Teaching Evolutionary Processes to Skeptical Students

Matthew Bobrowsky

Change is constant (or so the saying goes) and scientists in a variety of fields have been observing changes in nature throughout history. Evolutionary ideas abound throughout the interdisciplinary field of astronomy, which incorporates some physics, chemistry, geology, and biology. All of these disciplines involve phenomena that take place, and change, over both short and very long periods of time.

During classroom discussions of evolutionary change and long time scales, some students object to some of the scientific results (usually, but not always, on the basis of faith or suspicion, rather than scientific logic). Creationists have a deep belief that the long time scales that scientists have discovered are not correct. Other students are skeptical simply because they have heard a lot of misinformation. Teachers can not only present correct information, but also inform the students of the methods by which we came to know this information, and the certainty with which it is held.

There are detailed technical sources of information[1] on this topic suitable for more advanced classes, but here I address some of the more basic questions and misconceptions that often arise in introductory physics or astronomy courses. Teachers, both experienced and inexperienced, need to be prepared to appropriately deal with the perceived controversy. The following sections provide various incarnations of such controversies, particularly as they occur in cosmological and biological topics. I suggest methods for interacting with skeptical students, particularly those in the nonmajor courses.

Position Statements by Professional Organizations

The push by very conservative religious groups to affect how science is taught in public schools has resulted in a number of counterbalancing official position statements.[2] A common theme in these position statements is that the scientific method is a useful way to learn about the world.

Overall, the statements can be roughly summarized as indicating that there is overwhelming evidence for evolutionary processes, and to ignore our knowledge of these processes in classrooms does our children a disservice by not providing them with a basic understanding of contemporary science. Excerpts from official statements of scientific and educational organizations include:

- "[I]t has never been more important for American citizens to achieve a basic understanding of contemporary science and technology…. [L]earning and inquiry are severely inhibited if teachers are placed in a position where they may feel pressured to alter their teaching of the fundamental concepts of science in response to demands external to the scientific disciplines."
  —*American Association for the Advancement of Science statement adopted by Board of Directors Oct. 14, 1999*

- "An educated citizenry must understand these theories [of Earth history and organic evolution] in order to comprehend the dynamic world in which we live.…. [E]volution and relativity and plate tectonics are hypotheses that have survived extensive testing and repeated verification" and "are therefore the best-substantiated statements that scientists can make…. "
  —*American Geophysical Union statement adopted by council in 1981; (reaffirmed 1990, 1991, 1999)*

- "There is overwhelming geological and physical evidence that the Earth and Universe are billions of years old and have developed substantially since their origins."
  —*American Physical Society statement issued by Council Nov. 14, 1999*

- "Research in each of these areas [planets, stars, and the universe as a whole], and in many other areas of astronomy, has produced clear, compelling and widely accepted evidence that astronomical objects and systems evolve. That is, their properties change with time, often over very long time scales."
  —*American Astronomical Society statement adopted Jan. 11, 2000*

***Matthew Bobrowsky** is an astrophysicist at Challenger Center for Space Science Education, where he divides his time between research (mostly on planetary nebulae) and educational activities. He is also an Adjunct Professor at the University of Maryland University College, where he has taught for the past 17 years. He earned a B.A. from Northwestern University and an M.S. and Ph.D. from the University of Maryland, all in Physics and Astronomy.*

Challenger Center for Space Science Education
1250 North Pitt St. Alexandria, VA 22314;

Contact:
expert_education@rocketmail.com

Statements such as these should reassure anyone teaching about evolutionary processes in science that our understanding of these processes is on extremely firm footing and that there is ample evidence to justify teaching these topics as matter-of-factly as any other area of science. Indeed, anyone whose education does not include the benefits of our current understanding of these unifying principles will not only be denied part of their intellectual heritage, but may also be at a competitive disadvantage in our increasingly scientific and technological world.

The Validity of Science

Some students who do not want to believe in evolutionary ideas try to discount the entire enterprise of science. They ask questions like those in Table I. Possible responses to such questions are included in the table.

These questions show that science instructors need more than an understanding of just the scientific content of the course. They also need to be able to convincingly discuss the process of science as it relates to society (particularly a religious society) and popular misconceptions about science.

Table I.

Question/Objection:

Why is your explanation any more valid than mine?

Possible Response:

In science, one explanation will have more credibility than another if there is more evidence that supports it. What you learn in this course has an enormous amount of supporting evidence and has withstood repeated testing. So, the information in this course is not simply conjecture.

You've said that all data are interpreted. Isn't it true that scientists slant their interpretations to support their theories?

Scientists approach their work in a skeptical way, constantly checking each others' results. If one scientist tries to draw conclusions that are not warranted by the evidence, other scientists will quickly point that out. The scientific ethic requires that the truth (not public opinion or personal belief) be paramount. Scientists usually try to avoid "slanting" their interpretations beyond what the data will support because doing so would damage their reputations as scientists and severely limit their professional advancement.

Since most scientists are atheists, isn't it in their interest to try to use science to disprove God?

Some scientists are atheists; some are not. Scientists who are not atheists look at how the universe works and assume that God had a hand in it. Their belief in God does not prevent them from learning about the world based on experiment and observations. New knowledge obtained from scientific work does not imply anything about the existence or nonexistence of God. Thus, the question "Does God exist?" is not a scientific question; it is not "falsifiable." Some mainstream religions support the scientific enterprise and view it as an effective way to appreciate God's handiwork.

Since you've admitted that there are some things your model cannot answer, doesn't that call the whole thing into question?

First, it is not *my* model. What I am teaching is the sum of the knowledge of thousands of scientists. Second, we learn more and more as time goes on. The fact that we don't yet know everything doesn't imply that we don't know *anything*. In certain areas, we understand the situation quite well (again, based on the evidence and rigorous testing). This continues to be true even while there are some things that we do not yet fully understand.

Reliability of Dating Methods

Many objections to evolutionary ideas concern the methods, particularly radioactive dating techniques, by which very long time scales are established. Current knowledge of biological evolution, as well as the age of the solar system, is supported by the dating methods that now exist. It is therefore worthwhile to understand that radioactive dating methods have been extensively checked against other dating methods. As a simple example, consider the basic idea that as you dig deeper into the Earth, the strata become older. In order to test this, potassium-argon dating was tested against the Cenozoic-era North American land mammal ordering.[3] "Ordering" means that rock layers were numbered with increasing depth. (Geologists call this *stratigraphic* order.) Each fossil was given the number of the rock layer in which it was found. The results show that the dates and depths are well correlated. It is therefore quite safe to say "deeper is older." Data such as these help students connect the abstract concept of radioactive dating with the real world of Earth's layers.

Nevertheless, some students are likely to ask, "How do you know that rates of radioactive decay haven't changed over time or are inaccurate for some other reason?" There are many good answers to this question. First, if radioactive decay rates had changed, some of the fundamental physical constants must have changed, and there would be observable consequences from such changes. Such effects are not observed.[4] Second, dates derived from different minerals within a rock, or using different radioactive elements, all give consistent ages. Third, radioactive dating using carbon-14 can be directly checked using samples of known ages (such as tree rings). Finally, an intercomparison between sedimentary, radiometric and astrochronological[5] dates shows strong agreement among these disparate dating methods.[6]

Only after the reliability of radioactive dating is established is it possible to adequately respond to the question, "How do we know that Earth is 4½ billion years old?" Radioactive dating methods indicate that the age of the solar system is that old. Dates derived from Earth rock, Moon rock, and meteorites are consistent with that age.

Caution: Radioactive dating of Earth rocks alone do not show an age of 4½ Gyr (gigayear). The oldest Earth rocks dated so far have ages of 3.8–3.9 Gyr, but contain minerals as old as 4.1–4.2 Gyr.[7] Rocks that old are rather rare.

Rocks having ages of ≥3.5 Gyr have been found on North America, Greenland, Australia, Africa, and Asia. These ages provide a lower limit to the age of Earth. Meteorites turn out to have ages of 4.2–4.6 Gyr. The oldest ages for reliably dated meteorites, determined by multiple radiometric means, or multiple tests across different samples, cluster very close to 4.55 Gyr, the current best estimate for the age of the solar system.

Biological Evolution

Biological evolution is often included in an introductory astronomy course as the final segment of a discussion of "cosmic evolution." Cosmic evolution includes the creation of hydrogen and helium in the big bang, the formation of stars out of hydrogen and helium, nucleosynthesis (creation of heavier elements in stars), enriching of the interstellar medium with heavier elements, formation of subsequent generations of stars that include terrestrial planets, and formation of life on those planets. Biological evolution is also included in astronomy courses because astronomical events have affected the development of life on Earth (e.g., the K-T impact 65 million years ago or mutations produced by cosmic rays). In addition, some time in astronomy courses is often spent on the prospects for finding other Earthlike planets in the galaxy and the possibility of life on those planets. An intelligent discus-

Table II.

Question/Objection:

I simply cannot accept the idea of evolution because it is not compatible with my religious faith.

Possible Response:

That's all right. You are not required to believe it; but, you *are* required to understand the concepts and the reasons why scientists find them so compelling.

Isn't evolution just a theory?

In science, the word theory doesn't mean that the idea is just a guess or a hunch. For scientists to refer to an idea as a theory, it must have a substantial amount of supporting evidence. Sometimes scientists continue to use the word *theory* even after an idea becomes an established fact (as in the "theory of flight," about which all airplane pilots must learn).

Biological evolution is a change in the characteristics of living things with time.[8] That this happens is a fact.

Biological evolution also refers to the common descent of living organisms from shared ancestors. The evidence for historical evolution–genetic, fossil, anatomical, etc.–is so overwhelming that it is also considered a fact.[9] The parts that are not certain are the mechanisms by which evolution occurs. Scientists carry out research on the mechanisms of evolution, but they no longer debate whether evolution actually occurred. The vast amount of evidence makes that unquestionable. Would you like to hear about some of that evidence?

How can I believe in evolution if I believe in God?

Evolutionary ideas say nothing (pro or con) about the role of a deity in creation. Many people (including many biologists) understand that evolution has occurred, but still believe in God. Some people figure that evolution is how God decided to have life on Earth develop. Science is silent on the subject of God; God is not specifically rejected.

If evolution really occurs, why don't we actually see it happening?

Evolution is generally a slow process, but for small organisms that reproduce quickly, such as bacteria or fruit flies, evolution has actually been observed.[10]

If evolution is true, why aren't there any fossils that show a transition between species?

Actually there are many transitional fossils. There are fossils showing transitional organisms between fish and amphibians,[11] between amphibians and reptiles,[12] and between reptiles and mammals.[13] All of these transitional fossils provide one way of seeing that evolution has occurred.

If man descended from apes, why are there still apes around?

This question contains the misconception that man descended from apes when, in fact, both man and apes descended from a common ancestor. But, you're really asking how it is possible for an ancestral species to still exist. A useful analogy for this question is something like the following: Some Americans immigrated to this country from Germany. Does that mean that there shouldn't be any more Germans? Of course not. Similarly, just because some apes evolved into different creatures doesn't mean that there shouldn't still be apes around.

I've seen pictures of fossils oriented vertically, cutting through multiple layers. How can that occur?

This phenomenon should be expected to occur now and then, and is observed to be occurring in various places today. Some reasons include tree roots growing through soft, lower layers of Earth, or simply inclined strata. The latter explanation applies to a whale skeleton purportedly found to be oriented vertically through millions of years of strata. In fact, it was tilted only 40°–50° relative to the strata, which had been tilted by tectonic processes.[14] Also, another, partially buried whale skeleton was recently found off the coast of California, and provides an example of how an organism can get buried at odd angles relative to the stratigraphy.[15,16]

Since evolution is the result of random events, isn't it extremely improbable that evolution could result in the diversity of life that we see? It seems like you're asking me to believe that a tornado could pass through a junkyard and assemble the parts into a working airplane.

While there is an element of chance in evolution, natural selection does not proceed by chance. The random part of evolution involves the mutations that occur, giving rise to variations among organisms. But then natural selection occurs, and the less favorable variations are not retained over successive generations. This is not a random process.

Doesn't evolution violate the second law of thermodynamics by increasing complexity?

No, the second law of thermodynamics applies only to closed systems, i.e., where no energy enters or leaves. When you have energy being added (as Earth does from the Sun), you can get increased order or complexity without violating the second law of thermodynamics.

Fig. 1. In a single picture, the Hubble Space Telescope captured several different stages in the evolution of stars. At right bottom are cool clouds of molecular gas out of which new stars can form. Dark clouds at upper right represent one of the earliest stages of star formation when gas and dust become dense and completely opaque. Near the center is a cluster of very young stars, some more evolved than others. To the upper left of center is an old, blue supergiant star surrounded by gas containing material processed in nuclear reactions that go on in the cores of stars. This star is near the end of its stellar evolution life cycle. ***Credits: Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington), You-Hua Chu (University of Illinois Urbana-Champaign), and NASA.***

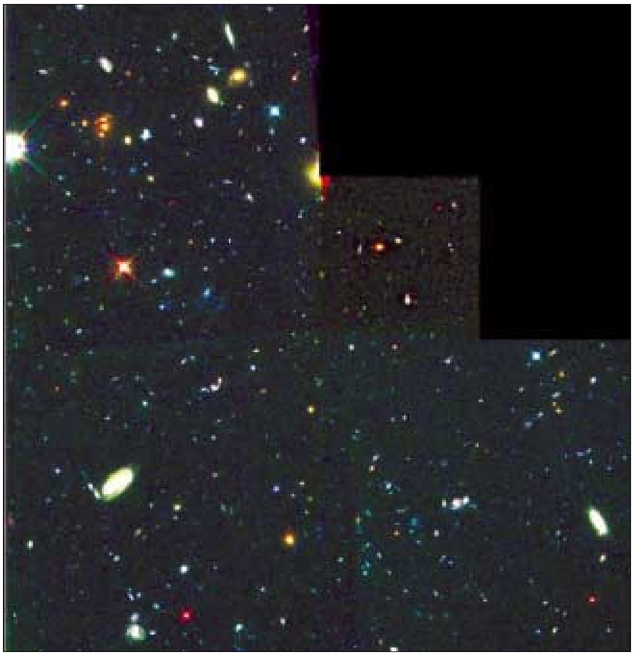

Fig. 2. Hubble Space Telescope image shows galaxies under construction in the early universe. Giant star clusters are so close to each other that they will eventually merge into a few galaxy-sized objects. These stars and galaxies are so far away that the light we see from them started on its journey 11 billion years ago—around the time we believe the galaxies were formed. ***Credit: Rogier Windhorst and Sam Pascarelle (Arizona State University) and NASA.***

sion of what life might be like on other worlds requires an understanding of the development of life on Earth.

Skeptical students are likely to raise many questions about the credibility of our scientific claims. Some common objections along with possible responses are presented in Table II.

Stellar Evolution

A physics teacher discussing nuclear fusion is likely to mention the nuclear reactions in the Sun and other stars. Observations of stars, combined with computer models of stellar nuclear reactions, leave no doubt that stars last for billions of years. Figure 1 shows, in one image, both young and old stars. The long lifetimes of stars are also consistant with the solar system's age of 4.55 Gyr. In this regard, teachers can point out that scientists gain confidence in their theories when independent lines of evidence point to the same conclusion. This can be said not only for stellar evolution, but for all well-established scientific knowledge.

Cosmology

Students may question the age of the universe and the standard big-bang model that leads to scientists' age estimates. Similarly, they may question the age of Earth. Some questions that often arise, along with possible responses, are shown in Table III.

Following the theme of independent confirmation of ideas in science, a teacher can point out that, if our understanding of the big bang and subsequent formation of galaxies is correct, then we should expect to see evidence of galaxy formation around 11 or 12 Gyr ago. As shown in Fig. 2, that appears to be the case. The big bang became almost universally accepted among scientists following the discovery of the 3º cosmic microwave background radiation in 1965 by physicists Arno Penzias and Robert Wilson (see Fig. 3).[17]

Interaction with Students

How instructors interact with students has a very strong influence on how readily students accept what we teach. Students do not enter the classroom as blank slates. They come burdened with preconceived notions and misinformation that effective instructors take into account. And, of course, students (like most people) have great resistance to giving up what they already "know." It can be counterproductive for the instructor to take the view that students must simply accept what they hear because the instructor is the authority. A student may think, "Whom should I believe—an astronomer that I've known for a few weeks, or someone (e.g., a religious leader) I've known for a long time, have had dealings with, and whom I trust?" There are more effective approaches as shown here. In particular, it is important to treat the student with respect and speak from the evidence (rather than from a position of authority) to explain why scientists believe what they do.

Table III.

Question/Objection:	Possible Response:
How do we know that the universe is approximately 15 billion years old?	We can measure the velocities of galaxies, and we find that almost all are receding. Based on their speeds and distances, it is a simple matter to calculate when the galaxies were all together—that is, when the universe began its expansion. That turns out to be 12 to 15 billion years ago.
How do we know that the speed of light hasn't changed over time, leading to an incorrect age for the universe?	If the speed of light had changed over time, there would be observable consequences of that change. There would be differences in the spectra produced by light from distant galaxies, and we do not observe any such difference. Also, in no other area do we see any evidence of laws of nature changing over time.
How can you be sure that the same laws of physics apply throughout the universe?	Objects in distant parts of space appear to obey the same laws of nature as apply here on Earth. For example, the law of gravity, which explains so well the motion of objects on Earth, also accounts for the motion of the Moon around Earth, planets around the Sun, and distant stars and planets around other stars. In addition, the spectra we see from the light of distant stars show the same features as spectra produced in laboratories here on Earth.

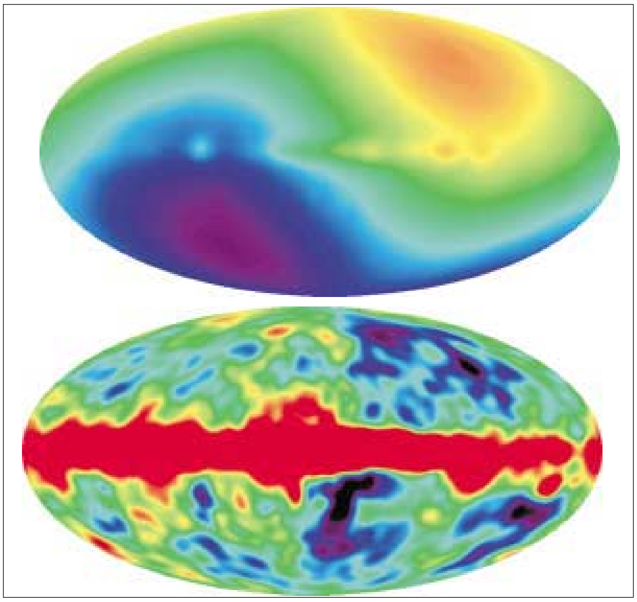

Fig. 3. Two false-color images of the sky as seen at microwave frequencies. Plane of the Milky Way runs horizontally across center of each image. Top image shows the temperature on a scale where blue corresponds to 2.724 K and red is 2.732 K. The "yin-yang" pattern is the dipole anisotropy that results from motion of the Sun relative to rest frame of cosmic microwave background. Bottom image shows microwave sky after dipole anisotropy has been subtracted from the map. This removal eliminates most of the fluctuations in the map: the ones that remain are 30 times smaller. These small temperature variations indicate slight density variations that eventually led to formation of clusters of galaxies. *Credit: COBE science team and NASA.*

Acknowledgment

I would like to thank Dr. Timothy Slater for useful suggestions during the preparation of this paper.

References

1. For example, Gary Kessler, "Creation science: A challenge in the physics classroom," *Phys. Teach.* **31**, 300 (May 1993).
2. For example, statements by the American Civil Liberties Union and the National Education Association; a resolution (June 1984) at the Iowa Annual Conference of the United Methodist Church; an address by Pope John Paul II to the Pontifical Academy of Sciences (Oct. 3, 1981); testimony by Nina Cortell on behalf of the American Jewish Congress. See also, *Voices for Evolution*, edited by J. Matsumura (National Center of Science Education, 1995).
3. G. Brent Dalrymple, USGS Open-File Report #86-110 (United States Geological Survey, 1986).
4. P. Sisterna and H. Vucetich, "Time variation of fundamental constants: Bounds from geophysical and astronomical data," *Phys. Rev. D* (Particles and Fields) **41**(4), 1034-1046 (1990).
5. Astrochronological dates are based on the fact that Earth's orbital cycles are preserved in the climatic records of deep-sea sediments. See J.D. Hays and N.D. Opdyke, "Antartic radiolaria, magnetic reversals and climatic change," *Science* **158**, 1001-1011 (1967).
6. F.J. Hilgen *et al*., "Breakthrough made in dating of geological record," *Eos* **78**(28), 285, 288-289 (July 15, 1997).
7. D. York and R.M. Farquhar, *The Earth's Age and Geochronology* (Pergamon Press, 1972); C. Stassen, "The age of Earth," (1967); http://www.talkorigins.org/faqs/faq-age-of-earth.html and references therein.
8. W.T. Keeton and C.H. McFadden, *Elements of Biological Science* (Norton, New York, 1983), p. 509.
9. L. Moran (University of Toronto) 1993; http://www.talkorigins.org/faqs/evolution-fact.html.
10. For example, T. Dobzhansky and O. Pavlovsky, "Experimentally created incipient species of Drosophila," *Nature* **230**, 289-292 (1971).
11. For example, M.I. Coates and J.A. Clack, "Polydactyly in the earliest known tetrapod limbs," *Nature* **347**, 66-69 (1990).
12. *The Phylogeny and Classification of the Tetrapods,* edited by M.J. Benton (Clarendon Press, Oxford, 1988).
13. For example, T. Rowe, "Definition, diagnosis, and origin of mammalia," *J. Vert. Paleontol.* **8**(3), 241-264 (1988).
14. D. South, "A whale of a tale," 1995; http://www.talkorigins.org/faqs/polystrate/whale.html.
15. P.A. Allison *et al*., "Deep-water taphonomy of vertebrate carcasses: A whale skeleton in the bathyal Santa Catalina Basin," *Paleabio*. **17**, 78-89 (1990).
16. C.R. Smith *et al*., "Vent fauna on whale remains," *Nature* **341**, 27-28 (1989).
17. J. Van der Veen *et al*., "Small-scale anisotropies: The final frontier," *Phys. Teach*. **36**, 529-538 (December 1998).