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VIEWS FROM UNDERSTANDING EVOLUTION

Communicating Evolution as Science

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If you are a scientist or science teacher reading this journal, you almost certainly recognize evolutionary biology as straightforward science and intelligent design and creationism as non-science; which belongs inside the science classroom is clear. Unfortunately, the distinction is a blurry one for many. Most Americans support the teaching of creationism in public schools (Plutzer and Berkman 2008), and around one-fourth of biology teachers in some states think that creationism is scientifically founded (Moore and Kraemer 2005).

Some anti-evolution groups have taken things a step further, by not just promulgating misconceptions about creationism's scientific status, but attempting to redefine science to include creationism. In 2005, the Kansas State Board of Education enacted a change in the state's science teaching standards (Wilgoren 2005). Science went from being "the human activity of seeking natural explanations for what we observe in the world around us" to being "a systematic method of continuing investigation that uses observation, hypothesis testing, measurement, experimentation, logical argument and theory building to lead to more adequate explanations of natural phenomena." Though longer and more jargon-laden, the altered definition was *less* specific about the types of explanations science can build—not just natural explanations, but *any* sort of explanation deemed "more adequate." By opening the door of science to supernatural explanations, the new definition threw out one of the key characteristics that make science work: the testability of its explanations. Happily, with the election of a new state board of education, the original definition was restored.

These are the sort of battles that the National Center for Science Education and Eugenie Scott have been fighting for decades and that Kenneth Miller fights to keep science textbooks free of ideas that have "failed as science," as he describes in an article in this issue (Miller 2010). Such conflicts often play out on a political stage, shaping classroom practice in a top-down manner. Is there something that science teachers can do within the walls of their own classrooms to impact the broader discussion of what ideas belong in science class? Science teachers can lighten the load of the next generation of evolution defenders by helping students recognize the distinction between science and non-science. This means finding ways to communicate the fundamental characteristics that set science apart from other endeavors and helping students learn to interpret representations of evolution in the media, such as those described by Carl Zimmer in this issue (Zimmer 2010). Here, we'll examine what students need to know about these topics, provide evolutionary examples, and discuss how this content can be incorporated into science teaching. In so doing, we will introduce content from the University of California Museum of Paleontology's Understanding Science website (www.understandingscience.org).

What is Science and Why Does Evolution Count?

This is a harder question to answer than it might at first seem. The term "science" applies to a remarkably broad set of human endeavors, and the edges of this set are fuzzy. We can't give a simple, one-sentence definition of science that draws a clear black line around the sorts of things

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considered to be science. On the one hand, we have things, like the investigation of evolutionary relationships among organisms, which definitely *are* science; on the other, we have things, like the formulation of intelligent design "theory," which definitely are *not*—with a gray area in between. In the philosophy of science, the issue of distinguishing science from non-science is known as the demarcation problem (Godfrey-Smith 2003). For a more complete discussion of the demarcation problem as it relates to evolution and creationism, see Pennock and Ruse (2009).

Despite the challenge of distinguishing science from non-science, teachers can give their students something concrete to help them make this determination. Scientific endeavors have a set of key characteristics (summarized in Fig. 1), involving both the topic being studied and the way it is studied, which can help distinguish scientific investigations from other sorts of human endeavors:

- *Science asks questions about the natural world*. The natural world includes the components of the physical universe around us, like atoms, organisms, societies, and outer space, as well as the natural forces at work on those things. Science cannot study supernatural forces and explanations—things that aren't expected to behave according to the laws that govern the natural world.
- *Science helps us explain and understand*. Classically, science's goal has been to build knowledge and understanding, regardless of what we might do with that knowledge. However, increasingly, scientists undertake research with the explicit goal of solving a problem, and along the way, new knowledge and explanations are built. Whether "pure" or "applied," such studies are scientific in that they help us understand how the natural world works.
- *Science works with testable ideas*. A testable idea generates expectations (also called predictions) about the sorts of observations we should be able to make if the idea were true and the sorts of observations we should be able to make if it were not true. A scientific idea may be difficult to test or may only be testable at some point in the future, but somehow, it must be testable. A lack of testability is generally what puts supernatural explanations outside the realm of science.
- *Science relies on evidence*. Scientists strive to test their ideas, preferably with many lines of evidence. This characteristic is at the heart of science. Endeavors that do not involve or lead to the fair testing of ideas with evidence are not a part of good science.
- *Science is embedded in the scientific community*. Science is rarely a solo project. It involves a community of people that generate scientific ideas, test those ideas, publish scientific journals, organize conferences, train scientists, and distribute research funds. Even scientists who work alone depend on the broader scientific community in many ways. Perhaps most importantly, the scientific community provides a forum in which scientific ideas and evidence can be sorted through and evaluated from many different perspectives.
- *Scientific ideas lead to ongoing research*. Typically, answering one scientific question inspires deeper and more detailed questions for further research. Similarly, coming up with a new scientific idea to explain an observation frequently leads to new expectations and areas of research. Science continues to build on itself as we learn more and more about how the world works.
- *Participants in science behave scientifically*. Science is able to build new, reliable knowledge about the world because scientists have an informal code of conduct that helps keep science moving forward. These behaviors include considering existing knowledge and evidence, being willing to change one's ideas in the face of contradictory evidence, and openly communicating ideas and test results to others. These behaviors are essential to the progress of science, and science has safeguards in place to ensure that they are followed.

Fig. 1 Science cannot be absolutely defined; however, scientific endeavors have a set of key characteristics, summarized in the Science Checklist. Illustration reproduced with permission from the Understanding Science website

The list above outlines the characteristics most typical of scientific investigations. It should not be interpreted as all-or-nothing. For example, a study of the evolutionary relationships among an exotic group of nematodes may not ultimately lead to ongoing research, but may have all the other characteristics of science and may be perfectly scientific. However, some of the characteristics listed above *are* particularly important to modern science and cannot be forgone—for example, working with testable ideas and relying on evidence. Ascribing the origins of nematodes to a supernatural being and writing a fictional account of nematode behavior are activities far outside of science's fuzzy borders. If an activity doesn't meet most of the characteristics listed above, or misses some of the most important ones, it shouldn't be treated as science.

Using this checklist, students can see exactly why investigations of evolutionary biology stand up as science. To see how, we can consider a study by paleontologists Budd and Johnson (1991). Among many other ideas, they were interested in the factors affecting species' survival of mass extinction events—specifically, whether small body size increases a species' chance of survival. Their study focused on a group of Caribbean snails (the genus *Strombina*), which have left behind a dense fossil record. They compared the shell sizes of species that survived a mass extinction event to the shell sizes of those that perished—and found that size didn't make much of a difference in a species' chance of surviving (Fig. 2). How does this study fare against the Science Checklist? Pretty well. The extinction of snails is definitely an event in the natural world; the investigation helped us better understand the process of extinction; their idea about small body size changing a species' odds of survival was testable—and they actually tested it by collecting evidence from fossil snails; they published their ideas and evidence in a scientific journal (the *Journal of Paleontology*) where other members of the community could review it; it has been cited by seven other scientific papers, suggesting that it has led to ongoing research; Budd and Johnson seem to have followed all the guidelines for good scientific behavior. The investigation is clearly well inside the bounds of science.

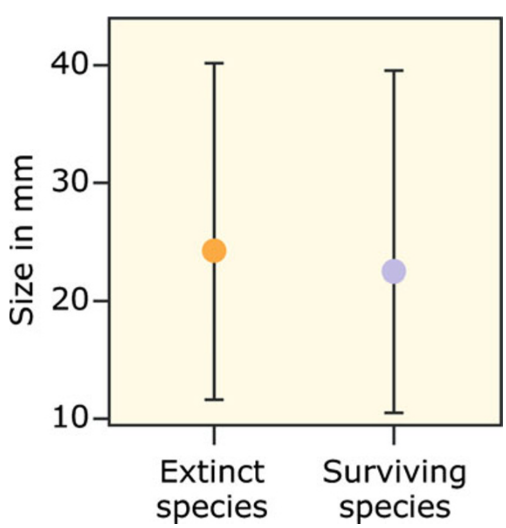

Fig. 2 Budd and Johnson found that size was not related to whether or not a species survived an extinction event. For each group of species, the mean size, maximum size, and minimum size are shown. Illustration adapted from Budd and Johnson (1991) and reproduced with permission from the Understanding Science website

Similarly, the checklist can be used to analyze non-scientific endeavors, like the intelligent design movement and astrology, to figure out where they fail as science. For example, intelligent design proponents *do* offer an explanation for natural phenomena—that the action of an intelligent designer is responsible for some features of organisms—though, compared to most scientific explanations, this one is not very specific. Furthermore, running down the rest of the checklist reveals that intelligent design has remarkably little in common with science. As an explanation, intelligent design is untestable and so doesn't rely on evidence. And without evidence or natural explanations, members of the scientific community cannot evaluate the explanation or base new research upon it. Intelligent design falls far outside of science's fuzzy boundaries. The appropriateness of a classroom exercise that uses the checklist to evaluate non-scientific endeavors, like intelligent design, is highly dependent on the community and classroom context.

Analyzing Media Coverage of Evolution

By using the checklist described above, we can help students build the knowledge necessary to distinguish science from non-science in light of all the facts. At the same time, we need to prepare them to identify cases in which all the facts may not be up front or accurately presented. Because science is so critical to our lives, we are regularly targeted by media messages about science in the form of advertising or reporting from newspapers, magazines, the Internet, TV, or radio. Students need the skills to appropriately interpret portrayals of science in the media–especially in the case of evolution.

Not surprisingly, media coverage of science tends to focus on controversy—after all, conflict is exciting—and this sets the stage for misinterpretation. Especially when it comes to evolution, students need to recognize that all controversies aren't created equal. At least five different sorts of science-related controversy can be recognized, and they each have different implications about the science at stake:

- *Fundamental scientific controversies* occur when scientists disagree over the central ideas of the theory that frames a discipline. There is no fundamental scientific controversy over evolution. Based on the evidence, scientists agree that the diversity of life on Earth today and throughout life's history has arisen from common ancestors through evolutionary processes. To find an example of a fundamental scientific controversy, we can turn to physics, where scientists currently disagree about the validity of string theory, a set of ideas that could reshape theoretical physics.

- *Secondary scientific controversies* occur when scientists disagree about the validity of a less central scientific idea. These controversies are often picked up in the popular media, as described by Carl Zimmer in his article in this issue (Zimmer 2010). Such controversies are healthy parts of normal science and are a sign that new knowledge is being built. In evolutionary biology—and indeed in all sciences—there are many secondary scientific controversies. For example, evolutionary biologists disagree about what sort of mutations are most likely to contribute to adaptive evolutionary change (Hoekstra and Coyne 2007), whether *Homo habilis* is the direct ancestor of modern humans or an ancient cousin (Fig. 3; Spoor et al. 2007), and how important hybridization is in the process of speciation (Mallet 2007)—to name just a few. Nevertheless, scientists on both sides of these issues agree about the same central ideas of evolutionary theory.
- *Conflicts over ethicality of research* occur within the scientific community or broader society when there is disagreement over the appropriateness of a scientific research technique or the behavior of a scientist. For example, studies of developmental genetics are reshaping how we think about evolution at a genetic level, but these studies often involve animal testing (e.g., Averof and Patel 1997), which some people see as an unethical research method. In these cases, it is not the content of scientific ideas that is controversial, but the ways in which we go about studying them that are.
- *Conflicts over applications* occur when people disagree about the technologies, policies, and decisions that are informed by scientific knowledge. For example, evolutionary theory and research can tell us that using pesticides in particular ways is likely to lead to the evolution of resistant pests (e.g., McGaughey and Whalon 1992); however, there may be disagreements within the agricultural and broader communities about whether and how this knowledge should be translated into enforceable policy. Similarly, evolutionary studies and theory can highlight which species are most likely to go extinct in the face of climate change, but there may be disagreement about whether such species should be granted protection before they show any signs of trouble (e.g., see Zimmer 2007). Controversies about the applications of scientific knowledge affect us all, but it is important to recognize that they don't represent a conflict over the scientific knowledge itself.
- *Conflicts between a scientific idea and a non-scientific viewpoint* are particularly prominent when it comes to evolution. These are the sort of conflicts that we see acted out in school board meetings and evolution "debates," as creationists and intelligent design proponents clash with those defending evolution's status as the central theory of modern biology (e.g., see Miller 2010). This *is* a conflict over scientific knowledge, but not one within the bounds of science.

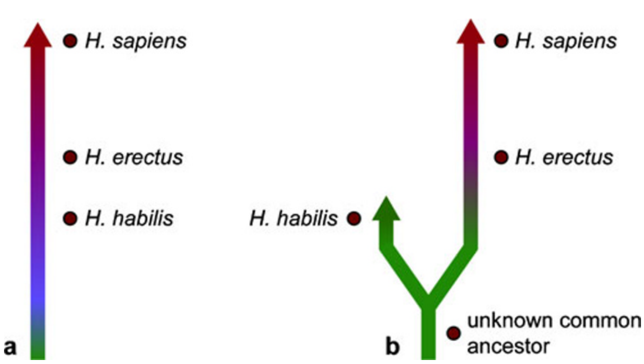

Fig. 3 Two hypotheses regarding the relationship of *H. habilis* to modern humans. Illustration reproduced with permission from the Understanding Evolution website

True scientific controversies (the first two sorts listed above) involve disagreements over data interpretation, over which theories and hypotheses are best supported by the evidence, and over which ideas should be investigated further. This sort of debate is a healthy precursor to scientific progress. It ensures that evidence is carefully and critically examined and stimulates additional research when more evidence is needed.

The problem for students and the general public comes when one type of controversy is incorrectly interpreted as another. In the case of evolution, it is especially pernicious when a secondary scientific controversy is viewed as calling all of evolutionary theory into question and when a conflict between a scientific idea and non-scientific viewpoint is treated as a legitimate controversy within the scientific community. The former makes evolutionary theory seem poorly supported when, in fact, evolutionary theory is supported by many converging lines of evidence—from DNA sequences to fossils to computer simulations—and is accepted by the scientific community as the central organizing principle of biology. The latter opens the doors for presenting so-called "alternatives" to evolution in science classrooms and textbooks. Students who can recognize these different sorts of controversy are less likely to be misled about the degree to which evolutionary theory is supported and about the topics that have a legitimate place in science class.

Conclusion

Teaching students to critically examine portrayals of science in the media and to understand the characteristics that distinguish science from non-science may require a little extra effort. After all, these topics are more nuanced than the steps of photosynthesis, meiosis, or even natural selection. However, the effort is justified. These topics, especially when embedded in a general understanding of the nature and process of science, are just as important for students to learn as is standard, biology content. In terms of evolution, a broad and accurate understanding of the nature of science will help students see evolutionary biology as a science like any other and recognize attacks on evolution for what they are: attacks of the scientific endeavor itself. More generally, it is essential for students to gain the skills to think critically about evidence, particularly when bombarded with conflicting representations of "scientific" evidence in the media. And because assessment of that data may critically affect one's consumer choices, political and policy decisions, and health, students must understand the characteristics of scientific evidence and the strengths and limitations of science as an institution. Such an investment in our students' understanding of the nature and process of science will ultimately result in a more scientifically literate society that is able to appreciate the pragmatic outcomes of science, distinguish science from non-science, and make decisions and judgments in a world increasingly informed and affected by the products of the scientific enterprise—and hopefully, one in which the jobs of evolution defenders like Eugenie Scott and the National Center for Science Education are made just a little easier.

Give me an Example of That

The discussion of media coverage of scientific controversy above gave a few examples of secondary scientific controversies in evolutionary biology. Want more examples? Check out Understanding Evolution's general introduction to some big issues in evolution that biologists have not yet settled:

- The big issues. All available evidence supports the central conclusions of evolutionary theory—that life on Earth has evolved and that species share common ancestors. Biologists are not arguing about these conclusions, but they do continue to investigate big questions about how evolution happens. Does evolution tend to proceed slowly and steadily or in quick jumps? Why are some clades diverse and others sparse? How does evolution produce new, complex features? Are there trends in evolution? If so, how are they generated? Find out more at: http://evolution.berkeley.edu/evolibrary/article/evo_50.

Branch Out

As Carl Zimmer points out in his article in this issue, poor coverage of evolutionary research is not uncommon. Fortunately, Zimmer provides helpful suggestions for where to find trustworthy news stories for use in class, but what about outside the classroom? How can students find reliable information about evolution on their own, and how will they know it when they see it? Teachers can equip their students to uncover the real meaning of media messages about science and evaluate the science behind policies using a tool from the Understanding Science website:

- The Science Toolkit (Fig. 4). The Science Toolkit provides a set of questions that can help your students apply critical thinking skills, evaluate media messages about science, and improve their own decision making. When considering a scientific message or policy, students should be encouraged to consider sources of information, quality of evidence, and potential biases and misrepresentation. Find an introduction to this tool at: http://undsci.berkeley.edu/article/sciencetoolkit_01.

Dig Deeper

The section on the Science Checklist above uses the checklist to analyze a study performed by Ann Budd and Kenneth Johnson. To learn more about this study and learn about what makes a fair scientific test of an idea, visit the Understanding Science website:

- Fair tests: A do-it-yourself guide. This handy guide explains the basics of experimental design and the design of other sorts of scientific tests, using examples

Your Science Toolkit: Evaluating Scientific Messages

- Where does the information come from?
- Are the views of the scientific community accurately portrayed?
- Is the scientific community's confidence in the ideas accurately portrayed?
- Is a controversy misrepresented or blown out of proportion?
- Where can I get more information?
- How strong is the evidence?

Fig. 4 Understanding the nature and process of science can help students evaluate media messages about science and the science behind policies. Illustration reproduced with permission from the Understanding Science website from medical research, paleontology, and physics: http://undsci.berkeley.edu/article/fair_tests_01.

The section on scientific controversy above briefly describes secondary scientific controversies about human evolution and controversies over the application of evolutionary research to conservation. To learn more about these topics, check out the following Evo in the News stories:

- When it comes to evolution, headlines often get it wrong. Newly discovered fossils are prompting some scientists to consider a minor revision of the relationships shown on the human family tree. This news brief from September 2007 clarifies the occasionally misleading news coverage of the story: http://evolution.berkeley.edu/evolibrary/news/070901_headlines.
- Tough conservation choices? Ask evolution. The earth is facing a biodiversity crisis. Nearly 50% of animal and plant species could disappear within our lifetime. To stem this rapid loss of biodiversity, we'll need to act quickly—but where should we begin? This news brief, from December 2008, explains how evolutionary history can help us set conservation priorities: http://evolution.berkeley.edu/evolibrary/news/081201_phylogeneticconservation.
- Evolving conservation strategies. This news brief, from June 2007, explains how biologists are using evolutionary theory to protect the biodiversity that exists today and that may evolve tomorrow: http://evolution.berkeley.edu/evolibrary/news/070601_hotspotstrategy.

In the Classroom

Teachers who aim to teach the nature of science in a meaningful way may find themselves thwarted at several levels. The majority of states include some components of the nature of science within their standards, but these are most often presented as simplistic, discrete skills (e.g., students will be able to "develop a hypothesis" or "interpret a sequence of events"). In a few states, the nature of science better reflects the scientific enterprise but remains decontextualized and strangely disjointed from the scientific content that students are expected to learn. Textbooks provide little additional support. They typically present the scientific method as a linear process that leads to a conclusion within five to six basic steps and fail to address the iterative nature of science, peer review, skepticism, or other characteristics of science that distinguish it from non-science.

The Understanding Science website (www.understandingscience.org) provides valuable resources for teaching the nature and process of science. It accurately portrays the scientific process, the language and relevance of science, and science as an ongoing, intellectual journey, depending on creativity and critical thinking. Most importantly, the site provides discipline and grade level specific tips, strategies, and tools for integrating key concepts regarding the nature and process of science across disciplinary content. Two resources from the site, the Science Checklist and the Science Toolkit, were introduced above.

The Science Checklist was developed to help students distinguish scientific investigations from other human endeavors. It can be integrated into science classrooms in many ways:

- Assign and discuss background reading on the checklist from the Understanding Science website (http://undsci.berkeley.edu/article/whatisscience_01).
- Have students read a historical case study about a scientist (e.g., the American Museum of Natural History's online Darwin exhibit: http://www.amnh.org/exhibitions/darwin/) and apply the checklist.
- Provide examples of different sorts of investigations (e.g., SETI's [Search for Extraterrestrial Intelligence] studies of astrobiology vs. those of the National UFO Reporting Center). Have students research the characteristics of those investigations and apply the checklist to them to see how scientific they are.
- Have students read and discuss *Umbrellaology* (http://physics.weber.edu/johnston/astro/umbrellaology.htm), an ironic article regarding the philosophy of science. Ask them to apply the checklist to determine how scientific umbrellaology is.

The Science Toolkit was developed to help students detect bias and misrepresentations of science in the media and improve their own decision making on science-related issues. It can be integrated into science classrooms in many ways:

- Assign and discuss background reading on the toolkit from the Understanding Science website (http://undsci.berkeley.edu/article/sciencetoolkit_01).
- Gather examples of reports in the media that make a scientific claim. Ask groups of students to analyze the reports based upon the toolkit. Begin a bulletin board on scientific claims, encouraging students to bring in their own examples of science spin or misrepresentation.
- Have students look at science articles in the popular press to find examples referencing the tentativeness of scientific ideas (e.g., "Numerous uncertainties remain regarding …") or the views of the scientific community regarding the idea (e.g., "Some scientists believe that …"). Is the tentativeness of the idea exaggerated, underplayed, or justified? Discuss each example.
- Look for hyperbolic headlines, such as "Gene therapy: A new weapon for medicine," and discuss with

students. Start a bulletin board of examples that students find in the print media.

- Find examples of newspaper articles where scientific controversies are mentioned. Discuss the validity of the claim of controversy. Discuss the benefits of true scientific controversy.
- Have students do an Internet search on a topic such as hamburger nutrition and find examples of both reliable and unreliable resources. Ask them to explain their reasoning.
- Have students offer examples of circumstances in which they or a member of their family has needed to evaluate scientific claims to make a decision (e.g., purchasing a new car). Ask students to explain how they investigated the claims and made their decision.

These and many additional teaching resources can be accessed at http://undsci.berkeley.edu/teaching/index.php.

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