

Teaching evolution (and all of biology) more effectively: strategies for engagement, critical reasoning, and confronting misconceptions

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Synopsis The strength of the evidence supporting evolution has increased markedly since the discovery of DNA but, paradoxically, public resistance to accepting evolution seems to have become stronger. A key dilemma is that science faculty have often continued to teach evolution ineffectively, even as the evidence that traditional ways of teaching are inferior has become stronger and stronger. Three pedagogical strategies that together can make a large difference in students' understanding and acceptance of evolution are extensive use of interactive engagement, a focus on critical thinking in science (especially on comparisons and explicit criteria) and using both of these in helping the students actively compare their initial conceptions (and publicly popular misconceptions) with more fully scientific conceptions. The conclusion that students' misconceptions must be dealt with systematically can be difficult for faculty who are teaching evolution since much of the students' resistance is framed in religious terms and one might be reluctant to address religious ideas in class. Applications to teaching evolution are illustrated with examples that address criteria and critical thinking, standard geology versus flood geology, evolutionary developmental biology versus organs of extreme perfection, and the importance of using humans as a central example. It is also helpful to bridge the false dichotomy, seen by many students, between atheistic evolution versus religious creationism. These applications are developed in detail and are intended to be sufficient to allow others to use these approaches in their teaching. Students and other faculty were quite supportive of these approaches as implemented in my classes.

Introduction

Public resistance to accepting evolution seems to have become stronger even as the strength of the evidence supporting evolution, already overwhelmingly strong, has increased markedly in the advancing molecular era in biology. There is a tendency among faculty to attribute public distrust of evolution almost entirely to religious fundamentalism or even to nefarious political manipulation or pandering. These are very convenient views as they absolve faculty of responsibility for asking whether evolution and the nature of science are being taught effectively in our introductory and specialized courses (Alberts 2005).

For at least three decades, the evidence has been quite strong that traditional teaching is not very effective in college and university classes in science and other disciplines (Terenzini and Pascarella 1994). More precisely, the problem is that while traditional methods are “not ineffective” and work for some students, they are not nearly as effective as some well-documented alternative approaches (Pascarella and

Terenzini 2005). For student learning in introductory physics, Hake (1998, 2002) showed that “interactive engagement” is more effective than traditional teaching on average by a factor of two and for best practices by a factor approaching three. Lion Gardiner (1994), a zoologist at Rutgers, wrote a classic summary of how one can easily make large gains: *Redesigning higher education: producing dramatic gains in student learning*. Although science faculties are experts at using data, they have often continued to teach ineffectively, even as the evidence that those ways are inferior has become stronger and stronger. I will summarize three foundational pedagogical changes that, when used together, increase the understanding and, even, acceptance of evolution in college and university courses. These strategies are also applicable to a wide range of other science courses. They increase deep mastery of the content of the course and, perhaps more importantly, they increase the students' mastery of scientific thinking and of critical thinking, generally, and their understanding of the nature of science—outcomes that are of fundamental importance for scientific literacy

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and public support of science and its appropriate applications.

I also present some illustrations of classroom activities that combine these three changes. The activities mostly have not been published previously but the core ideas draw on several prior summaries focused on teaching evolution effectively, summaries that also provide more extensive literature reviews (Nelson 1986; Nickels et al. 1996; Nelson et al. 1998; Nelson 2000; Alters and Nelson 2002; Alters 2005; Scharmann 2005; Scharmann et al. 2005; Verhey 2005a, 2005b; Wilson 2005, 2007). The tables provide key introductory citations both for college teaching generally (Table 1) and for finding some of the advanced literature on learning and teaching in colleges and universities (Table 2).

Fundamental change 1: use structured active learning extensively

Hake (1998, 2002) assembled the most impressive dataset illustrating the effectiveness of alternative pedagogical strategies in college and university science. The data are for key concepts in introductory physics. Hake (1998) defined “traditional” teaching of physics as “relying primarily on passive-student lectures, recipe labs, and algorithmic problem exams” and “interactive engagement” methods as “those designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors.”

Table 1 Getting started in more effective college teaching

I. Teaching Basics [Check the descriptions of all books on Amazon or etc.]

Good teaching overviews—Pick one (or one of many others) for your library:

- McKeachie WJ, Svinicki M. 2006. McKeachie's teaching tips: strategies, research and theory for college and university teachers. 12th Edition. Boston: Houghton Mifflin.
- Nilson LB. 2003. Teaching at its best: a research-based resource for college instructors. 2nd Edition. Bolton (MA): Anker.
- Weimer M. 2002. Learner-centered teaching: five key changes to practice. San Francisco: Jossey-Bass.

Handbooks on college science teaching:

- Kalman CS. 2007. Successful science and engineering teaching in colleges and universities. Bolton (MA): Anker.
- Mintzes JJ. 2006. Handbook of college science teaching. Arlington (VA): National Science Teachers Association.

Great first downloads:

- IDEA Papers. Manhattan KS: The IDEA Center. [Improving: Lectures, discussions, essay tests, student writing...with literature] 4–8 p. Free PDFs. Available from: <http://www.idea.ksu.edu/resources/Papers.html>
- Tomorrow's Professor Listserv. Stanford [University] Center for Teaching and Learning. Archives. <http://ctl.stanford.edu/Tomprof/index.shtml> [Blog at MIT <http://amps-tools.mit.edu/tomprofblog/>]

Use one of these in designing or revising a course:

- Bean J. 1996. Engaging ideas: The professor's guide to integrating writing, critical thinking, and active learning in the classroom. San Francisco: Jossey-Bass.
- Fink LD. 2003. Creating significant learning experiences: an integrated approach to designing college courses. San Francisco: Jossey-Bass.
- Wiggins G, McTighe J. 2000. Understanding by design. Association for Supervision and Curriculum Development [ASCD].

Use one of these in designing or revising student evaluation and grading:

- Walvoord BEF, Anderson VJ. 1998. Effective grading: a tool for learning and assessment. San Francisco: Jossey-Bass.
- Stevens DD, Levi AJ. 2004. Introduction to rubrics: an assessment tool to save grading time, convey effective feedback and promote student learning. Sterling (VA): Stylus.

Three key summaries of important research [for all faculty]:

- Baxter Magolda M. 2001. Making their own way: narratives for transforming higher education to promote self-development. Sterling (VA): Stylus. [Fundamental to understanding liberal education.]
- Gardiner LF. 1994. Redesigning higher education: producing dramatic gains in student learning. ASHE Higher Education Report. (All the fundamentals in p. 200.)
- Mentkowski M and Associates 1999. Learning that lasts. San Francisco: Jossey-Bass.

Two major collections of teaching resources:

- Pescosolido BA, Aminzade R (Editors). 1999. The social worlds of higher education: handbook for teaching in a new century. Pine Forge Press. [55+ articles]. Companion CD: Field guide for teaching in a new century: ideas from fellow travelers. (70+ items on pedagogical techniques.)
- Feldman KA, Paulsen MB (Editors). 1998. Teaching and learning in the college classroom. 2nd Edition. ASHE Reader/Ginn Press [50+ articles]. ASHE=Association for the Study of Higher Education.

II. Structured Student-Student Interaction—A Key to Effective Learning and Teaching

Good sources of proven techniques:

- Barkley E, Cross KP, Major CH. 2004. Collaborative learning techniques: a handbook for college faculty. San Francisco: Jossey-Bass.
- Bonwell CC, Eison JA. 1991. Active learning: creating excitement in the classroom. ASHE-ERIC Higher Education Report.
- Millis BJ, Cottell PG. 1997. Cooperative learning for higher education faculty. American Council on Education/Oryx Press.

(continued)

Table 1 Continued

Starting sites for a few different important techniques:

- Pedagogies. Project Kaleidoscope. [Overview of 12 active-learning pedagogies, focused on science but broadly useful.] Available from: <http://www.pkal.org/keywords/Pedagogies.cfm>
- Case Study Teaching in Science, National Center for at SUNY-Buffalo. (Clyde Herreid) [How to and many cases.] Available from: <http://ublib.buffalo.edu/libraries/projects/cases/case.html> Don't miss the links to other case studies sites: <http://ublib.buffalo.edu/libraries/projects/cases/webcase.htm>
- Collaborative Learning. National Institute for Science Education, University of Wisconsin Madison. Available from: <http://www.wcer.wisc.edu/archive/CL1/CL/default.asp> Includes: Cooper J, Robinson P. 1998. Small-group instruction in Science, Mathematics, Engineering and Technology (SMET) Disciplines: a status report and an agenda for the future, Cooper J, Robinson P. 1997. Small-group instruction: an annotated bibliography of science, mathematics, engineering and technology resources in higher education.
- Just-in-Time-Teaching. Available from: <http://134.68.135.1/jitt/>
- Problem Based Learning Clearing House. University of Delaware. Available from: <https://chico.nss.udel.edu/Pbl/>. See also list of more sites: <http://www.udel.edu/pbl/others.html>; and Problem-based Learning, especially in the context of large classes. Available from: <http://chemeng.mcmaster.ca/pbl/pbl.htm>
- Team Based Learning. Available from: <http://www.ou.edu/pii/teamlearning/>

III. Using Writing (without grading killing you, even in large classes)

- Calibrated Peer Review Available from: [http://cpr.molsci.ucla.edu/\(CPR\)™](http://cpr.molsci.ucla.edu/(CPR)™) “is a Web-based program that enables frequent writing assignments even in large classes with limited instructional resources. In fact, CPR can reduce the time an instructor now spends reading and assessing student writing.” Developed for science.
- Smith R. 1994. Sequenced microthemes: a great deal of thinking for your students, and relatively little grading for You. Teaching Resources Center Newsletter 5. Available from: <http://www.indiana.edu/~wts/cwp/assign/microseq.html>
- Wenker A, Pearce T. 2008. The WAC clearinghouse bibliography: communication across the curriculum. Available from: <http://wac.colostate.edu/bib/index.cfm?category=1>. Discipline specific writing guides, available from <http://wac.gmu.edu/guides/GMU%20guides.html> and <http://www.marquette.edu/wac/>

IV. Is it Working? (Assess and document what is happening in your classes)

- Assessment Resources, National Resource Center on the First-Year Experience and Students in Transition, University of South Carolina. Includes a searchable database of assessment instruments and much more. Available from: <http://www.sc.edu/fye/resources/index.html>
- Angelo TA, Cross KP. 1993. Classroom Assessment Techniques. 2nd Edition. San Francisco: Jossey-Bass. See also for online examples: <http://www.siue.edu/%7Ededer/assess/catmain.html>
- FLAG: Field-tested learning assessment guide for Science, Math, Engineering, and Technology. Available from: <http://www.flaguide.org/>
- Knowledge Surveyor (course, curriculum, and program assessment tool; helps faculty discover strengths and weaknesses). Available from: <http://www.knowledgesurveyor.und.edu/>
- Hutchings P (Editor). 1998. The course portfolio: how faculty can examine their teaching to advance practice and improve student learning. Sterling, (VA): Stylus.
- Bernstein D et al. 2006. Making teaching and learning visible: course portfolios and the peer review. Bolton, (MA): Anker.
- Example portfolios at: Indiana University. (Available from: <http://www.indiana.edu/~deanfac/portfolio/def.html>), Xavier University. (Available from: <http://cat.xula.edu/initiatives/cpwg/>), Gallery of Teaching and Learning, Carnegie Foundation. (Available from: <http://gallery.carnegiefoundation.org/>), and see: Werder C. 2000. How to prepare a course portfolio. Available from: <http://pandora.cii.www.edu/cii/resources/portfolios/preparation.asp>

Scores of books and several thousand papers have been published on improving college and university teaching. Any selection is necessarily idiosyncratic and incomplete. This list focuses on US resources.

Interactive engagement methods ranged from inquiry labs without lectures (Laws 1991, 1997) to large classes in which mini-lectures alternated with conceptually focused multiple-choice questions that students answered individually and then discussed with their neighbors for two minutes before answering the questions again (Crouch and Mazur 2001). Four key components of effective interactive engagement are extensive structuring of learning tasks by the teacher, strongly interactive student-student execution of the tasks, effective debriefing or other assessments that provide prompt feedback to the teacher as to the extent that the intended learning succeeded and, finally, instructional modifications by the teacher that take account of this feedback.

The assessments in physics that allowed comparisons among courses (Hake 1998) used qualitative,

multiple-choice pretests and posttests, tests on which the wrong answers were based on common student misconceptions. (One can approximate this measure of teaching effectiveness for other courses by using short-answer questions; the commonest wrong answers can then be used subsequently to generate multiple-choice assessments.) The measure of teaching effectiveness asked: How much of the total possible improvement in conceptual understanding did the class achieve? This “average normalized gain” was defined as the ratio of the actual average gain ($\%<post> - \%<pre>$) to the maximum possible average gain ($100 - \%<pre>$) where $\%<pre>$ is the class average (as a percent) on the pretest and $\%<post>$ is the class average on the posttest (Hake 1998). Note that this measure is quite harsh in that it gives the instruction credit only for net

Table 2 Scholarship of teaching and learning (SOTL): selected examples for STEM disciplines It is essential to examine items from other disciplines for insights into possible approaches

I. Fundamentals

Overviews

- Handelsman J et al. 2004. Scientific teaching. *Science* 304: 521–522.
- Suter LE, Frechtling J. 2000. Guiding principles for mathematics and science education research methods: report of a workshop. nsf00113 [NSF sponsored overview. Not focused directly on undergraduates but very interesting.] Available from: www.nsf.gov/pubs/2000/nsf00113/nsf00113.html
- Angelo T. Editor. 1998. *Classroom assessment and research: an update on uses, approaches, and research findings*. San Francisco: Jossey-Bass.
- Nelson CE. 2004. Doing it: selected examples of several of the different genres of SOTL. *Journal of Excellence in College Teaching*. 14: 85–94. [PDF of short version available from: http://mypage.iu.edu/~nelson1/00_Genres.pdf]

Basic resources

- Carnegie Foundation for the Advancement of Teaching. 2007. Gallery of teaching and learning [classroom research projects]. Available from: <http://gallery.carnegiefoundation.org/>
- SOTL programs with diverse resources and links include Indiana University (Available from: www.indiana.edu/~sotl/) and Illinois State (Available from: <http://www.sotl.ilstu.edu/resLinks/index.shtml>).
- Meeting abstracts for the new International Society for the Scholarship of Teaching and Learning. Available from: <http://www.issotl.org/conferences.html>

Compare your course designs with those at MIT:

- MIT Open CourseWare. Available from: <http://ocw.mit.edu/OcwWeb/web/home/home/index.htm> [Lecture notes, exams, and other resources from more than 1800 courses spanning MIT's entire curriculum.]

Student and teacher conceptions in science:

- Duit, Reinders. 2007. Bibliography – STCSE: Students' and teachers' conceptions and science education. Available from: www.ipn.uni-kiel.de/aktuell/stcse/stcse.html [Searchable; 7700 citations.]

Overviews of Alternative Assessment Approaches:

- National Science Foundation. 1997. User-friendly handbook for mixed method evaluations. NSF97-153. Updated 5/00, p 131. Free PDF available from: www.ehr.nsf.gov/EHR/REC/pubs/NSF97-153/pdf/mm_eval.pdf
- National Science Foundation. 2002. User-friendly handbook for project evaluation. Available from: <http://www.nsf.gov/pubs/2002/nsf02057/start.htm>

II. Discipline Focused Resources

Biology:

- Coalition for Education in the Life Sciences (CELS). Links to professional societies in the biological sciences educational activities. Available from: <http://www.wisc.edu/cels/cels/edulinks.html>
- Hake RR. 1999. REDCUBE: Research, development, and change in undergraduate biology education: a web guide for non-biologists. Available from: <http://physics.indiana.edu/~redcube/>
- Anderson DL, Fisher KM, Norman GJ. 2002. Development and evaluation of the conceptual inventory of natural selection. *J Res Sci Teach*, 39, 952–978. Available from: www.biologylessons.sdsu.edu/CINS6_03.pdf
- Biology Concept Inventory. Available from: <http://bioliteracy.net> [Also an online web tool for coding student responses to essay questions and "Ed's Tools" for inventory development].

Chemistry:

- Bibliography of science teaching pedagogy with an emphasis on chemistry. Available from: <http://www.calstatela.edu/dept/chem/chem2/LACTE/References1.html>
- Tomlinson Project in University-Level Science Education (T-PULSE) at McGill University. 2007. Chemistry education research. Available from: <http://www.mcgill.ca/science/tpulse/resources/chemistry/>
- Greenbowe TJ. Chemical education research group list of readings, Part 1. Available from: <http://www.chem.iastate.edu/group/Greenbowe/sections/readingsp1.htm>

Engineering:

- The art and science of engineering education research. (Special issue). *J Eng Educ* 94. Available from: http://www.asee.org/publications/jee/2005jee_sample.htm [entire issue]

Geology and Knowledge Surveys—a tool for all fields:

- Nuhfer E, Knipp D. 2003. The knowledge survey: a tool for all reasons. *To Improve the Academy* 21:59–78. Available from: http://www.isu.edu/ctl/facultydev/KnowS_files/KnowS.htm
- Wirth K, Perkins D. 2006. Knowledge surveys: the ultimate course design and assessment tool for faculty and students. *Proceedings of the Innovations in the Scholarship of Teaching and Learning Conference*. Available from: <http://www.maclester.edu/geology/wirth/WirthPerkinsKS.pdf>

Mathematics:

- American Mathematical Association of Two-Year Colleges. 2006. Beyond crossroads: implementing mathematics standards in the first two years of college. [Html and PDFs of chapters with links and other resources.] Available from: <http://www.beyondcrossroads.com/>
- Research in undergraduate mathematics education. Available from: <http://www.rume.org/>

Physics:

- Martinez Kristy, Margaret Eisenhart. 2004. Literature review of best practices in college physics and best practices for women in college physics. Available from: http://www.colorado.edu/facultyaffairs/leap/research/research_best_practices.html

(continued)

Table 2 Continued

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- Tomlinson Project in University-Level Science Education (T-PULSE) at McGill University. 2007. Physics education research. Available from: <http://www.mcgill.ca/science/tpulse/resources/physics/>

Where to find or publish SOTL research:

- Education Resources Information Center (ERIC) The place for initial literature searches (at least before Google Scholar). Available from: <http://eric.ed.gov/>, also available from: <http://searcher.eric.org/readme.htm>
 - SoTL Outlets for Presenting or Publishing. Illinois State's SOTL program. List, links to other lists. Includes lists by discipline. Available from: <http://www.sotlilstu.edu/pubOuts/index.shtml>
 - Journals in Higher Education ("especially, those that focus on higher education pedagogy" and SOTL; 572 titles internationally). Available from: <http://edpsych.clahs.vt.edu/jihe/>
-

improvements in the average scores for students' conceptual understanding.

The average normalized gain for traditional teaching in introductory physics was 23% of possible (0.23 ± 0.04 , mean \pm SD) and was similar across a range of institutions from high schools to Harvard. The average normalized gain for interactive engagement was about two standard deviations higher at 48% (0.48 ± 0.14). No traditionally taught physics course exceeded an average normalized gain of 33%—none approached the mean for interactive engagement. In contrast, the most successful interactive engagement courses had average normalized gains of about 69% (presented graphically by Hake 1998, 2002; Sundberg 2003).

The implications are both distressing and elating for many of us. Distressing because time spent on improving lectures is largely wasted unless pedagogy has already been rather radically transformed—and many of us have spent a lot of time trying to improve lectures. Elating because pedagogical transformation is relatively easy (e.g., Crouch and Mazur 2001; see also Tables 1 and 2) once one accepts that reducing coverage is an essential part of effective teaching (for introductory biology: Sundberg and Dini 1993; Sundberg et al. 1994).

Similar conclusions can be drawn from a variety of studies. For an understanding of natural selection, Sundberg (2003) found very little (2 sections) or no (15 sections) pretest to posttest gain in class average when traditional pedagogy was used but an average normalized gain of over 25% for each of three interactive engagement sections. Similar studies now could be conducted using the Conceptual Inventory of Natural Selection as pretests and posttests (Anderson et al. 2002). Effects can be quite large with no reduction in rigor for previously under-achieving groups such as chemistry students with low math SAT scores (Jacobs 2000) or African-Americans who were previously doing disastrously in calculus (Fullilove and Treisman 1990; Treisman 1992). Sometimes the gains are large enough to eliminate

all grades of F, as in calculus (Angelo and Cross 1993, p. 69–72) and economics (Nelson 1996). Introductory reviews include those by Gardnier (1994), Handelsman et al. (2004) and Smith et al. (2005). Springer et al. (1997) provide a powerful meta-analysis.

To increase learning and lower student resistance to change, it is best to start with carefully tested methods for interactive engagement. Fortunately, guides are widely available, both to interactive engagement in general (Table 1) and with particular reference to science (Cooper and Robinson 1997, 1998; Committee on undergraduate education 1999; Michael and Modell 2003; Herreid 2004; Donovan and Bransford 2005). Project Kaleidoscope (2008) provides an online introduction to several of the most powerful pedagogies as applied to science. Part II of Table 1 lists some more exemplary printed and on-line resources for increasing the extent and effectiveness of active learning in any college or university science course.

Fundamental change 2: focus on scientific and critical thinking

The fundamental justifications given for requiring nonmajors (and majors) to take science courses typically include the importance of understanding science as a mode of knowing or reasoning. However, scientists often find covering the content to be so fascinating and important that little serious consideration is given to scientific reasoning and the nature of science. I personally found limiting content to be so difficult that I later argued that this is the most difficult step in becoming a good teacher (Nelson 2001). A study of students in multiple institutions (Seymour and Hewitt 1997) found that introductory major courses in science were regarded as too content crammed and of limited utility both by students who continued to major in science and by equally talented students who initially had planned to major in science but later changed their minds.

Here, again, when we are not well versed in the literature on student learning in post-secondary classes, we tend to assume that if we have presented it clearly and somewhat slowly, the problems that result in limited learning are due to students' lack of talent or preparation or lack of effort. I certainly thought so for some years. Instead, there are problems that help explain "what (even) 'good' students cannot understand" (Herron 1975). Sinatra et al. (2008) reviewed several fundamental barriers to learning that limit students' understanding of evolution. Resources now available make it easier to find what is already known about learning in science courses and to design assessments to see how well one's students are doing (Table 2). One broadly important kind of problem, beyond those addressed by Sinatra et al. (2008), has to do with a functional understanding of ratios and permutations. These problems are typically said to limit about 50% of freshmen (Herron 1975), but I have been told of recent assessments from one selective-admission liberal arts college that found these problems to affect at least two-thirds of their freshmen. Arons (1997) explained the problems that students have with ratios and illustrated the pedagogical interventions required to deal with these problems in any quantitative discipline. Herron (1975, 1978) did the same with special reference to chemistry. An example from genetics is the use of Punnett squares to help students understand the biology and resulting quantitative aspects of Mendelian recombination. In teaching evolution, I found these problems especially pertinent in addressing population genetics and experimental design and analysis generally. It was very helpful to try to fit both genetic analyses and experimental-design analyses into matrices analogous to Punnett squares and to use even more student-to-student discussion.

Students' deep views of knowledge and their consequent expectations for learning also greatly limit their learning wherever critical thinking is required. Many students arrive at colleges or universities with the expectation that knowledge in at least some areas, usually including science, is unquestionable truth passed on by authority. In such areas, these students expect faculty to present clear answers that the students can memorize or problems that they can solve by "plug and chug" using memorized equations. As students come to see that apparently valid authorities can disagree on the answers (as on creation and evolution) they conclude that any choices among answers are arbitrary and based on how one feels about the answers or about the authorities. The students do not expect to consider

evidence and have no well-developed ways to rationally evaluate the comparative validity of alternative hypotheses. Two key pedagogical tasks become clear. First, for each topic we must help the students understand how there are (or were) apparently reasonable alternative hypotheses. Second, we must help them use appropriate criteria to decide which of the alternatives are stronger and which are weaker. Without a clear comparison and a set of criteria, little critical thinking can occur and the nature of science remains buried in content to be memorized. These ideas were initially developed to explain learning difficulties experienced by Harvard students (Perry 1970). They have since been confirmed in many other educational contexts (Bleneky et al. 1986; King and Kitchner 1994; partial review in Hofer and Pintrich 1997; Baxter Magolda 2004;). Applications were developed especially well by Bleneky et al. (1986) and Baxter Magolda (1999). Discipline-specific examples are available for chemistry (Finster 1991, 1992; Zielinski 1995) and biology (Baxter Magolda 1999). Nelson (1996, 1999, 2000) has provided a guide to classroom applications generally and specific applications to teaching evolution.

Fundamental change 3: directly address misconceptions and student resistance

Some 7,700 papers, reviews, and books have been published addressing students' and teachers' conceptions in science (Duit 2007). The online, searchable bibliography includes 67 papers on evolution among 383 on biology in post-secondary education and includes many more on high-school biology, many of which are relevant at the post-secondary freshman level or beyond.

Students' pre-instructional conceptions are typically little altered by traditional science teaching. More precisely, traditional teaching can often help students add content to fundamental models they already have mastered or "assimilation," but is of little consequence when the underlying student models are different from the scientific ones and need to be changed or "accommodation" (Sinatra et al. 2008). Effective approaches to helping students alter inadequate models first help students to see the limitations of their initial conceptions and then help them construct more scientifically valid understandings (Duit and Treagust 2003). Interactive engagement becomes essential in the face of the tenacity of students' misconceptions. Further, the diversity of students' misconceptions typically well exceeds the time available for faculty to discover them all,

let alone to address them individually, again making structured interaction among students essential.

The conclusion that students' misconceptions must be dealt with systematically can be especially difficult for faculty when teaching evolution since much of the students' resistance is framed in religious terms. It is difficult, on a variety of grounds, for many scientists (as it was for me) to decide to include non-scientific views in their classes as it might seem to be a waste of time when there is a surfeit of good science to teach.

This resistance to teaching against the reasons for rejecting evolution may be changing. A critical examination of creationism has been forcefully advocated by Bruce Alberts (2005), a recent president of the US National Academy of Sciences: "intelligent design should be taught in science classes, but not as the alternative to Darwinism.... 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."

Verhey (2005a, b; this symposium) had students read and discuss popular books supporting evolution and intelligent design. Students in other sections read and discussed only readings supporting evolution. In accord with the strong consensus from the research on the effects of interactive engagement on misconceptions and in accord with Alberts' suggestion, there was a much greater shift towards full acceptance of evolution when students explored both views. Similarly, instruction that broadly and interactively compared creationist ideas with standard science produced increased acceptance of evolution, especially by students who were initially undecided (Ingram and Nelson 2005).

Note that I am not advocating the "teach the controversy" model in the sense of presenting a critique of evolution and assuming that any issues raised, whether spurious or not, support some alternative. Rather, the focus must be on comparing the alternatives using appropriate scientific criteria. This was the approach applied by Verhey and advocated by Alberts.

Other beneficial consequences may flow from this strategy. Students' attitudes toward evolution can affect their grades as well, with students who have a more black-and-white view of knowledge or more fundamentalist religious views tending to make lower grades (Lawson 1983; McKeachie et al. 2002). However, interactive engagement with creationism while showing that the scientific case for evolution is exceedingly strong also can result in students' grades being largely decoupled from their religious views

(Ingram and Nelson 2005) and from their view of knowledge (Ingram and Nelson, in preparation).

In summary, three strategies that can make a large difference in understanding and accepting evolution are extensive use of interactive engagement, a focus on scientific and general critical thinking (especially on comparisons and explicit criteria) and using both of these in advancing the third major strategy: helping the students actively compare their initial conceptions (and publicly popular misconceptions) with more fully scientific conceptions. The most effective approaches combine all three. The following examples illustrate how these can be applied in teaching evolution. The precise examples are drawn from my senior course on evolution for biology majors, but I have used quite similar exercises with freshmen nonmajors. I am presenting only selected examples but am doing so in detail sufficient to allow easy modification and use in others' classes of both the examples and the approaches. I am providing a few lightly modified excerpts from actual class materials in order to make the applications clear and thus facilitate their use by other faculty. These excerpts are given in *italics*.

Application 1: criteria

One key pedagogical task is the development of criteria for comparing alternative hypotheses. A key criterion is confirmation by a "fair test," one that could have supported either hypothesis and that also is based on a new line of evidence, one that is independent of the lines on which the ideas were initially based. Radioactive dating was a new line of evidence that could have supported any age for geological formations—from too young to date to many billions of years. It was thus a fair test of young earth versus old earth hypotheses. I developed several criteria while teaching age and macroevolution and then reused them where appropriate on other topics. As listed for the students these were: *A scientific theory is better science (than the alternatives to which it has been compared):* (1) *If it better matches the data from one fair test.* (2) *If it is confirmed by multiple independent fair tests.* (3) *If initially conflicting data can be shown to agree.* (4) *If there are no conflicting lines of scientific evidence.* (5) *If the scientific test that supports it is particularly strong* (radioactive clocks have a clear causal basis and a number of internal checks). (6) *If the alternatives are seriously defective conceptually.* (Several young earth ideas are *ad hoc* and/or untestable.) (7) *If the overall weight of evidence is greatly in its favor.* (We reject creationist ideas generally not because the hypotheses

originated in religion but because they either fail several fair tests or remain *ad hoc* or untestable.)

As these criteria were developed in class, frequent use was made of questions for each student to answer individually in class and then discuss with his/her neighbor (i.e., of interactive engagement). The same criteria were used repeatedly for different topics and for comparing popular misconceptions with scientifically appropriate ideas. The study guide for the second exam asked students to review key applications and to discuss the criteria across topics: *Define each of the following criteria [the seven just listed] and explain what it is used for. Show how each criterion applies to an important example for each of five major topics in the course.*

Explicit questions on the study guide, some of which are used with little or no modification on the exam, allow the students to study in small groups outside of class. It thus facilitates teacher-structured, student-executed informal interactive engagement (Nelson 1996).

Before the exam, students were also asked to prepare a multi-page worksheet that asked them to apply each criterion outside of science: *Examples can be from any non-scientific area including incidents that might cause jealousy, sports, consumer goods, mechanics, business decisions, crimes, mystery novels, or issues for parents. Criteria for better answers are: (1) The examples accurately illustrate the criteria. (2) The examples are interesting (non-trivial, help one understand). (3) The examples are fascinating or funny.* The specific questions varied by topic. One example will suffice. *Explain the two criteria: Fair tests and multiple independent tests. State what basic task each criterion could be used for outside of science. State a specific non-scientific question to which these two criteria could be applied. Explain at least two alternative possible answers to the question. Explain at least two potential fair tests and indicate which conclusion would be supported by what results from each.* Discussion of these worksheets in groups of about six students required, with some whole class debriefing, an entire class period.

Although I was initially reluctant to devote this much time to non-scientific applications, I was driven to it by persistent failures by many students to really understand the applications in science. From noticeably improved exam grades on questions applying criteria in science, it was clear that the exercise had helped.

The key point is not that all faculties should use these particular criteria. Rather, my suggestion is that one needs a set of criteria that one can use repeatedly to make a series of important

comparisons within a course and, ideally, among courses. A careful approach to teaching experimental design and critique would serve many of the same purposes, especially if it focused on how one tells what issues the controls should address and whether they really achieved this.

This critical-thinking approach focuses on comparing hypotheses and contrasts to more common approaches such as “here is what we found (take it on faith and memorize it)” or “here are the data that show that this is true.” While it often seems to us as scientists that we really do have the full truth, a quick study of the history of science will show that such an assumption has often, even usually, been wrong. Thus, a key point, often not emphasized in the way we present material, is that data can not really show that a hypothesis is true, only that it is better than a set of specified alternatives. This is the reason that the results of analyses are always tentative, at least in principle. An approach that asks what alternatives have been compared and what criteria have allowed us to choose among them keeps the emphasis on better hypotheses.

It is important to frame this tentativeness carefully. A full understanding of the nature of science will highlight its tentativeness, its deep predictive and explanatory power and the way change usually builds upon and expands previous findings. This means that the tentativeness is often replaced with much more firmly secured findings of the same general nature. We repeatedly, and almost dependably, move from good to better hypotheses.

Is it also important to note that some areas we teach may not be easily understood by students at a particular level while others may be ideas we lack the time to teach as scientific reasoning. For these, I have often explicitly noted that I am not taking my usual critical-thinking approach but rather am going to summarize what philosophers of science term the “received view,” the one that most experts in the area currently support. It is essential, however, that these be a small fraction of any course in which we want to foster deep understanding and critical thinking.

Application 2: geological record

Students in my courses tended to have almost no understanding of the extent and importance of the geological record in documenting evolution. Instead, they thought of fossils as rare and more or less haphazardly distributed across the landscape, almost like meteorites. I found that the descriptions of some rich fossil sites in Gould (2001) were very useful

in helping students form a more realistic view of the fossil record. I have not encountered any other overview of the fossil record that presented equally rich, short site descriptions.

I framed the task before I had the students read appropriate excerpts. *One important thing that this book does is to allow us to compare the hypotheses that the sedimentary record of the earth was deposited (a) rather gradually over hundreds of millions of years versus (b) rapidly in layers one on top of the other during a one year-long global flood. The central question is thus whether normal geology or flood geology better explains the features we find (remember that explanation is the central task of science). Important sub-questions include: Are the kinds of organisms mixed up as they would be in a global flood or are the organisms those one would have expected to find living in a local area? Are the deposits the kind that would be formed from suspension, mixing, and deposition during one year or are the deposits those that would be formed locally and, often, over a long period of time? How can we explain the presence or absence of major groups? (Normal geology would often note that many of the differences were due to the fact that different organisms lived at different times—in many cases they either were already long extinct or had not evolved yet.)*

The students then read the descriptions of some deposits with these context-specific criteria in mind. They filled out worksheets and discussed them in class for four or more of the sites described in detail in Gould. One example will, again, suffice. *The mid-Paleozoic, Orcadian basin deposits (including the Old Red Sandstone beds) of the Devonian of Scotland consist of vast, then-equatorial, lake sediments. These deposits have yielded many kinds of early fishes. Why are the fishes so well preserved? Why do only a fraction of the layers contain abundant fishes? Why do so many layers contain fishes? How can we tell how often the fish-rich layers were deposited? How long would it have taken to deposit the rocks in this deposit if the estimated deposition rate (1 mm/year) applies to the whole thickness? Briefly summarize the diversity of vertebrate animals found in this deposit. How do we explain the diversity of (or lack of) teleosts, turtles, crocodiles, pterosaurs, dinosaurs, birds, mammals, and flowering plants in it?*

A study question for the final exam asked students to synthesize across deposits: *Compare the hypotheses that the sedimentary record of the earth was deposited (a) rather gradually over hundreds of millions of years versus (b) rapidly in layers one on top of the other during a one year-long global flood. Frame your answer in terms of the central scientific criterion*

of explaining features and differences. Include at least five of the following considerations in your discussion: (a) The span of time over which individual fossil beds were deposited, as indicated by the geological evidence, (b) The extent to which the associated sediments and the associated fossils make ecological sense, (c) The reasons the fossils in many sites are so well preserved, (d) The extent to which similar fossils are found together, (e) The differences among the kinds of fossils found in rather similar ecological conditions at different times, and (f) The extent to which the distribution of many deposits makes geographic and ecological sense when placed on a map of continental positions at the time, as reconstructed from paleomagnetic evidence. For each of the five, explain how at least one rich fossil deposit illustrates your main points and for each of the five answers explain: Would this aspect of the record be easy or hard to explain with flood geology? How so?

Again, I was initially reluctant to invest so much effort in paleontology while teaching a biology class. However, the lack of any real understanding of the fossil record was limiting some students' acceptance and was leaving most students unable to effectively help others outside the class to understand the strength of the scientific support for evolution. Note the use of teacher-structured interactive engagement, the use of context-specific criteria for critical thinking and the engagement with creationist ideas on topics that are quite important in understanding the strength of evolution.

Application 3: organs of extreme perfection

Similar approaches were utilized whenever reasonable (Flammer et al. 2007, provide complete lessons that are appropriate at the freshman level and sometimes beyond). For example, the evolution of eyes and of wings both were framed as persistent puzzles of the organs of extreme perfection kind. For such traits, it appears naively (and intelligent design proponents claim) that natural selection could not have formed them since intermediate steps would seem to be inviable or nonfunctional. The evolutionary origins of eyes and of wings have been greatly clarified by evolutionary developmental biology. The students also examined some other examples cited recently by proponents of intelligent design, together with their scientific explanations (Behe 1996, 2003; Miller 1999, 2003; Matzke 2006). In the study guides for the final, I asked: *Suppose you become a research biologist and you find a feature of*

some or all organisms that is so complex that its evolution by natural selection seems inconceivable to you, one where the intermediate incremental steps would appear to be nonfunctional. What attitude are other scientists likely to take towards your findings? Why? What attitude should they take? Why? [Hint: Remember eyes and insect wings.] If my teaching has been successful, it will be obvious to the students that a long chain of resolved claims citing the impossibility of the evolution of particular structures because of their extreme perfection means that we will appropriately treat any new claim as a puzzle to be addressed as time allows, just as a large number of strong lines of evidence that the earth and universe are old makes suspect any claim that a single new line of evidence shows the contrary. Again, giving the students the questions before the exam and encouraging them to work together fosters an informal form of interactive engagement.

Application 4: humans too

An important barrier to accepting evolution is the feeling that we did not evolve. Sometimes this flows from an almost visceral revulsion at the idea that we had ape-like ancestors, to say nothing of worm-like ones. In other cases, it may follow from carefully articulated positions on issues such as the nature of the soul, the nature of God, and the extent of appropriate materialism. In either case it is important to use human evolution as an example whenever convenient (Nelson and Nickels 2001). Close examination of a series of skull casts in small groups using a structured worksheet was the single most effective strategy we found for addressing the rejection (Nelson and Nickels 2001). Another important exercise used data from a variety of primates, including humans, to go from molecular sequences to phylogenetic trees (Nelson and Nickels 2001). This exercise included practice in seeing that rotations about nodes contained scientifically equivalent information, even though some rotations spuriously looked like a ladder leading to humans and others with the same exact content looked like a ladder leading to lemurs (Nelson and Nickels 2001). Including humans in this exercise seemed to help hold students' attention in the face of needing to understand complex ideas. Comparing phylogenies that had been developed on morphological and on molecular bases, or on other disparate bases, for the same or similar sets of species, is also core to understanding the synthetic and predictive power of Darwinian phylogenetic trees (Nickels and Nelson 2005).

Making change easier

Students often seemed to feel initially that there were only two alternatives: atheistic evolution or religious creationism. I gradually found ways to help students transcend this false dichotomy. Most did not know of the broad theological consensus that acceptance of evolution is quite compatible with faith (Matusmura 1995; Zimmerman 2006). I also noted the gradient between young-earth creation (commonly advocated by fundamentalist Christians, Jews, and Muslims), progressive creation (evangelicals) and gradual creationism (theistic evolution; mainline protestants, Roman Catholics, reformed Judaism, and progressive Islam).

A key aspect of higher-order critical thinking is an understanding that rational decisions take into account positive and negative consequences and tradeoffs as well probabilities. I used an example based on the risks from pulling the pin on a rusty hand grenade to emphasize the importance of consequences as well as probability in making rational decisions (Nelson 1996, 2000). Religion has provided many students with an understanding of negative consequences that might flow from accepting evolution that seem much greater than those that we fear from rusty grenades. An introduction to alternative, but still deeply religious, theological frameworks may help students reframe the religious consequences (Nelson 1996, 2000). An emphasis on applied evolution helps students understand its massive practical benefits (Mindell 2006). Carefully showing how many of the important applications depend on macroevolution helps challenge the idea that microevolution is all that really matters.

I emphasize that I am not suggesting that a rationalist point of view is the only valid one. Indeed, many important decisions, including falling in love, are patently not rationalist, whether or not they are influenced by our evolutionary heritage (Wilson 2007). However, given many of the students' commitments as they enter our courses, we are often asking the students to expand the areas in which they consider scientific approaches. Verhey (2005a, 2005b, and this symposium) showed that we can foster such changes. In his classes, many students who initially doubted evolution changed to an approach that combined science and religion in ways that closely parallel those of many clergy (Zimmerman 2006) and the official positions of many denominations (Matusumura 1995). Again: just as it can be rational to refuse to pull the pin on a rusty hand grenade when it appears the consequences will be inconvenient if the less probable hypothesis proves true,

it can also be rational to reject any scientifically probable hypothesis when the consequences seem sufficiently bad. It may help to ask: when is the 5% level of statistical acceptance appropriate and when should we demand stronger evidence and when should we accept weaker evidence.

Some of the questions on the study guide for the final examination focused on these ideas for evolution: *Consider the array of Gradual Creation (Theistic Evolution), Progressive Creation and Quick (Young-Earth) Creation as a spectrum. Using the rusty-hand-grenade example as a base, explain how and why the increased recognition of the practical benefits of evolution should tend to affect peoples beliefs on this spectrum. Explain, in terms of the rusty hand grenade analysis (i.e., in terms of benefits and consequences), what stance you think the National Institutes of Medicine should take towards evolutionary-based medical analyses and treatments.*

Student and faculty responses

Despite or, perhaps, because of my increasing use of nontraditional pedagogies, my course evaluations were usually high. Students' comments typically favored interactive engagement, critical thinking and respect for religion. In addition, I received several teaching awards. These included ones for which the department nominated me and others given by student groups with no faculty or administrative input.

Concluding comments

When I started teaching evolution, I avoided any comment on religiously based ideas out of what I took to be respect for religion and from a feeling that there was just so much good science that I already could not cover for lack of time that it would be scientifically indefensible to spend time on such topics. I accidentally encountered the educational literature showing that students' initial ideas would usually persist unless they were directly challenged in an interactive engagement format. If everything in biology does indeed make sense only in the light of evolution, as Dobzhansky (1973) famously claimed, I asked myself, what could have really been accomplished in a biology course if students left it without understanding evolution and the powerful evidence on which it was based? Taking serious account of what is now known about teaching science effectively in college and university settings made a real understanding of evolution much more likely. Doing so, while using evolution as a clear example of scientific excellence, presented science more effectively as

a way of knowing and as a model of critical thinking. It also was perceived by the students and by me as being much more respectful of them and their initial ideas.

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