creation) be more understanding of others' views.

Here again, pedagogy matters. A modeling of patient listening and reasoned response by the teacher, rather than outright dismissal, is vital.

**Strategy: Draw a clear distinction between what science does and what religion does.**

A second strategy also helps make the game of science clear. Emphasize what science does not do, as well as what it does. Continuing with an example developed earlier: Many people would like to say that God makes the planets orbit the Sun in irregular ellipses due to the interaction of inertia and gravitation.

Science is of no help in deciding whether one should append "God makes" to the explanation. This is one of the roles of religion. Similarly, religion has been of no help for the core tasks of science. Religion does not help us determine the patterns (irregular ellipses or circles or squares), nor does it help us decide among the causal factors. Put differently, "God made it so" does not provide an explanation in the scientific sense; this reasoning is compatible, for example, with orbits of any shape (triangles or perfect circles, etc.). Newton's laws in contrast can explain only certain patterns (i.e., rough ellipses). They are not compatible with others, thus excluding perfect ellipses, circles, etc.

**Strategy: Focus on humans.**

For evolution, the evidence that Darwin compiled in support of a common ancestry of humans and apes was already quite strong. In recent decades the molecular, paleontological, and behavioral evidence also has become very strong. If the acceptance of scientific ideas was simply a function of the strength of scientific evidence, human evolution would be widely embraced. On the contrary, for many students human evolution is one of the most troublesome aspects of evolution, leading some to accept the evolution of all forms except humans. But virtually all students are quite interested in the details of evidence for human evolution. Nickels develops well the advantages of focusing on human evolution and describes several approaches for doing so.

Throughout science, a similar focus on the applications of science to human biology and on important applied problems usually increases student interest radically. Again in a rush for coverage, we often allocate little time for this focus. But these are typically the consequences that students regard as most important. By emphasizing them, we increase students' motivation to do the mental work necessary for questioning old positions and for cognitive growth.

**Summary**

Much of the public either doesn't understand or rejects many central theories of modern science. Some of the underlying problems are predictable results of tradi-
tional ways of teaching science. Others involve diverse views of the consequences of particular publicly controversial ideas. In both cases, powerful pedagogical strategies are available for our use. Although evolution has been my central example, most of the strategies apply to many publicly controversial issues and, indeed, to teaching most of science.

Areas of science that traditionally have not seen much challenge are now also becoming publicly controversial. The challenges by antievolutionists range well outside biology to encompass much of the core of physics and geology. The recent flourishing of “intelligent design” arguments, summarized and critiqued well by Pennock,

make the challenges to the naturalistic base of all science much more explicit. Strahler provides a superlative summary of many Creationist arguments and of their scientific limitations. His book is the most important source for teachers where evolution is challenged by fundamentalist groups. The National Center for Science Education is also a major source of support in such cases.

The strategies I have presented here focus largely on modifying the content we present. Changes in the way we teach, especially the increased use of active and hands-on learning and abundant opportunities for dialogue, even in lecture settings, are equally important. Indeed, they are especially important for the kinds of deep learning and rethinking required of students in effectively dealing with controversial issues. Both active learning and a more sophisticated approach to controversial issues make our classes more welcoming to students from diverse backgrounds.

The strategies I suggest make teaching more inclusive, more effective, and more fun.

**Table 3. Twenty-one questions that underlie the Big-Mac model.**

<table>
<thead>
<tr>
<th>Origin of Consciousness?</th>
<th>In the Big-Mac model the three layers of “bun” are areas where there are currently no solid scientific answers, only somewhat-informed, somewhat-airy speculation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diversification of Life</td>
<td>For the most part, the Gradual Creation position (see Table 2 for further detail) matches that of the non-theistic (Basic Science) position, except in the three bun areas, where it goes beyond science to assert the actions of a Creator.</td>
</tr>
<tr>
<td>Origin of Genetic System?</td>
<td>The two layers of “meat” are areas where science has comparatively solid answers. The comparisons on the pages that follow in the sections symbolized by the two layers of meat show that large-scale physical change and macroevolution have occurred—that is, they are strongly inferred facts (“the planets orbit the Sun” is a strongly inferred fact). The headings “lines of evidence” and “applications” provide only brief illustrative examples of the basic science position.</td>
</tr>
<tr>
<td>Age and Physical Development</td>
<td></td>
</tr>
<tr>
<td>Origin of Universe?</td>
<td></td>
</tr>
</tbody>
</table>
### Table 3. continued

#### Top Layer of Bun: The Origin of Consciousness

**Question 1.** How does consciousness arise out of molecular and cellular processes?
- **Quick Creation:** Consciousness is a consequence of souls.
- **Gradual Creation:** God individually implants souls, and this act underlies differences in (moral) consciousness between humans and animals.
- **Basic Science:** Consciousness evolved; it is present in apes and, though less well developed, in some other animals. But the mechanisms for evolution of consciousness are not at all clear, leading to much somewhat-informed speculation.
  - *Lines of evidence:* Observations show that apes are able to recognize themselves in mirrors, recognize paint on their faces, and actively deceive each other and humans. (See also question 1+ of the table, p. 44.) Souls are not amenable to scientific analysis (no fossil record, etc.), so science can neither confirm nor disprove their existence or origin.

#### Top Layer of Meat: Biological Evolution

**Group A: Classification and Geographic Distribution**

**Question 2.** Why do related species and genera usually occur in geographically adjacent areas?
- **Quick Creation:** Offers no explanation other than God chose to create this pattern. This does not answer the question, as the same explanation would be given if, for example, structurally similar species were always widely separated geographically.
- **Basic Science:** Related species evolved from common ancestors and have not widely dispersed.
  - *Lines of evidence:* Existing patterns of species distribution: relationships are confirmed by both functional DNA sequences and non-functional pseudogenes.
  - *Applications:* We look in adjacent geographical areas for related groups to find additional compounds and genes of medical or agricultural interest.

**Question 3.** Why is diversity “Linnaean”? (Why do we find discrete, nested groups?)
- **Quick Creation:** Offers no explanation other than God chose to create this pattern. This does not answer the question, as the same explanation would be given if the groups formed a spectrum (or some other pattern) instead of a nested hierarchy.
- **Basic Science:** Each group’s core similarities are inherited from a common ancestor by transmission of DNA. More inclusive groups (mammals are more inclusive than primates and rodents) had earlier common ancestors (the common ancestor of all mammals lived earlier in time than the common ancestor of all primates or the common ancestor of all rodents).
Table 3. continued

- **Lines of evidence:** Linnaeus' initial evidence for this pattern was morphological (physical) similarity. Strong confirmation of these patterns comes from molecular sequences and fossil groups.
- **Applications:** We look in related groups for related compounds and genes of medical or agricultural interest.
- **Darwin as 'Newton' of biology:** The pattern was clearly delineated by Linnaeus but not explained until Darwin. This relationship parallels Newton's explanation of Copernicus' patterns of planetary motion (see text).

### Group B: Fossil Record

**Question 4.** Why do new groups in the fossil record originate in geographical areas where biologically related groups occurred previously?

- **Quick Creation:** Offers no explanation other than God chose to create this pattern. This does not answer the question, as the same explanation would be given if structurally similar but more recent species were always widely separated geographically from earlier forms in the same taxonomic group.

- **Basic Science:** The new groups had to evolve from biologically appropriate ancestors—those that carried the genes that underlie the structurally similar characters.
  - **Lines of evidence:** There are many cases of these patterns from the fossil record. Rhinoceros-sized marsupial wombats and giant kangaroos (also marsupials) occurred in Australia—where marsupials occur earlier in the fossil record—at the same time that giant placental mammals were found on other continents. Darwin correctly predicted that ape-human fossil links would be found in Africa. Many geographic regularities, for both living and fossil groups, are the results of plate tectonics moving pieces of continents and carrying the animals and plants along. This pattern allows us to predict the geologic formations and geographic areas where new fossil links (older links between apes and humans, for example) are likely to be found.

**Question 5.** How much change should we find in the fossil record?

- **Quick Creation:** None, or just extinction. Proposes that an illusion of change may occur as a result of mobility and hydrodynamic sorting during the flood. These proposals don't explain the sequences (the evidence) for reefs, plants, etc.

- **Basic Science:** Immense change is expected because the complexity and diversity we see today had to evolve. Well before any early fossils were known, Darwin predicted that life started with a few very simple life forms.
  - **Lines of evidence:** The fossil record shows that only bacteria existed for the first 1.5 (out of 3.8) billion years. No land plants or land animals are found until the most recent 10% of the fossil record, and all Homo are found in the most recent 0.1%. (See Slehan's article, p. 13, for an illustration.)
Table 3. continued

- Comment: Darwin had no fossil support for evolution, but the fossil record provided a major test and after-the-fact confirmation of his theory.
- Applications: The stratigraphic sequences for some fossils are important when looking for oil.

### Question 6. Why has evolutionary change taken so long?
- Quick Creation: No explanation is offered, as no evolutionary change is recognized, and the bulk of the fossil record is explained as having been formed in a year-long flood.
- Basic Science: Initial oxygen concentrations on Earth were very low; therefore organisms more complex than bacteria (i.e., eukaryotes) had to wait on free atmospheric oxygen before they could diversify. Land animals and plants could only evolve much later, after higher oxygen levels allowed an effective ozone shield to form, blocking out most of the ultraviolet radiation.
- Lines of evidence: The extent to which minerals were oxidized (as in ferric versus ferrous iron) at different geological times provides a record of the extent to which oxygen was available. Geological processes (plate tectonics) control oxygen levels by controlling the rate of photosynthesis (by changing the area of shallow seas) and the rates at which oxygen is used up by newly-exposed sediments and unweathered rocks.

### Question 7. Why do we find fossils that are transitional between major groups?
- Quick Creation: Explicitly predicts that no transitions have ever existed, so none can be found.
- Basic Science: Major transitions must have existed if organisms formed through evolution. Because evolutionary change is slow, many of the transitions could be retained in the fossil record.
  - Lines of evidence: We have found fossils linking invertebrates to fish, fish to amphibians, amphibians to reptiles, and reptiles to birds and mammals. As Darwin predicted, a number of fossils linking apes and humans together have been found in Africa.

### Question 8. Why do most fossils occur in ecologically sensible assemblages?
- Quick Creation: No explanation is offered, as ecologically sensible communities would have been shuffled by the flood.
- Basic Science: Most fossils were buried in or near the communities in which they lived.
  - Lines of evidence: Most deposits contain fossils from only one or a few communities. This is especially true for the best-preserved sets of fossils. This, like much of the physical geology of the deposits, rules out a global flood as the major source of sediments.
Table 3. continued

**Group C: Evolutionary Processes**

**Question 9.** How have many structural aspects of organisms become adapted (well matched) to their functions?

- **Quick Creation:** The species were individually designed by a Creator.
- **Basic Science:** Natural selection: Organisms whose characteristics allowed them to survive and reproduce better left more descendents. Thus, structures generally became better matched to functions.
  - *Lines of evidence:* Natural selection has been verified by artificial selection and observation of wild populations.
  - *Applications:* Artificial selection is used when developing new crops and is important in understanding development of crop resistance to pesticides and disease resistance to antibiotics and other medicines.
  - *Darwin as "Newton" of biology:* The pattern of widespread adaptation was clearly summarized by Paley but not explained until Darwin. This parallels Newton’s explanation of Copernicus’ planetary patterns.

**Question 10.** Why are so many aspects of organismal structure simultaneously both not adaptive and similar to those found in related groups?

- **Quick Creation:** No explanation is offered, as this contradicts direct design. Some suggest degeneration following ejection from Eden, but that does not explain why the degenerate characters would resemble characters found in related groups.
- **Basic Science:** In many cases these aspects are inherited from ancestors. Every feature of every creature reflects its evolutionary history as well as adaptation.
  - *Lines of evidence:* Many aspects of structure and physiology reflect ancestry rather than adaptation. Vestigial characteristics provide one set of examples—in humans these include wisdom teeth, the cavity in the appendix, and ear-wagging muscles. Characteristics that develop in embryos but disappear before organisms are born or hatched provide another set (e.g., some human embryonic gill arches or fetal teeth in baleen whales). A third set encompasses characters that are adaptive, but whose form is strange or inefficient in ways that reflect ancestry. The nerve to the larynx in the mammalian throat passes down the neck, around the aorta, and back up the neck to the larynx—an especially indirect route in giraffes.
  - *Comment:* Darwin summarized these examples as “whole great classes of facts” his theory explained.
  - *Applications:* This is the core of the new field of Darwinian medicine (see references in text).

**Question 11.** How do new species form?

- **Quick Creation:** They don’t, or are only variants within created “kinds.” Each kind was created separately.
Table 3. continued

- **Basic Science**: New species form through several processes, including geographic isolation or changes in the number of sets of chromosomes (polyploidy).
  - **Lines of evidence**: By experimentally making particular polyploids, we can remake existing species of plants and make new ones that are fully isolated from their still-living ancestors. The more extreme breeds of dogs (e.g., Chihuahua and Great Dane) cannot interbreed successfully. Thus, they would be separate species if the other breeds and mixed-breed dogs didn’t exist.
  - **Applications**: Human-made plant species are commercially important and are found in many flower gardens (e.g., large-flowered petunias).

**Question 12.** How does life, once started, become structurally more complex?

- **Quick Creation**: It doesn’t—only micro-evolutionary change (within kind) is possible, and this cannot produce major new levels of structural complexity.
- **Basic Science**: Major increases in structural complexity occur by symbiosis and gene duplication followed by selective differentiation of the copies to perform different functions. (For example, the sequences of myoglobin and the various hemoglobins were derived by duplication from a single ancestral gene.)
  - **Lines of evidence**: DNA sequences demonstrate extensive and sequential duplication of genes. Further, DNA sequences of mitochondria and chloroplasts are clearly bacterial, and thus these organelles are symbiotic in origin. Some molecular sequences suggest that even the deepest surviving lineages were mosaics. Moreover, symbiotic root fungi are key to plants inhabiting uplands, and bacterial and protozoa in animals’ digestive systems are key to the digestion of plants.

**Question 13.** How do new or exceptionally complex characters form?

- **Quick Creation**: Unique and complex characters are taken as evidence of design and, lacking evolution, can only have been formed by a Creator. This argument is based fundamentally on an assertion that there is no reasonable way for these characters to evolve, and thus collapses if a reasonable way is found.
- **Basic Science**: New, complex characters can evolve in at least two ways. First, natural selection can produce a fairly gradual improvement of a function such as vision. For example, the simplest known photoreceptors are simple pigment spots. Structural complexity increases sequentially through eyes that are simple cups, to eyes that are jelly-filled cups to image-forming eyes. The second major way is by a change in function followed by gradual improvement for the new function. Fossils suggest, for example, that insect wings first served as larval gills for breathing at the surface of the water, allowing them to evolve gradually to a reasonable size. They could then be expressed in adult insects and used for
Table 3. continued

propulsion, first for skittering across the surface of the water, and then, following gradual improvement for faster skittering, for flight.

- **Lines of evidence:** Gradual improvement: series of existing or fossil organs such as eyes. Change in function: similarities in core structure (forearms, wings, and paddles in vertebrates) or in embryology (two mammalian middle ear bones start as part of the nascent jaw in the fetuses).

**Question 14.** Has culture developed from animal antecedents?

- **Quick Creation:** No.
- **Basic Science:** Yes, it too evolved.
  - **Lines of evidence:** In the wild, apes (and some monkeys) use tools spontaneously. Some wild apes make simple tools, and some carefully teach their young to use them, as well. Anthropologists define making and using tools and teaching others to use them as core aspects of culture.

**Middle Bayer of Bun: Origin of Life?**

**Question 15.** Origin of life? (Specifically, how did a genetic system mediated by transfer-RNA get started)?

- **Quick Creation:** Divine intervention.
- **Gradual Creation:** Divine intervention or natural processes.
- **Basic Science:** Natural processes.
  - **Lines of evidence:** There is very little direct evidence for how the genetic system first formed.
  - **Comment:** Once the universe starts in a Big Bang, its development at least up through the origin of planets and the synthesizes of diverse organic molecules is inevitable, given the basic processes of physics and chemistry (see question 16, below). The probability of developing a genetic code is unknown. Once the code is working, genetics and natural selection make evolution a physical necessity. However, many specific details of evolutionary history, such as whether the land can be inhabited, appear to depend on particular geological circumstances.

**Lower Layer of Meat: Physical Development**

**Question 16.** What was the origin of organic molecules and simple systems prior to life with genetic code?

- **Quick Creation:** Life began within days of the origin of the universe, precluding any lengthy period of earlier synthesis.
- **Basic Science:** They were synthesized by natural chemical processes.
  - **Lines of evidence:** Basic organic chemistry shows that organic molecules must form in a hydrogen-rich environment, and the universe is about 98% hydrogen. Experiments verify that some organic molecules must form in virtually any non-oxidizing environment. Further, organic molecules are found within some meteorites and are routinely detected in interplanetary space by radio-telescopes.
Table 3. continued

- **Applications**: Organic syntheses that are the same or similar to those that form interstellar molecules are also very important in industrial chemistry.

**Question 17.** Over how long a period did the geological record form?
- **Quick Creation**: Quickly, in a year-long flood.
- **Basic Science**: Slowly, by gradual processes and local catastrophes.
  - **Lines of evidence**: Most fossils occur in ecologically sensible local assemblages. Most physical features of sedimentary rocks are incompatible with a global flood. Examples include thousands of meters of limestone formed from oceanic ooze, ancient lake beds with millions of varves (annual layers), and fossilized reefs with the coral heads pointed to the position of the ancient Sun, as reconstructed from paleomagnetic evidence of continental drift. This is all in addition to the various techniques for estimating the ages of deposits.
  - **Applications**: Starting in the 1960s, plate tectonics revolutionized geological explanation and allowed us for the first time to understand the distributions of earthquakes and volcanoes—the processes by which mountains have formed—and the structural features of Earth’s crust in general. These same ideas now underlie oil exploration and the explanations for where we find economically valuable minerals, as well as major features of both current and ancient animal distributions.

**Question 18.** How old are the universe and Earth?
- **Quick Creation**: 8,000 to 20,000 years, as estimated from Biblical genealogies and narratives.
- **Basic Science**: Billions of years.
  - **Lines of evidence**: The immense age of Earth was first evident from analyses of rates of erosion and deposition. Immense age is now explicit in fundamental geological explanations, including plate tectonics (time for continents to move and for mountains to form) and in the results of radioactive dating (which could have shown that no rocks were older than 20,000 years but instead showed that the oldest are about 4 billion years old on Earth and 4.65 billion years old on the moon and in meteorites). Astronomy also requires an old age to explain the development of stellar clusters, the oldest of which would have required more than 10 billion years to reach their current state. Finally, an old age is required to account for how far out we can see into the depths of space. Because light takes time to travel, to see into space is to look into the past. (If the universe were only 20,000 years old we should only be able to see 20,000 light years away. But the Milky Way alone is 100,000 light years across, and we can see some 10 billion light years away and, therefore, some 10 billion years into the past.)
Table 3. continued

♦ **Applications:** Great age is fundamental to most of geology and astronomy and is implicit in the match of many features of the universe with nuclear physics (quantum mechanics) and relativity. Age coupled with plate tectonics is now powerful in geological explanation and mineral exploration. Quantum mechanics is important in electronics, computers, nuclear reactors, and nuclear medicine.

**Question 19.** What is the magnitude of physical change of the universe since its initial days?

• **Quick Creation:** By the end of Creation week the Earth was covered with all of the kinds of living organisms. There has been some degeneration since the fall, but only enough to account for the changes from Eden to here.

• **Basic Science:** The universe apparently started out so hot and dense that no atoms or elements could exist. Expansion cooled the universe and made it less dense. Initial element formation led almost exclusively to hydrogen and helium. (The oldest stars are nearly pure hydrogen and helium.) The other elements were synthesized in these simple stars or when the stars exploded. The elements were then dispersed throughout their galaxies when the stars exploded. This dispersion allowed the subsequent formation of stars that had planets and the syntheses of organic molecules.

♦ **Lines of evidence:** Red-shift increases with distance (Hubble’s Law), showing that the universe is expanding. The cosmic microwave background appears to be the fireball from the Big Bang cooled by this expansion to three degrees absolute. The oldest stars lack metals and so could have had neither planets nor life.

♦ **Applications:** Relativity and quantum mechanics govern these changes. Quantum mechanics is important in electronics, computers, nuclear reactors, and nuclear medicine.

**Question 20.** Direction of change of thermodynamic order in the universe?

• **Quick Creation:** Decrease in order after Eden.

• **Basic Science:** The second law of thermodynamics requires a system-level decrease in thermodynamic order (i.e., from very hot particles everywhere to mostly space with scant low temperature radiation). Can increase order in subsystems by input of energy from other parts.

♦ **Lines of evidence:** Second law of thermodynamics.

♦ **Applications:** Second law is fundamental to physics and, thus, engineering.

**Lower Layer of Bun: Origin of Universe?**

**Question 21.** What is the origin of the universe?

• **Quick Creation:** Created—Creation week.

• **Gradual Creation:** Created—Big Bang or “inflation.”

• **Basic Science:** We have mainly some highly speculative scientific ideas on origins and start of Big Bang (or of inflation).
Notes

2 1998.
3 1997.
4 1993.
5 Treisman and Fullilove 1990.
7 Flammer et al. 1999.
10 Strahler 1999.
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