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Evolution Challenges: Integrating Research and Practice in Teaching and Learning about Evolution

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Why Don't Undergraduates Really "Get" Evolution? What Can Faculty Do?

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Abstract and Keywords

Scientists frequently attribute public misunderstanding of evolution to religious or political influences. Ineffective undergraduate teaching has also contributed. Faculty often ignored strong pedagogical evidence. Five research conclusions are discussed: The traditional lecture approach is inadequate. Active learning is much more effective. Fundamental reasoning difficulties limit students' understanding. Simple steps help overcome these. Misconceptions typically persist unless directly addressed with a conceptual-change approach. Evolution is a complex set of ideas that cannot be adequately understood without advanced critical thinking. This is infrequently mastered without intentionally designed learning tasks. Understanding evolution is typically insufficient for its acceptance. But acceptance as valid for real-world decisions is important. This requires helping students consider social and affective factors related to evolution.

Keywords: misconceptions, conceptual-change, intentional design, evolution acceptance

Scientists frequently attribute the public misunderstanding of evolution largely to conservative religious influences or dubious political motivations. Indeed, Mazur (2004 2010) found Christian religiosity to be the strongest correlate of "disbelief" in evolution with low educational attainment and political conservatism also important.

How science is taught in undergraduate education is a powerful additional factor that usually has been ignored in analyses of

public misunderstanding of evolution. Rejection and misunderstanding of evolution are not simply the results of some facets of American culture. Rather, they are also the predictable results of traditional, didactic teaching strategies. Postsecondary science teaching often ignores strong evidence on ways to make instruction much more effective (e.g., Labov, Singer, George, Schweingruber, & Hilton, 2009; for evolution: Alters, 2005; Alters & Nelson, 2002; Nelson, 1986, 2000, 2007, 2008; Sinatra, Brem, & Evans, 2008).

The first part of this chapter focuses on four broadly applicable results of research on teaching undergraduate science. The latter part turns to strategies that take account of factors that apply more strongly to evolution than to much of the rest of science.

Key Result 1: Active Learning Is More Effective

Active learning substantially increases achievement when compared with traditional pedagogy in undergraduate science, a conclusion featured in a review in *Science* (Handelsman et al., 2004; see also Handelsman, Miller, & Pfund, 2006; see also K. A. Smith, Sheppard, Johnson, & Johnson 2005). A critical review of the evidence found especially large effect sizes for collaborative and cooperative approaches to active learning (Prince, 2004). Sinatra, Brem, and Evans (2008) reviewed key reasons that active learning increases learning for evolution. They concluded: “if the instructional design ... does not require the high engagement **(p.312)** required by discussion, debate, argumentation, experimentation and the juxtaposition of ideas, little change will result” (p. 193). Since traditional, didactic pedagogy (lecture) is devoid of these elements, little learning is likely to result.

The inadequacy of the traditional lecture approach in undergraduate science has been demonstrated most extensively in physics, where active methods roughly doubled average normalized pretest to posttest gains in learning, an effect approximating a two standard deviation difference (Hake, 1998a, 1998b). A meta-analysis for science and related fields showed similarly strong gains to be typical in undergraduate settings (Springer, Stanne, & Donovan, 1999). Active-learning exercises increased conceptual mastery in introductory physics to 90% of students versus 15% after traditional instruction (Thornton, 1999)

A number of researchers have examined the effectiveness of active learning in teaching biology including evolution and related topics. For example, Sundberg (2003) compared multiple sections of more traditionally taught introductory biology with three sections taught with an integrated lecture and lab that used a variety of active-learning approaches. Assessments targeted common misconceptions for scientific literacy, variation, Mendelian genetics, and natural selection. On average, virtually no change from pretest to posttest on *any* of the four topics was found for the traditionally taught sections. Normalized gains on natural selection for the *two best* of over 20 traditional sections were less than 5%. In contrast, the gains were over 25% for each of the three integrated-investigatory sections. Similarly, Cummings (2008) found that a studio approach doubled the gains for evolution as compared with traditional lecture for introductory biology. Gains for ecology were negative (posttest scores lower than pretest) for traditional lecture but positive with a studio approach. As a final example, Knight and Wood (2005; see also Wood, 2008) found substantial gains in learning when they replaced one-third of the lecture time in developmental biology with in-class active learning.

Thus, one answer to the question “What can faculty do to increase the proportion of students who ‘get’ evolution?” is to switch further toward structured active learning in lieu of more didactic pedagogies. The implications of this conclusion can be both distressing and elating. This conclusion can be distressing because time already spent on improving lectures would often have been spent much more effectively on improving pedagogy. The conclusion can be elating because changes can be fairly easy and can have large effects.

Unfortunately, faculty often have reservations about adopting active learning. These reservations include loss of content coverage, possible loss of control over the class, and possible failure of the activities. Tanner (2009) addressed a number of these. Similarly, several dysfunctional illusions that falsely suggest a lack of rigor for more effective pedagogies probably have slowed their adoption (Nelson, 2009).

Nelson (2010a) described several active-learning approaches that help students understand evolution. Allen and Tanner (2005) described additional approaches useful in large enrollment biology courses. Many applications of active learning in teaching evolution or biology more generally have been published in, for example, **(p.313)** *The American Biology Teacher*, *CBE—Life*

Key Result 2: Fundamental Reasoning Difficulties Limit Understanding

The difficulties many students have with basic reasoning are often misunderstood or ignored by faculty. Simple tests of reasoning (e.g., Lawson, 1994) have been shown to have strong power for predicting grades in college science even though none of the questions require prior knowledge of science. Students who cannot correctly answer many of these basic reasoning questions often have been described as being at a *concrete* reasoning level whereas those who successfully answer most of the questions have been labeled as at a *formal* level. Roughly 50% of college freshmen test at the concrete level, 25% at intermediate levels, and only 25% at the formal level (e.g., Herron, 1975).

Although Piagetian terminology (i.e., concrete, formal, and, sometimes, postformal) has been used extensively by researchers investigating undergraduate science learning, some research in developmental psychology has suggested that such reasoning is related to mastery of specific knowledge in children (Wellman & Gelman, 1992; 1998) and, sometimes, in high school and college students (Jiménez-Aleixandre, 1992). Elby (2011) discussed three theoretical frameworks (epistemological, context-dependent, and misconceptions) and illustrated how the same student behaviors can be alternatively seen as fitting more than one framework. Overall, it often may be preferable to use terminology less laden with Piaget's theory developed for children and now controversial in various research contexts. For example, Lawson and Johnson (2002) used the terms "descriptive" and "hypothetico-deductive." Nevertheless, for accuracy in summarizing the literature I have usually adopted the terminology used by the authors.

However one chooses to label these reasoning abilities, scores on reasoning tests have often been shown to predict achievement in undergraduate science courses and, sometimes, in precollege science (e.g., Hudak & Anderson, 1990; Lawson & Thompson, 1988; Lawson & Worsnop, 1992; Ward & Herron, 1980). Some studies have addressed college biology (Lawson, Banks, & Logvin, 2007; Lawson & Johnson, 2002; Johnson & Lawson, 1998).

These findings have profound implications for understanding and teaching molecular aspects of biology generally, and of evolution specifically, as shown by studies of undergraduate chemistry. For example, Herron (1975) listed startling differences between core ideas in chemistry that the concrete students can and cannot understand without altered pedagogy. These students will be a large fraction of any first-year class.

(p.314) Scores on reasoning tests were also related to the acceptance of evolution. Students who scored lower on tests of basic reasoning were less likely to accept evolution on the pretest and were more likely to continue to reject evolution on the posttest than individuals who performed better on the reasoning assessment (Lawson & Weser, 1990; Lawson & Worsnop, 1992).

A major advance for understanding how differences in reasoning play out in learning biology was recently provided by Lawson, Banks, and Logvin (2007). A basic reasoning test accounted for 32% of the variance in course grade in an introductory biology course. Crucially, Lawson et al. (2007) provided examples of three kinds of largely nonquantitative multiple-choice questions, many on evolution. These corresponded to three types of analytical tasks:

1. Descriptive predictions could be mastered by most students whatever their scores on reasoning tests.
2. Tasks requiring understanding and testing hypotheses involving perceptible causal agents (e.g., light, moisture) were usually mastered only by students with higher reasoning scores.
3. Tasks using hypotheses involving causal agents that cannot be as directly perceived (e.g., genetic versus environmental causation, chemical communication) were usually mastered only by students with even higher reasoning abilities.

Much greater pedagogical support is needed for tasks requiring the use of causal hypotheses, especially those using inferred causal agents. These distinctions are fundamental to students' difficulties in understanding evolution and to the development of effective ways to help them master it.

Unfortunately, the underlying reasoning patterns are not changed easily with conventional teaching. Arons (1976) emphasized the importance in promoting more complex reasoning of (1) using hands-on activities, (2) helping the students understand the meaning of basic mathematical reasoning (multiplication and division) as applied to concepts in science, and (3) having students at

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without teaching the students how to do them. Nelson (2010a) applied Grossman's ideas to helping students move among equations, graphs, and concepts in population biology.

Other researchers have made additional suggestions for fostering more complex reasoning. For example, a nice example of the use of hands-on modeling to support more complex thinking in a large molecular biology class was provided by Malacinski and Zell (1996). The common use of matrixes in teaching genetics (Punnett squares) and for analyzing experimental designs provides an example of how to support forms of reasoning that would otherwise be too difficult for many (p.315) students. Ward and Herron (1980) found that learning cycles substantially reduced the differences between formal and concrete students on formal questions. They suggested that also using a mastery learning approach (i.e., allowing the student to proceed at a pace that results in high achievement) might reduce the difference even further. Lawson (2006) reviewed ways to foster formal thinking in biology. He stated, “The key point ... is that for progress to occur, students must personally and repeatedly engage in the generation and test of alternative hypotheses and theories.” (See Lawson, 2002, for more extended examples and justification). The case-based, problem-posing, and peer-persuasion approach used by BioQuest illustrates optimal levels of support for mastering more complex ways of thinking about evolution and biology generally (Jungck, Kiser, & Stanley, 2005; Peterson & Jungck, 1988).

In summary, the answer to the question “What can faculty do to increase the proportion of students who ‘get’ evolution?” from this second perspective is that faculty often need to pay more attention to students’ basic reasoning and to teach in ways that better support (rather than just require) scientific understanding and reasoning. Without such support many students cannot understand what is being taught even when they are trying quite hard to do so.

Although these problems and many of the solutions have been clear for decades, they have not been widely adopted. “Because we [as faculty] are at the point that concrete experience ... is superfluous, we tend to forget that it was not always so [for us] and in our rush to ‘cover the material,’ we omit the very kind of experiences that can make our subject meaningful to beginning students” (Herron, 1978, p. 167). Arons (1976) emphasized the importance of having students draw heavily on their own observations and express their understanding in their own words. He added: “Telling them the correct answers in lucid lectures, explanations or text presentations is futile” (Arons, 1976, p. 835).

Many faculty will be skeptical (as I was) that well-performing students are deficient in understanding the basic concepts that should underlie their successes in class. It may be hard to accept that even “facility in solving standard quantitative problems is not an adequate criterion for functional understanding” (Thornton, 1999). In order to see the limitations of current approaches and the effects of changes we need more sophisticated ways of writing in-class and exam assessments (Crowe, Dirks, & Wenderoth, 2008) and of writing conceptual assessments to use, for example, as pre- and posttests (reviewed by Knight, 2010, for biology, including genetics and evolution; for natural selection see D. L. Anderson, Fisher, & Smith, 2010; Nehm & Schonfeld, 2008, 2010; for macroevolution see Nadelson & Southerland, 2010).

Key Result 3: Misconceptions Require Direct Active Intervention

The terms *alternative conceptions*, *naïve conceptions*, and *misconceptions* refer to ideas that differ from well-established scientific ideas. These are widespread and (p.316) typically persist despite intensive didactic instruction, as demonstrated in the thousands of studies listed in Duit's (2009) extensive, searchable bibliography. Alters and Nelson (2002), Banet and Ayuso (2003), Nehm and Reilly (2007), Nehm and Schonfeld (2007), and M. U. Smith (2010b), among others, have listed common misconceptions about evolution. Some were core misunderstandings of the nature of science (evolution is a “theory” and therefore weak, well-supported theories become facts, evolution cannot be proven and is thus invalid). Some were problems in understanding genetics (use and disuse explain the origin and loss of characteristics, new characters develop as needed, all mutations are harmful and are unimportant for evolution). Some were misunderstanding of the fossil record (geological time, there are no fossil intermediates, humans coexisted with dinosaurs). A final set addressed anthropomorphic and teleological views. Approaching this latter set from another perspective, probes of student thinking have suggested that broader worldviews “leak” into scientific language and foster erroneous goal-driven accounts of evolution (see Kelemen, this volume). Concepts such as purpose, design, cause, and chance have often been taught in ways that unnecessarily engender confusion with nonscientific ideas (Mead & Scott, 2010a, 2010b).

macroevolution is central to an understanding of the strength of the evidence showing that evolution has occurred (Padian, 2010). Further, macroevolution “is perhaps the primary stumbling block” for students, teachers, and other adults who have difficulty accepting evolution (M. U. Smith, 2010b, p. 541).

The switch in students’ understanding from misconceptions or alternative conceptions to scientifically valid views is termed *conceptual change* (for evolution: Banet & Ayuso, 2003; Sinatra et al., 2008; Tanner & Allen, 2005). Researchers have suggested that the ideal design for producing conceptual change has three key features (e.g., Banet & Ayuso, 2003): (1) a question, problem, or activity that leads students to explicitly state their current understandings; (2) activities that challenge these ideas; and (3) discussion and further activities that foster the restructuring of the students’ conceptions to more closely match scientific ideas and also aid in their retention. Dole and Sinatra (1998; see also Pintrich, Marx, & Boyle, 1993) proposed a more comprehensive model of conceptual change, one that notes the roles of several initial learner characteristics (including social context, commitment to prior beliefs, and motivation for change) as well as characteristics of the presentation of the new model (including comprehensible and rhetorically compelling or not). Empirically, didactic lectures typically have not provided an effective challenge to misconceptions even when they have explicitly addressed misconceptions found in the very students being taught (Arons, 1976; Grant, 2008).

Various approaches to teaching evolution have attempted to produce major conceptual change and understanding generally. M. U. Smith (2010b) provided a concise (p.317) overview. Six examples merit special discussion. Although these mostly address microevolution, they could be modified for topics in macroevolution.

1. *An Exemplary Conceptual Change Approach*. Banet and Ayuso (2003) provided essentially a primer for applying conceptual change strategy to inheritance and evolution. They listed common naive conceptions and summarized the conceptual complexity that students needed to master. They taught an 18-lesson unit on inheritance and evolution. Lamarckian ideas predominated on the pretest (86% of the students), but Darwinian ideas predominated at the end of the instruction (70%) and three months later (52%). Even greater success was found for inheritance.
2. *Historically Rich Comparisons*. Jensen and Finley (1995) used small-group discussions for a unit (two laboratory periods) designed to foster conceptual change. They first taught Lamarck’s ideas to help the students understand their own conceptions and then taught the evidence that led to Darwin’s ideas. Fully Darwinian answers were given 25% of the time on the pretest and 45% of the time on the posttest. They later (Jensen & Finley, 1996) examined the effects of changing the pedagogy and content for a 1-week evolution unit in introductory biology. Pretest to posttest increases in Darwinian responses were 22–23% for both traditional pedagogy with traditional content and for traditional pedagogy with historically rich comparisons, were 35% for paired problem-solving with traditional content, and were 45% for paired problem-solving with historically rich comparisons. Darwinian responses for the latter two approaches exceeded 80% on the posttest.
3. *Guided Reinvention*. Various critiques of basic conceptual change approaches have emerged (Dole & Sinatra, 1998; Geraedts & Boersma, 2006; Sinatra et al., 2003). Guided reinvention is one response. In this approach teachers address common misconceptions in developing lessons but do *not* ask students to explicitly consider their own initial conceptions (Geraedts & Boersma, 2006). The goal is for students to understand the logic of the Darwinian model thus leading them to *reinvent* the concept of natural selection. After a 2-period evolution unit using this approach, 72% of the students satisfactorily applied natural selection to explain a new example, and 59% included mutation in their explanations (Geraedts & Boersma, 2006).
4. *An Equilibrium Process View of Natural Selection*. Ferrari and Chi (1998) reviewed explanations for persistent misconceptions that focused on the difficulties with the underlying concepts (populations, frequencies, and adaptation), problems in reconciling the different levels of organization or explanation (genes, individuals, populations, species), and difficulties in understanding the time frames. They suggested that, alternatively, “category mistakes” are “a key reason why some science concepts engender deep misconceptions, even after extended instruction” (p. 1235). Specifically, some processes are events and some are equilibrations. Events like a baseball (p.318) game have a distinct beginning and end and a sequential structure, and are contingent, causal, and goal directed. Equilibration processes, including natural selection, are continuous with no distinct beginning or end, involve simultaneous processes, and depend on net effects

Roscoe, this volume).

5. *Participatory Action Research*. In a multiyear study, Grant (2008) examined the misconceptions his first-year biology students held about natural selection. “Many students who presented evidence on pre-tests that they harbored substantial misconceptions in fact remained highly resistant to instruction, and often defended their misconceptions using course appropriate terminology, but incorrectly, on the course final exam. In other words, many had hijacked course content in service of their misconceptions” (Grant, 2008, p. 15). He iteratively designed ways to address these in a large class setting. Key changes included repeatedly presenting summaries of in-class surveys of prior knowledge and misconceptions. He also asked students to discuss with their neighbors what evidence and arguments would be needed to foster the replacement of these misconceptions with expert knowledge. He termed this “participatory action research.” It required substantial reductions in content and rearrangements of topics. There were large increases over previous years in the grades on the final examination questions on evolution: On a key question assessing natural selection, good answers (8 to 10 of 10 points) increased from about 3% of students (2000–2005) to 54% (2006–2007), and very low scores (0–2 points) were eliminated. This approach has considerable promise for improving undergraduate science learning generally.

6. *Whole Course Transformation*. In what is essentially a deep conceptual change approach, BioQUEST has emphasized computer-facilitated, case-based learning with a focus on problem-posing, problem-solving, and peer persuasion, often addressing topics in evolution (Peterson & Jungck, 1988; Jungck, Kiser, & Stanley, 2005; BioQUEST website). Their exercises could also be used as parts of a course.

In summary, the answer to the question “What can faculty do to increase the proportion of students who ‘get’ evolution?” from this third perspective is that faculty often need to give even more attention to students’ persistent misunderstandings and to teach in ways that better support conceptual change (rather than falsely assuming that telling students the right idea or showing them the data will be sufficient to elicit change). Without explicit, active support for conceptual change, most students will retain their initial misunderstandings.

(p.319) Key Result 4: Complex Thinking Is Requisite for Understanding Evolution

Many of the difficulties we encounter in getting students to understand evolution are well explained by differences in their approaches to knowledge, specifically to how they expect to understand new topics. These approaches range from “just tell me what to memorize” to expecting us to help them understand the applications, implications, and trade-offs in various contexts. These different approaches are usefully understood as differences in adult cognitive development.

There is a substantial body of research on cognitive development in college and its implications for learning and teaching. This approach began with Perry's (1970) study of “intellectual and ethical development” in undergraduates. Perry's work has been cited by hundreds of subsequent studies (partially reviewed by Kniefelkamp, 1999; W. S. Moore, 2002). Several subsequent, related schemes have been proposed (reviews include Hofer & Pintrich, 1997, 2002; Love & Guthrie, 1999; *Educational Psychologist*, 2004). Bendixen and Rule (2004) proposed a model of the mechanisms underlying cognitive development, drawing in part on conceptual change theory (Dole & Sinatra, 1998).

Cognitive development beyond that typically found in undergraduates is a prerequisite for an adequate understanding of evolution. Sinatra, Southerland, McConaughy, and Demastes (2003) found a significant positive association between greater epistemological sophistication and greater acceptance of human evolution. The relationships with epistemological sophistication were also positive, but not statistically significant, for knowledge of evolution and for acceptance of animal evolution.

Applications of cognitive development in undergraduate teaching generally have been presented by, among others, Baxter Magolda (1999, 2000); Belenky, Clinchy, Goldberger, and Tarule (1986); King, Baxter Magolda, Barber, Brown, and Lindsay (2009); Mentkowski and Associates (1999); Meszaros (2007); and Nelson (1989, 1999). Applications in science have included some for evolution (Ingram & Nelson, 2009; Nelson, 1986, 2000, 2007, 2008), chemistry (Finster, 1991; 1992; Scharberg, 2006; Zielinski, 1995), environmental science (Bekken & Marie, 2007; Nelson, 2010b), and undergraduate research (Ryder, Leach, & Driver, 1999; Taraban, Prenskey, & Bowen, 2008). Baxter Magolda (1999, winter biology) showed how an interactive biology lecture course could be made developmentally effective.

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they termed *absolutism*, *relativism*, and *evaluativism*. Perry's terms for these three approaches (dualism, multiplicity, and relativism) have been widely used, although some studies have used alternative terminologies. A simplified summary of these major cognitive differences will make clearer the implications for teaching evolution.

(p.320) Absolutism (Perry's Dualism)

About two-thirds of first-year students and half of sophomores had absolutism as their core approach (Baxter Magolda, 2004a). These students think that knowledge is either clearly true or clearly false. The basis for the distinction is what one's “Authority” says. The question as to why one's authority (professor, parent, preacher, etc.) accepts those ideas is basically meaningless—the authority states it because it is true. No pertinent evidence or other support is expected, and none is helpful. Students applying this approach will dogmatically assert that evolution is false or, equally dogmatically, that it is true.

Relativism (Perry's Multiplicity)

When students first encounter meaningful uncertainty in a new area they typically have no idea how it might be resolved. In the face of uncertainty all opinions seem to be equally valid—any answer that one prefers on whatever grounds is fine. Personal experience, personally interpreted, has the preeminent role. This is the approach most of us usually use in picking a flavor of ice cream, but it is a terrible approach to critical thinking (Nelson, 2010b). Students using this approach will think that whether one accepts evolution or some version of creationism is a matter of unjustified personal preference, precisely parallel to the choice of a flavor of ice cream.

About one-third of first-year students and perhaps 80% of seniors were “transitional”: they regarded knowledge in some areas as absolute and knowledge in others as uncertain and, hence, arbitrary (Baxter Magolda, 2004a). Only about 16% of seniors were predominantly “independent knowers” who used relativism as their major approach (Baxter Magolda, 2004a). In this sense, liberal and disciplinary education failed for some 85% of the seniors.

Burgoyne and Downey (2011) have suggested that we ask students to see absolutism and relativism as two misconceptions: (1) There is only one right meaning, which should be provided by the teacher, and (2) If there is no one right meaning, then all should be treated as equally correct. Treating these as misconceptions should help students see that they might explicitly agree with them in at least some contexts and, crucially, that the faculty member is asking them to reject the misconceptions. Treating these ways of thinking as misconceptions implicitly also asks faculty to remember that these ideas will be resistant to change and will probably require the students to engage in several rounds of active reconsideration. As discussed in detail above, simply telling students what is wrong with a misconception is seldom adequate to transform it into a more useful view.

Contextual Knowing (Bendixen and Rule's Evaluativism; Perry's Relativism)

The approach where students have learned to make context-framed, criteria-based comparisons has also been termed contextual relativism (e.g., Knefelkamp, 1999) (p.321) and contextual knowing (Baxter Magolda, 2004a) to clearly distinguish context-framed, criteria-based choices from multiplicity. I will use *contextual knowing* for this approach as it clearly contrasts with the prior stages. Students here can understand and apply basic scientific thinking. They will be able to clearly explain how evolution is a powerful theory that is almost universally accepted by the scientific community.

As students become more cognitively sophisticated, they (like many older adults) typically use a mosaic of approaches, perhaps treating some topics in dualism/absolutism and some in multiplicity even while struggling to master contextual knowing in others (Baxter Magolda, 2001; Perry, 1970). Unfortunately, Baxter Magolda (2004a) found only 2 of 80 seniors studied who used predominantly contextual knowing. However, “post-college environments prompted movement toward independent and contextual knowing” (Baxter Magolda, 2004a, p. 37).

Beyond Contextual Knowing

The limitations of simple contextual knowing are evident when we consider complex problems. The core difficulty is that students who have learned to operate within a series of individual disciplines often have no coherent way to deal with differences that arise when a variety of disciplines apply to a complex problem. They consequently see any choice among combinations of disciplinary

For example, even a local environmental issue, such as the appropriateness of a nuclear power plant, requires a consideration of trade-offs across multiple perspectives including science, waste disposal, environmental economics, politics, and environmental racism, to name just a few (Nelson, 2010b).

To deal with such issues constructively, students must learn to consider the benefits and negative consequences illuminated by each perspective. As students learn to make such analyses they begin thinking in a way that Perry termed “Commitment [within contextual relativism]” and Baxter Magolda termed “self-authorship.” This approach is exceedingly rare among undergraduates except under transformed curricula (Baxter Magolda, 2000; Mentkowski & Associates, 1999) or intensive developmental interviewing (Perry, 1970). Despite its rarity, this would be the ideal outcome both for curricula in traditional liberal arts and for professional programs (Baxter Magolda, 2004b, 2007).

Applications to Teaching Evolution

“Perhaps the most useful developmental theory to be applied to evolution instruction is that of Perry” (M. U. Smith, 2010b, p. 541; also Nelson, 1986, etc.). Classroom applications that strive to foster cognitive development can profitably focus on key aspects of the three transitions between the four main approaches to understanding. **(p.322)** These are: initially understanding uncertainty, then using comparisons and criteria to address uncertainty (contextual knowing) and, later, using consequences and values to frame arguments and justify choices.

Uncertainty in evolution can be invoked, for example, by listing (or having the class list) currently viable alternative hypotheses, listing ones that were historically viable or by asking for deep understanding of experimental designs (Why is this control included? Are any controls missing? What untested hypotheses might have produced the same results?). Once some important uncertainty has been made clear, the alternative hypotheses or design considerations or other factors need to be compared, and possibly resolved, using appropriate criteria. Unless both the alternatives and the criteria are made explicit, most of the critical thinking will be tacit and therefore incomprehensible—and the students’ approaches to thinking will be unaffected.

For comparisons of historically grounded alternatives in evolution, such as what sequences should have been expected from the fossil record, an appropriate criterion is the result of a fair test. A fair test is a new set of data that could have confirmed any of the alternatives and that is different from (and not tightly tied to) the data sets on which they were proposed. We can ask: What patterns of change in the fossil record might have been expected of the fossil record when the geological column was first put into its modern order in the 1840s, noting that evolution was not really available except to Darwin. Alternatives included: all kinds at the beginning with just extinction, Lyell’s large cycles with great reptiles perhaps returning again (and again), Sedgwick’s extinctions and new recreations, vertebrates first and invertebrates by degeneration, and, of course, evolution starting, as Darwin noted, with one or a few very simple kinds. Students will suggest some of these ideas, if asked. The fossil record itself provides a fair test of these alternatives, as most of them were not based on the ordered sequence of rocks in the newly emerging geological column and as any of the alternative patterns could have been found.

A number of other criteria are also important. These include accounting for apparently conflicting scientific data and the availability of causal explanations (e.g., Nelson, 2008). The results of a number of fair tests and other criteria often can establish one set of scientific alternatives as very much more probable than another set, as has occurred with evolution.

However, even when we understand that one alternative is much more probable than another we may choose not to accept it. It is often appropriate to reject hypotheses that are probably true when there are serious risks to accepting the hypothesis and being wrong. Thus, for many considerations of safety in the face of severe consequences we demand not just that safety be very probable but that it be overwhelmingly probable (basic decision theory, below). This requires moving beyond contextual knowing.

For students studying evolution, going beyond contextual knowing would require that students understand the force of the evidence in the context of the nature of science generally; understand and know how to weigh the consequences **(p.323)** from the applications of evolution, both positive and negative; and understand how to fit evolution into larger cultural contexts. It thus becomes crucial for faculty members who teach evolution to help students address its consequences and applications. Faculty also need to consider whether to address the cultural contexts for evolution and, if so, how to do so effectively.

If we step back from focusing just on conceptual understanding or scientific reasoning, things become more complicated. Baxter Magolda (e.g., 2004a) noted that students make meaning of their experiences using their own perspectives rather than accepting the instructor's meaning and perspective. Further, the development of more complex ways of understanding is inextricably intertwined with the development of a different and more complex sense of self and of different and of more complex ways of relating to others. “Interviewees who developed complex ways of knowing [after graduation] often could not live those ways of knowing until they had developed complex ways of seeing themselves and their relations with others” (Baxter Magolda, 2004a, p. 39). Belenky et al. (1986) called this process the development of self, voice, and mind. More recently, the focus has been on the development of a sense of “self-authorship” using “Learning Partnerships” models of student-faculty collaboration to intentionally address cognition, identity, and peers (Baxter Magolda, 1999, 2009; Baxter Magolda, & King, 2004; Baxter Magolda, Abes, & Torres, 2008; King et al., 2009; Meszaros, 2007).

Let me stress again the importance of making extensive use of structured active learning and not just because it fosters content mastery. Appropriately structured collaborative and cooperative learning also helps foster increased cognitive sophistication and the other changes that are essential to that cognitive development.

I found two techniques to be especially powerful in fostering cognitive development:

1. In teaching evolution to seniors, I developed a worksheet based on Perry's descriptions of the cognitive tasks required for deep understanding (Nelson, 2010a), and had students complete the worksheet outside of class. Then, I implemented a whole-period discussion of applications of Perry's principles, a discussion that fostered deep rethinking with peers.
2. In courses ranging from first-year to graduate, I had the students either discuss excerpts from Perry's (1970) book including his summary of the student's experience (Nelson, 2010a) or presented and had them discuss and repeatedly refer back to a graphical synopsis of Perry (as in Nelson, 2010b).

Using either approach, I repeatedly asked students how a person would respond to the evolution-creation controversy (and to other issues) from the perspective of an absolutist, versus from multiplicity, versus, in turn, from contextual knowing and, later, from self-authorship (Nelson, 1986, 2000, 2007, 2010a, 2010b). These approaches (**p.324**) provided the metacognitive frames (Bendixen & Rule, 2004) and conversation types that foster and support changes in cognition and in sense of self (Baxter Magolda, 2004a). They were core to producing modest advances in students' cognitive development and helping them master evolution (Ingram & Nelson, 2006, 2009).

In summary, the answer to the question “What can faculty do to increase the proportion of students who ‘get’ evolution?” from this fourth perspective is that faculty need to design their courses to foster greater cognitive sophistication. In contrast, science faculty often teach as if science were discovered truths that can be memorized. This may reduce conflict with naive students' expectations but it leaves the students unable to understand even basic scientific reasoning let alone the overall argument for evolution. Alternatively, faculty may try to require that students understand how evidence is related to conclusions and, even, how to tell when a conclusion is suggestive versus very strongly supported and how to simultaneously consider multiple lines of evidence. But faculty may fail to recognize that most students cannot understand key parts of what is being asked without substantial help even if they are working quite hard at trying to do so, a finding that drove Perry's (1970) initial research.

Key Result 5: Understanding Evolution Often Is Not Sufficient for Its Acceptance

Scientists are used to changing their minds in the face of sufficient new evidence. They may tacitly or explicitly assume that students would accept evolution if they really understood how it works and the strength of the evidence supporting it. This was certainly my tacit expectation when I started teaching.

Empirically, however, increased mastery of evolution usually has not been associated with increased acceptance (Blackwell, Powell, & Dukes, 2003; Demastes-Southerland, Good, & Peebles, 1995; Demastes-Southerland, Settlage, & Good, 1995; Nehm & Schonfeld, 2007; Rice, Olson, & Colbert, 2010; Sinatra et al., 2003; Southerland & Sinatra, 2003). A key caveat is that most studies have assessed the students' understanding of natural selection and not their understanding of the evidence for large-scale evolutionary change.

extensive discussion of complicating factors, including contextual and measurement issues, which have resulted in considerable uncertainty regarding the relationships among understanding, acceptance, and other factors.

It is clear from studies of cognitive development that there is no necessary relationship between understanding and acceptance (e.g., Ingram & Nelson, 2006). Students who use either absolutism or relativism (see above) will tend to either accept or reject evolution independently of whether or not they understand the (p.325) underlying science. And students who use contextual knowing can deeply understand a series of contradictory arguments without needing to accept any of them. Nevertheless, increased cognitive complexity tends to increase students' acceptance of evolution, as discussed above.

Basic Goals in Teaching Evolution

What then should be our goals in teaching evolution? There is general agreement that these goals should include “a working (‘meaningful’) understanding of modern evolutionary principles” and an “acceptance of evolution as the best current available scientific explanation of the origin of new species from preexisting species” (M. U. Smith, 2010a, p. 525). As argued above, we should include a meaningful understanding of the evidence for large-scale change and other aspects of macroevolution. Implicit in the ideas of “meaningful understanding” and “acceptance of the best available scientific explanation” is a more general goal: helping students develop the abilities required to evaluate alternatives using appropriate criteria and helping them develop other aspects of cognitive complexity. Only then can they have a meaningful understanding and make an informed choice as to whether to accept or reject evolution in part or whole.

But are these goals enough? Several considerations have led to suggestions that more is required. These considerations include the importance of evolution in personal and practical affairs, the consequences of evolution as perceived by students, and the ways in which many or most people actually consider accepting evolution.

Personal and Practical Applications

M. U. Smith asked (2010a, p. 525): “Why is it important to understand evolution and accept it as a sound scientific explanation if that understanding does not result in some action—in some real-world decision-making that is informed by the precepts of evolution?” He proposed (p. 526) that “belief in the validity of evolutionary theory as an effective basis for decision making in the real world” is one of the “desirable outcomes of instruction, even though changes in beliefs are inappropriate goals on which students are to be evaluated.” In teaching senior biology majors, many of whom were contemplating biomedical careers, I found it especially effective to focus on the emerging field of Darwinian medicine as a way of illustrating the personal and practical benefits of evolutionary explanations (Greaves, 2002; Nesse, Stearns, & Omenn, 2006; Stearns & Koella, 2007; Trevathan, Smith, & McKenna, 2007).

Consequences as Perceived by Students

Students often have seen evolution as having major negative implications. Whether students accepted or rejected evolution, they usually viewed the consequences of accepting it negatively: “increased selfishness and racism, decreased spirituality, (p.326) and a decreased sense of purpose and self-determination” and, worse, both *more* exposure to evolutionary ideas and a *greater* knowledge of the principles and mechanisms of evolution were associated with *more* negative views of its consequences (Brem, Ranney, & Schindel, 2003, p. 181). These negative views of evolution make it especially important in teaching evolution to explicitly address benefits (as in Darwinian medicine) and the potential negative consequences. Wilson (2005) suggested that we should begin in teaching evolution by addressing the perceived negative consequences. His book (2007) provides a primer on how to do this.

Thinking about Accepting Evolution: Affective Components

A study of the effects of students' initial scientific and religious conceptions on subsequently understanding and accepting evolution found that “conceptual change has significant affective components” as “evaluation is often based on extralogical criteria” such that “goals, emotions and motivations play a significant role” (Demastes-Southerland et al., 1995, pp. 637–638, 661). Even when students clearly understand natural selection and other aspects of evolution, some “may choose not to believe” evolution “because they use different standards of evidence or refuse to abandon alternative core beliefs” (Ferrari & Chi, 1998, p.



Thinking about Accepting Evolution: Science with Religion

In practice, individuals often decide how to combine their religious views with their scientific views while they are in the process of trying to understand evolution. Evans, Legare, and Rosengren (2010) analyzed several alternative ways that people combine science and religion. The competitive (science *or* religion) model was contrasted with various reconciliations. Coexistence models included causal chains (creation and then evolution) and target dependent choices (animals evolved but humans did not; microevolution occurs but macroevolution does not). Coexistence models could be combined with intuitive or commonsense models, including essentialism and need-based and goal-directed reasoning. (See also Coley & Muratore, this volume; Gelman & Rhodes, this volume; Shtulman & Calabi, this volume, regarding essentialism; and Kelemen, this volume, regarding goal-directed reasoning.) Evans et al. (2010) suggested that need-based reasoning might serve as a transitional step from intuitive to evolutionary reasoning as it allows an acceptance of common ancestry. They noted that evolution is “particularly problematic [for learners], because it is highly counterintuitive, denying even the appearance of stability and purpose to the natural world” (p. 131). They noted that coexistence models provide a solution to this problem for many theologians and scientists.

A combination of religious belief with a partial or full acceptance of evolution is common. Students frequently used coexistence models (Brehm et al., 2003). Much (p.327) of the American public also uses coexistence models (Evans et al., 2010). Several prominent scientists have advocated combining full acceptance of evolution with religious belief (Alexander, 2008; Ayala, 2007; Collins, 2007; Gingerich, 2007; Gould, 1999; Miller, 2008; Roughgarden, 2006). Coexistence models with full acceptance of evolution have been advocated also by science faculty at religiously conservative colleges (Falk, 2004; Gibberson, 2008; Haarsma & Haarsma, 2007; Harrell, 2008), by thousands of Christian clergy and hundreds of Jewish rabbis (Zimmerman, 2010), and in official statements by various Christian denominations (Sager, 2008). The American Association for the Advancement of Science has published *The Evolution Dialogues: Science, Christianity, and the Quest for Understanding* (Baker, 2007), produced with input from scientists and theologians specifically for use in Christian adult education programs.

Thus, many people integrate evolution with their other views, including their religious commitments. Several authors have suggested that rather than ignoring these attempts, it is better to offer students some help in arriving at more complex ways of integrating evolution with their other beliefs, whether religious or not.

Pedagogical Implications

How could we foster the integration of evolution with the other aspects of students' lives? Dagher and BouJaoude (1997) suggested that learning evolution was likely to be facilitated by opportunities to discuss relevant values and beliefs. Similarly, W. W. Cobern (1996) suggested that when students understand but do not accept evolution, faculty should initiate a discussion of the nature of science and of its place in personal and cultural worldviews. Further, “teachers should promote discussions about the reasons one has for believing and thinking the things that one does” (W. W. Cobern, 2000, p. 237). He subsequently agreed with Noddings that religious and metaphysical questions should be “treated wherever they arise,” that students usually are implicitly asking such questions, and that faculty “should plan their lessons to include such material” (Noddings, 1993, p. 132, as quoted by B. Cobern, 2004, p. 588.)

Brehm et al. (2003, p. 200) suggested a complex approach to teaching. They advocated both fostering conceptual understanding and going beyond it to include “communication of, reflection upon and respect for multiple perspectives.” This approach would include “open-ended discussions about why multiple perspectives may be supported and how social and political agendas may shape science.” It should help students understand that “arriving at a single class perspective is unlikely, and even undesirable, both because the science is too rich and complex to support just one account, and because personal commitments and beliefs have a valid role in issues of social and personal import.”

Sinatra et al. (2003, p. 524) argued that in teaching evolution, “teachers must explicitly address the beliefs and knowledge students bring into the classroom.” They argued further that the goals should include lessening the emotional demands (p.328) on students who view evolution as contrary to their religious beliefs and fostering a “willingness to think deeply about a complex problem and question one's own beliefs” (p. 524).

Why is it so difficult for is not the conversion of students either to our own ways of accommodating science and spirituality or to



Does Treating Creationism in Science Courses Increase Acceptance of Evolution?

There is some direct evidence that addressing creationism is helpful. A recent president of the U.S. National Academy of Sciences argued that "intelligent design should be taught in science classes" as "it is through the careful analysis of why intelligent design is not science that students can perhaps best come to appreciate the nature of science itself" (Alberts, 2005, p. 741). Verhey (2005, 2006) compared two versions of a course on introductory biology. Each version included structured discussion sessions. Students in one version read Dawkins's (1996) *Blind Watchmaker* together with a prodesign critique of evolution (Wells, 2002) and an analysis of the critique (Tamzek, 2004). Students in the other version discussed only readings elaborating on evolution (such as Ridley, 1995). When students explored both views, there was a much greater shift toward full acceptance of evolution, especially among students who initially rejected macroevolution. Similarly, instruction that asked students to compare creationist ideas with standard science produced an increased acceptance of evolution, especially among students who were initially undecided (Ingram & Nelson, 2006).

Fostering understanding also may not be enough in preparing high school teachers. A graduate course on evolution increased prospective teachers' knowledge of evolution and reduced their misconceptions but did not change their views on what should be presented to precollege students (Nehm & Schonfeld, 2007). Both before and after the course approximately half of the prospective teachers favored the inclusion of antievolutionary ideas in high school classes and approximately half favored presenting only evolution.

Adding a consideration of creationist ideas can change what teachers are willing to do. Experienced high school biology teachers decided to teach evolution more extensively after they learned to teach how multiple lines of evidence support evolution together with a complex view of the nature of science and were shown how to counter common creationist claims (Nelson et al., 1998; Scharmann & Harris, 1992). Thus, as suggested by Sinatra et al. (2003), a comparative approach to evolution and creationism grounded in a rich view of the nature of science would seem to be an essential part of the preparation of precollege science teachers specifically, just as it seems essential for teaching undergraduates generally.

(p.329) Advanced Approaches to Teaching Evolution to Undergraduates

We thus have a paradox. Interactive comparisons of religious views with evolution are more effective in getting students to accept evolution than are approaches that focus only on the science. However, many college faculty, like many high school teachers, have been reluctant to directly or indirectly address creationism. The reasons for this have included viewing the teaching of creationism as fundamentally inappropriate, feeling pressure to cover specific scientific content, feeling a lack of appropriate preparation (limited knowledge of creationist arguments and appropriate counters), and being reluctant to confront students' beliefs or to be challenged in class (Alters, 2005, 2010; Blackwell et al., 2003; Griffith & Brem, 2004). As just discussed, there are strong reasons to reconsider these objections in addition to the obvious importance for teacher preparation. Perhaps most fundamentally, traditional approaches to teaching evolution have not fostered any substantial change in its acceptance by the general public over the last few decades (Newport, 2009) despite a considerable increase in the proportion of the population that is college educated.

Several alternative approaches have been suggested for dealing with students' nonscientific conceptions. It is possible to ignore their conceptions or to insist that any nonscientific ideas be restated as testable scientific hypotheses before they can be discussed. Here, the stated goal is for science students to believe that evolution affords the best current scientific account. Whether they accept it or not is seen as beyond the scope of the class. However, given the research discussed above, this approach seems unlikely to achieve even limited success with goals like "belief in the validity of evolutionary theory as an effective basis for decision making in the real world" (M. U. Smith, 2010a, p. 526). Further, students generally are not prepared to intelligently compare evolution with other frameworks on their own. They have had no practice in distinguishing science and nonscience and have no real knowledge of the criteria used in science to distinguish good ideas from terrible ones. Five strategies seem predictably better for fostering the understanding, application, and acceptance of evolution.

Strategy 1. Implicit Refutations of Creationist Ideas

One could discuss selected creationist misconceptions with only implicit reference to creationism, thus addressing key ideas without calling explicit attention to their creationist connections (Nelson, 2007). For example: "one might think that evolution w

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fossils from sites quite distant from those that had been studied previously and by molecular phylogenies. **(p.330)** As a final example, one could also note Darwin's discussion of the problem posed by organs of “extreme perfection” together with current evidence on the origins of eyes, insect wings, cilia, blood clotting cascades, and so forth, without explicitly noting the use of these examples by creationists.

The apparent advantages of this strategy, avoiding direct confrontation with students' religious views and saving more time for science, lead directly to its weaknesses (Nelson, 2007). Students may conclude that although pieces of what they thought were wrong, the basic creationist argument is sound and thus they may seriously underestimate the scientific strength of evolution. This strategy also lacks the power of having students examine their own ideas.

Strategy 2. Limited Direct Comparisons

Alberts's (2005) suggestion that intelligent design should be included in college science courses in order to teach the nature of science requires providing students with appropriate resources. Having students read Behe's (1996, 2003) canonical presentations of intelligent design together with counterarguments (Miller, 1999, 2003) should be a powerful strategy in parallel to Verhey's (2005) use of other readings.

Strategy 3. Treat the Nature of Science Extensively

If we want our graduates to deal with any controversies involving science and its applications, we must provide students with tools that allow them to compare claims—we must teach them critical thinking and an operational model of the nature and limits of science that goes well beyond memorizing “the” scientific method (Nelson, 1986, 2007; Sinatra et al. 2003).

Holding a complex view of the nature of science may facilitate the acceptance of evolution (Lombrozo, Thanukos, & Weisberg, 2008; Rutledge & Warden, 2000; M. U. Smith, 2010a). Sinatra et al. (2003) suggested teaching the nature and limits of scientific knowledge to foster such acceptance (an approach developed in detail for evolution by Nelson, 1986, 2000; 2007; Nelson, Nickels, & Beard, 1998; Scharmann & Harris, 1992; Scharmann, Smith, James, & Jensen, 2005; Wilson, 2005). Southerland and Sinatra (2003) suggested that a good start on fostering broader understanding and acceptance of evolution would be to focus on a rich understanding of the nature and limits of science, one that included its relationships to belief.

Students who were taught about scientific arguments developed better arguments, as did students who were more cognitively complex (Nussbaum, Sinatra, & Poliquin, 2008). Students who had a deeper understanding of the nature of science were more likely to accept evolution (Southerland & Sinatra, 2003). High school biology teachers who understood the nature of science better were more likely to teach evolution extensively (Nelson et al., 1998; Scharmann & Harris, 1992). Key aspects of the nature of science deserve some elaboration (examples mostly from Nelson, 1986, 2000, 2007).

(p.331) Patterns, Causes, and Limits

At its core, science summarizes empirical patterns (the planets go around the sun in irregular ellipses) and finds causal explanations that explain why those patterns exist (the orbits are due to the interaction of inertia and warped space). Religion has been of no direct help in choosing among alternative patterns or in finding their causes. Attributing the orbits to design fails as an explanation because it could apply to any pattern of planetary movement (triangles, for example). This distinction between *explanation* in the scientific sense and *attribution* to a supernatural power helps students understand the nature of science and the limits of religion in thinking about the natural world.

Limits, Origins, and Key Ideas

It is always useful when teaching science to make a distinction between those aspects for which the evidence is strong and those where ideas are very tentative or speculative. Viewed in its broadest sense, evolution consists of two areas where knowledge is generally well supported that separate three “origins” questions where scientific ideas are very speculative and direct evidence is slim or absent (Nelson, 2000). The processes and history of the physical and chemical development of the universe are generally well understood as are the processes and history of the evolution of life. However, our ideas are much more speculative on the origin of the universe in or before the big bang; the origin of life (Kumala, 2010), particularly the origin of a tRNA mediated genetic code; the origin of consciousness from molecular reactions.

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evolution is an explanation of the origin of species from ancestral species, not the origin of the first living thing” and argued that “this narrow interpretation of evolution has dramatic positive implications for instruction ... individuals do not have to accept a totally materialistic explanation of the creation of the first life on earth, which many students view as a religious issue.” The same is true for the origin of the universe and the origin of consciousness (which is related to conceptions of souls). Note that making these distinctions does *not* claim that these origins were not wholly naturalistic or that we will not be able to show their naturalistic origins in due time or, even, that we are not making substantial scientific progress on each of them. Rather, it simply acknowledges that we do not currently have secure scientific knowledge of how they happened.

Human Origins and Evolution

The central point in the three origin questions just addressed is not that we should avoid issues that may challenge some or many students’ prior beliefs but, rather that we should be careful to acknowledge when scientific ideas are heavily speculative. In contrast to those three origin questions, the evidence for human evolution is very strong. Much intuitive resistance to evolution centers on human evolution for (p.332) psychological reasons, for reasons of personal incredulity and for reasons flowing from perceived consequences (Sinatra et al., 2003; Evans et al., 2010) and for theological reasons including original sin (Nelson, 1986, 2000). Hence, it is important to use humans and other primates to illustrate many aspects of evolution (Nelson & Nickels, 2001; Nickels & Nelson, 2005; Wilson, 2005). As O’Brien, Wilson, and Hawley (2009) noted: “Including human-related material engages non-biologists and gives biology students a new perspective on an old topic.” Werth (2009) listed multiple examples of human-related content and showed substantial increases in understanding from their use.

Broadly incorporating humans into a treatment of evolution also makes the material more interesting. Engagement was particularly strong when we used plastic replicas of human, ape, and fossil skulls (Nelson & Nickels, 2001). Recent books have made it easy to provide human-related examples and readings. Good examples include Greaves (2002) on the evolutionary origins of cancer, Held (2009) on evolutionary-developmental explanations of the quirks of human anatomy, and Johnson (2007) on the development of our knowledge of genes and genomes using many examples from human evolution.

Patterns, Causes, and Scientific Advances: Darwin as the Newton of Biology

Copernicus summarized the empirical patterns of planetary movement. Newton provided the causal explanation (interactions of gravitation and inertia). In so doing he replaced direct action by God with the action of natural laws. Darwin’s role in biology was similar. Paley summarized a major empirical pattern, organisms have complex adaptations, and argued that this pattern was evidence of design by a creator. Darwin agreed that many features of organisms were adaptive but explained their origin by heritable variation and natural selection. Again, *attributing* a natural pattern to God was *not* a substitute for a scientific *explanation*.

Multiple Independent Lines of Evidence

Darwin (1859) used confirmation by multiple independent lines of evidence as the central argument for evolution. It is important to set side-by-side Darwin’s explanations of Linnaeus’s groups, of biogeography and paleobiogeography, of Paley’s list of adaptations, and of many other aspects of biology. Connecting these into a larger pattern allows students to understand multiple confirmation as a core aspect of scientific argumentation and also understand how evolution explains all of biology.

Breadth of Causal Explanation

Students should understand how far we have come with causal explanations. Darwin had three key processes: natural selection and, more vaguely, the tendencies of organisms to resemble their parents and other ancestors and to vary somewhat from their siblings and other relatives. His causal explanations for resemblance and (p.333) variation were inadequate. DNA provides a deep causal explanation for why groups of organisms that share a common ancestor *must* resemble each other and *must* differ from groups that do not share that ancestor. Molecular and comparative biology have documented causes and patterns for multiple modes of speciation (Coyne & Orr, 2004).

Use Darwin’s Writings and His Context

Campbell and Daughtrey (2006) proposed a historically framed and argument based approach to teaching evolution in the context of the nature of science. Specifically, they suggest setting a close examination of Darwin’s (1859) argument and his earlier



Advantages and Limitations of Focusing on the Nature of Science

This approach makes evolution, the nature of science, and the interactions between them central course themes. This makes it easier to prioritize content. The aspects of the nature of science that *must* be taught are primarily those needed for the larger picture. "The" scientific method and the nature of "theory" can be ignored unless the teacher uses them repeatedly. Similarly, biological content can be pruned to emphasize aspects that illustrate the larger framework.

It would be possible to use this strategy and remove the explicit discussions of religion. While systematically showing the scope and strength of the science that supports evolution and its relation to the general nature of science, many common creationist misconceptions could still be countered. However, an emphasis on scientific explanation versus religious attribution cuts to the heart of design arguments. This comparison can help students see how to integrate their scientific understanding with their religious commitments.

Strategy 4. Facilitate Deeper Consideration

In addition to helping the students to better understand the biology and the nature of science, we could help them articulate and compare alternative ways of integrating their understanding of science with their own religious or other personal or socially (or academically) derived frameworks. This approach directly addresses the problems discussed above and delineated by Brehm et al. (2003), B. Cobern (2004), Evans et al. (2010), Nehm and Schonfeld (2007), Nelson (1968, 2000, 2007), Sinatra et al. (2003), and Southerland and Sinatra (2003).

The six tactics described next have two main goals in addition to fostering a deep understanding of evolution. One is to make explicit the failure of creationist arguments in the realm of science. The second is to make it easier for students to change toward more fully scientific positions by helping them bridge the gap that many of them see between antiscientific creationism and antireligious evolution. The approaches described here (largely taken from Ingram & Nelson, 2006; Nelson 1986, 2000) have (p.334) been paralleled in part by those used or advocated by several others (Scharmann, 1993, 2005; Scharmann et al., 2005; Verhey, 2005).

Tactic 1: Emphasize Understanding as Prior to Belief or Acceptance

Announce that the central goal in teaching evolution is not to get students to accept or believe evolution. Rather, the central tasks are for them to understand how evolution is central to biological explanation and why most scientists evaluate evolution as great science. Note that asking them to decide whether to accept evolution before they understood these things would be premature and would make it harder for them to learn the critical thinking core of scientific reasoning.

Tactic 2: Student Discussions Analyzing Creationist Arguments

Provide creationist readings pertinent to any of the points addressed by the preceding strategies. Gould's (1985) essay, "Adam's navel," included extensive quotes from a pre-Darwin scientist who argued that the fossil record had been created intact as a necessary part of creating an earth that had the appearance of age. Gould provided a very sympathetic refutation. I found discussions of this article guided by a set of study questions to be quite successful.

Gould's (1993) summary of fossil history provides extensive descriptions of key fossil assemblages and their depositional environments. Having students discuss how these can or cannot be explained by evolution and by flood geology helps them understand the evidence for great geological age, the abundance of fossils and their occurrence in ecologically coherent assemblages, and the evidence they provide for macroevolution as well as of the scientific vacuity of flood geology.

Tactic 3: No Necessary Conflict

Many students believe that religion and evolution have fundamental conflicts. As discussed above, many prominent scientists think that there is no necessary conflict. Some science faculty at religiously conservative colleges and many Christian clergy and Jewish rabbis agree. Many students are quite surprised to learn this.

M. U. Smith and his colleagues (Smith 2010a, 2010b; M. U. Smith & Scharmann, 2008) have taught Gould's (1997) view of science and religion as separate, nonoverlapping magisteria together with J. A. Moore's (1984) view of science as a way of

view is valid, greater engagement with students' religious ideas is necessary.

Tactic 4: Affirmative Neutrality

College and precollege science teachers who are apprehensive about teaching evolution for personal or contextual reasons may be able to use "affirmative neutrality" (Hermann, 2008) to appropriately and effectively teach evolution even when their students are resistant. Meadows (2009) provided a detailed guide to such an (p.335) approach. He has developed an inquiry approach that helps students understand evolutionary evidence and explanations while the teacher maintains strict neutrality as to whether students should accept them personally. He also provided numerous suggestions for maintaining neutrality and alternative exercises designed especially for "resistant" students. Although Meadows developed this approach for precollege science, key aspects such as the use of alternative exercises for resistant students offer important pedagogical options for college faculty.

One might worry that this approach transgressed the limits appropriate for public school education. However, Scott (2009) endorsed Meadows's (2009) book as providing "a clear *how-to*" for "teaching with integrity the 'controversial' subject of evolution." Scott's view must be given considerable weight here as she is the Executive Director of the National Center for Science Education, the leading organization in protecting scientific integrity in the teaching of evolution, especially in precollege institutions.

Tactic 5: Bridge the Dichotomy

Many students see a chasm between biblical creationism and antireligious statements of evolution and have never considered intermediate positions, and, indeed, they may not know that such intermediates exist. M. U. Smith (2010b, p. 550) suggested: "Teachers will find it helpful to recognize both a range of religious views that students may hold and a range of views of the relationship between science and religion." Helping students understand a multiposition gradient (young-earth creationist, progressive creation, theistic evolutionist, nontheistic evolutionist, and atheistic evolutionist) encouraged them to explore what kind of creationist, if any, that they currently might be and, thus, to consider integrating evolution with their other views (Nelson, 1986, 2000). Alternatively, one might use the groups found empirically by Brehm et al. (2003): creationists (strong creationists, human-only creationists, nonspecific creationists), uncertain, and evolutionists (nonspecific evolutionists, interventionist evolutionists, theistic evolutionists, nontheistic evolutionists). Either way, it is important to emphasize the diversity of theological positions and the trade-offs that lead to some of these choices (Nelson, 1986, 2000). Haarsma and Haarsma (2007) discussed ten different theological positions pertinent to evolution and argued that "evolutionary creation" was preferable. A single combined lecture and laboratory period led to more positive views toward evolution and to more complex views of the nature of science when it was used for structured discussion of students' views on evolution and creation and for discussion of what should be taught in science classes (Scharmann, 1990).

Tactic 6: Basic Decision Theory

"All too often students believe that learning about evolution, much less 'believing' it, requires the rejection of currently held personal beliefs," and "individuals may fear that they risk eternal damnation" so that the justifications for any acceptance of evolution "have to be strong indeed" (M. U. Smith, 2010b, p. 549). Rejecting (p.336) evolution can be a fully rational decision under any assumption of such strong negative consequences (Nelson, 1986, 2000).

Decisions on which ideas to adopt from among an array of competing positions should take into account the costs and benefits of using the ideas as well as their relative probability. Although evolution is *the* essential idea for a biological scientist, its value to nonscientists often is not immediately apparent to many students, who may initially see only negative social and religious costs (Brehm et al., 2003; Wilson, 2005). As noted earlier, it is essential to have students consider the real world benefits of evolution and to help them discuss any negative consequences they may perceive.

Students' ideas of the religious trade-offs that arise from biblical literalism may become more complex if they consider Saint Augustine's (415/1982, pp. 42–43) argument in *The Literal Meaning of Genesis* that "Usually even a non-Christian knows something about the earth ... 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. ... How are they going to believe those books in matters concerning ... the kingdom of heaven, when they think their pages are full of falsehoods on facts which they themselves have learnt from



Strategy 5: Wilson's Evolution for Everyone

Wilson's (2005) innovative course, *Evolution for Everyone*, illustrates a powerful way to make broad connections to students' views and values (see also Wilson, 2007). Several features were key:

Begin with negative implications. “Evolution has been associated with immorality, ... genocide ... racism and sexism. All of these negative associations must be first acknowledged and then challenged” (Wilson, 2005, p. 2059).

Adaptationism. Understanding the reasoning behind natural selection yields a powerful way of explaining nature. Wilson initially asked students to suggest situations in which it might be adaptive for animals to kill their own offspring (infanticide).

Adaptationist thinking is broadly applicable. Many of these were addressed (sexual dimorphism, sex ratios, social behavior, etc.).

Humans too. Topics included sex differences, homosexuality, infanticide, and morality.

“Not everything is adaptive” and “adaptations are not always benign” (Wilson, 2005, p. 2061). Good biological reasons may keep characteristics nonadaptive.

Applications. The course turned to advanced topics such as Darwinian medicine and to student projects and posters.

Evaluation. One approach used anonymous responses to: “How much has this class changed your views on evolution and its relevance to human behavior, on a scale from –10 (negative change) to +10 (positive change)?” Only one student reported a negative change; over 100 reported positive changes with a mode at +5, reactions that were independent of religious and political stances.

(p.337) This approach has now been used to create broadly interdisciplinary, undergraduate and graduate certificate programs in evolutionary studies at Binghamton University and elsewhere (O'Brien, Wilson, & Hawley, 2009; Wilson, 2005).

Conclusions

Overall, we have arrived at a place in our understanding of how evolution might best be taught to undergraduates that I, and, I dare say, many of my scientific colleagues once would have rejected out of hand. Traditional teaching has not worked nearly as well as we thought. Newer pedagogies that work better when applied to simpler, less contested ideas are also quite helpful when applied to evolution, but now seem unlikely to be sufficient.

Frameworks that combine religion with an acceptance of some or all of the core ideas of evolution are common among major scientists, our students, the general public, and many theologians and clergy. Important research findings suggest that we should help students examine creationist ideas if we wish to foster a serious consideration of evolution by them.

If we are to address creationist ideas, we must provide the students with tools that allow them to compare claims—we must teach them an operational model of the nature and limits of science and of scientific reasoning that goes well beyond memorizing “the” scientific method (Nelson, 1986; Sinatra et al., 2003). We need to foster open-minded, nonabsolutist cognitive dispositions as suggested both by analyses of students' views (Sinatra et al., 2003) and by adult cognitive development as applied to evolution (Nelson, 1986).

Further, even when students understood and accepted evolution, they often viewed the consequences of accepting it as quite negative, with greater knowledge of evolution leading to more negative views (Brehm et al., 2003; Wilson, 2005). These findings suggest that we need to foster an explicit consideration of and respect for multiple perspectives (Brehm et al., 2003) and “explicitly address the beliefs and knowledge students bring into the classroom” in ways that foster a “willingness to think deeply about a complex problem and question one's own beliefs” (Sinatra et al., 2003 p. 524). Our aim should *not* be the conversion of students to our particular accommodations of science and spirituality or to our rejections of all such accommodations. Rather, we should help students understand why such a wide array of alternative combinations exists. This allows students to consider their own accommodations without us pushing them toward particular ones.

we avoid direct discussion of religion in contexts such as public school science, approaches that implicitly address creationist claims and focus on a complex **(p.338)** view of the nature of science seem likely to yield significant improvements in students' learning and in their acceptance of evolution.

Focusing on techniques that increase acceptance of evolution seems likely to further both our goals of more effectively teaching evolution and scientific thinking and the students' twin goals of learning and making good grades. Students in introductory biology who accepted evolution earned final grades one full letter grade higher on average than those of creationists, whether acceptance was determined before the course or after (McKeachie, Lin, & Strayer, 2002).

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