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ARTICLE

An Evolutionary Focus Improves Students' Understanding of All Biology

Alexander J Werth

Introduction

"Can we stop talking about evolution already and get to the *real* biology?" That student comment—not prevalent but not atypical in the author's Principles of Biology course—sends shivers down the spine, not so much because it demonstrates opposition to evolutionary thinking but because it reveals genuine ignorance of the truly unifying theme of all real biology. How can this be? How can (primarily first-year) students in this mixed group of biology majors and non-majors fail to recognize the primacy of evolution? On Day One students are asked if they have taken a previous biology course; the usual result is that *all* have done so, making the point that such a course should not really be considered *introductory*: each student has had one or more years of secondary school biology. How, then, can they not see the crucial role evolution plays?

Religious resistance may be partly to blame—and as studies have noted (Harris Interactive 2005; Miller and others 2006), philosophical opposition to evolution often stems from basic misunderstanding of the nature of science (NOS)—but more is at stake than worldview. How worthy is a student's knowledge of biology without a framework on which to support that knowledge (Alles 2001)? Can one truly understand ecology, microbiology, or immunology without the bedrock foundation of evolution? It may be possible for a student with little appreciation or acceptance of evolution to complete successfully, as measured by grades and other performance indicators, a basic biology course, but how reliable is that student's true understanding?

Previous research has addressed the issue of making evolution agreeable to resistant students (Linhart 1997; Cavallo and McCall 2008; Nelson 2008). The ten-year study described here was initially designed to improve feedback and thereby enhance teaching of evolution. A fortuitous finding was that reframing an entry-level college course with evolution as the central focus improved students' mastery of *all* areas of biology, not merely of evolution. Does it matter whether evolution is glossed over and assumed to be common knowledge versus making it a principal theme? Does it affect how well students learn varied aspects of biology, apart from evolutionary theory, in that and later courses (Simpson 1960; Hillis 2007)? This simple study offers empirical evidence suggesting that it makes a significant difference.

A survey reported by Schmid (2007) established that student performance in college science courses improved in direct correlation to the number of mathematics courses taken in secondary school. The research presented here argues, similarly, that comprehension of core biological concepts likewise benefits from emphasis on evolution as a consistent theme of instruction. Data from this investigation demonstrate changes in student attitudes toward evolution as well as improvement in student mastery of diverse biology content areas based on oral and written assessment, as well as quantitative and qualitative results of an anonymous questionnaire.

Materials and Methods

Study design

This study presents a ten-year investigation (1994–2003 inclusive) of students in a college general biology course. In 1999, directly in the middle of the decade-long study period, a new approach was adopted in which evolution became the overarching theme of the course. The new emphasis was neither downplayed to nor concealed from students. Following an extensive, two-week (six-class) introduction to both NOS—what science is (and is not) and how it "works"—and basic evolutionary principles (Appendix 1), students examined a number of evolutionary case studies. In the final two years (2002–2003), these cases were drawn especially from *human* evolution (Werth 2009). Instead of focusing on evidence *for* evolution, students considered what might constitute evidence *against* evolution. As part of the new focus, five journal articles were used as prompts for essay assignments. In all other respects, course content and pedagogical approach (exam format, assignments) was identical over the entire time span.

The aims of this study were (1) to measure the effects of the course redesign on students' attitudes toward evolution; (2) to document how a shift in course focus (with direct emphasis on evolution) affected students' understanding of specific biological concepts; and (3) to determine if increased mastery of evolutionary concepts led to better performance. The null hypothesis was that the explicit evolutionary focus would not aid comprehension of evolution or improve mastery of content areas (for example, genetics, ecology, physiology); an alternative hypothesis was that this shift in course emphasis would in fact improve these measures. Appendix 1 lists a comprehensive outline of curricular topics that were added or altered in the middle of the ten-year study (in the shift from no explicit emphasis on evolution to adoption of a clear evolutionary focus), providing a detailed pedagogical guide for course planners and instructors.

Three instruments were used over the decade-long study to measure student performance in various content areas and attitudes toward evolution: (1) an end-of-semester oral assessment with five specific questions (Table 1) that were graded both by the instructor and, to eliminate bias, by an independent biologist (with pairs of scores judged for inter-rater reliability); (2) written answers to final exam questions that were used unchanged throughout the ten-year study; (3) a 25-question anonymous survey (Appendix 2), developed and refined over a two-year pilot period (1992–1993), given as a pre- and post-semester questionnaire, for which students agreed or disagreed with statements using a seven-point Likert scale.

(1) Oral assessment

With regard to the general claim (Simpson 1963; Hillis 2007)—previously untested—that the pedagogical influence of an evolutionary focus aids students' understanding of major areas of general biology, the study involved oral assessment of students in the general biology course. This course (Biology 110: Principles of Biology) was taught in multiple parallel sections with differing instructors using the same syllabus, assignments, and affiliated laboratory (which remained the same over the decade-long study period). At the end of each semester, students have a 20–30 minute "exit interview" with their instructors, using five questions developed by the entire Biology Department. This serves as an outcomes assessment tool to gauge effectiveness in teaching core concepts (Table 1). Based on a student's responses, various follow-up questions may follow.

Departmental protocol mandates testing 20% of students per section for outcomes assessment, but all students in the author's sections are encouraged to participate, with excellent participation (86% averaged over four years, total n=79 for that period). Scoring involved an outside reviewer so as to avoid conscious or subconscious bias from the instructor (who designed and/or implemented this study). Scores are not revealed and do not affect grades, yet sessions offer an ideal review opportunity for students (preceding the final examination). Responses are scored on a five-point scale defined by a precise rubric (Table 1), noting specific terms and concepts per subject area.

(2) Exam questions

In addition to the oral assessment, common final exam questions (used throughout the decade-long study) provided another means of assessing student performance in specific content areas. Half of the final exam grade is determined by essay questions similar to the five oral questions, developed and used by the entire department (see Table 1). For example, students are asked to explain whether pesticide use *causes* insects to develop resistance, or if immunity is an *effect* of evolution. Other questions include: "Why are distantly related species often similar in appearance, whereas closely related species may be quite different? What does DNA do and why is it in all cells? What is the significance of genetic polymorphism? How do organisms acquire energy, and how does energy flow through ecosystems?" Each exam question is keyed to a content area so that statistics are compiled for categorized topics such as genetics or ecology.

(3) Survey of student attitudes

A 25-question anonymous survey (Appendix 2) that measured students' attitudes toward evolutionary thinking was developed in consultation with psychology colleagues and administered to all students in sections of the study investigator's general biology course. Statements were positively and negatively keyed to avoid psychometric response bias (for example, going down the list and filling out the same response for all statements instead of reading each one). The survey strategy was similar to those used in studies conducted by Osif (1997), Rutledge and Warden (2000), Rutledge and Mitchell (2002), Lovely and Kondrick (2008), and Baumgartner and Duncan (2009).

The questionnaire was given on the second day of class (after adds/drops had ended) and again on the final day. Responses were logged and compiled. The anonymous data showed how the class as a whole answered the questions before and after taking the course; we did not examine how individual students answered at these two time periods. Each class was considered a single sample over the course of the 10 years.

TABLE 1. *Biology content areas surveyed in individual oral end-of-semester interviews, with basic format and précis of five initial questions (each including extensive follow-up questioning), plus criteria for performance standards.*

1. **Evolution** (selection, adaptation, exaptation, radiation, speciation, and so on): Explain the process of natural selection (instructor offers a novel scenario and asks student to predict and explain changes).
2. **Ecology** (interaction and interdependence between species and abiotic environment): Explain how species interact and are interdependent.
3. **Genetics** (Mendelian and molecular basis of inheritance; genotypic and phenotypic intra- and interspecific diversity, and so on): Explain how biologists explain variation within species yet similarities between species.
4. **Molecular/Cell Biolog**y (life function at cellular and molecular levels, including inheritance and cellular operation): Explain why DNA and cells are necessary criteria for life.

Grading rubric

- **Complete Mastery**, 4: Student clearly and concisely discusses all relevant concepts and terminology thoroughly and with no prompting; develops logical explanations, distinguishes between mechanistic and teleological explanations; cites appropriate supporting examples and properly interprets unfamiliar example; does not confuse basic points with trivial details; demonstrates connections to related topics.
- **Partial Mastery**, 3: Like 4, but student may not cite best examples or has difficulty with unfamiliar example; may need prompting; is unlikely to draw connections with other topics.
- **Competence**, 2: Like 3, but student may not mention all concepts and terms or use them appropriately; can present proper explanation but may leave out elements without prompting; offers limited or rote explanations; often misinterprets minor details; does not independently make connections.
- **Partial Competence**, 1: Like 2, but student needs much prompting to provide adequate explanation; confuses causal mechanisms; incorrectly uses terms and concepts; is unable to provide appropriate examples.
- **No Competence**, 0: Student demonstrates inability to answer question independently.

(4) Statistical analysis

Questionnaire responses were compared at the start and end of semesters (pre-/post-instruction) and aggregated into two groups, with the first group representing the years before the shift in the course focus (1994–1998) and after (1999–2003). A t-test measured differences in these groups. Additional steps were taken to assure validity and reliability of the surveys, including use of a Cronbach's alpha test. A time series analysis (using an autoregressive moving average [ARMA] Box-Jenkins model) and a runs test were used to detect changes over time.

Although all course sections underwent the same shift in focus in 1999 (from non-evolutionary to evolutionary focus), only the author's sections used case studies involving human evolution (Werth 2009). This offered opportunities for additional comparison with the research group as to whether the specific focus on human evolution might produce a different effect. The responses from students in these sections were scored and analyzed in the same ways as those in other sections. Then, responses from students in the author's sections where human evolution was emphasized were compared against those of students in other sections. Multiple instructors independently rated student performance on oral questions with inter-rater reliability (IRR) scores calculated via Fleiss' kappa statistic and Spearman's rank correlation coefficient.

Results

Most sections were taught in the fall semester; one was taught in spring 1994. There was a total of 262 students in these 10 classes (mean 26/semester). The proportion of prospective biology majors (~1/3 of each cohort) to non-majors held constant throughout the decade-long study period. Students demonstrated increased mastery of several specific content areas as judged by both oral and written assessment.

(1) Oral assessment

Figure 1 presents interview results (questions in Table 1), showing changes in mean scores given by individual students, before and after the pedagogical shift to a strong, semester-long evolutionary focus. In all other ways the course was taught with identical assignments and resources. Scores in all five content areas showed improvement from 1994 to 2003, which was significant in three areas. For questions about evolution, scores rose from 2.54 (mean, SD=0.21) to 3.48 (SD=0.29), $p=0.022$; for ecology the mean increased from 2.73 (0.20) to 3.09 (0.18), $p=0.036$; and for genetics from 1.88 (0.28) to 2.19 (0.26), $p=0.048$. The kappa statistic for inter-rater reliability (N=61 oral judging events with two scorers) was $k=0.77$, interpreted as substantial (almost perfect) agreement, indicating impartial scoring rather than bias by the instructor/researcher.

(2) Exam questions

Figure 2 shows changes over the decade-long study in average scores of individual students on written final exam questions in five content areas. Other final exam questions were not counted as part of this study. All answers were graded by the investigator (the author). For evolution, average scores rose from 15.1 (SD=0.17) to 17.3 (0.21), $p=0.034$; for ecology the mean increased from 15.8 (0.26) to 17.3 (0.25), $p=0.041$; and for molecular & cellular biol-

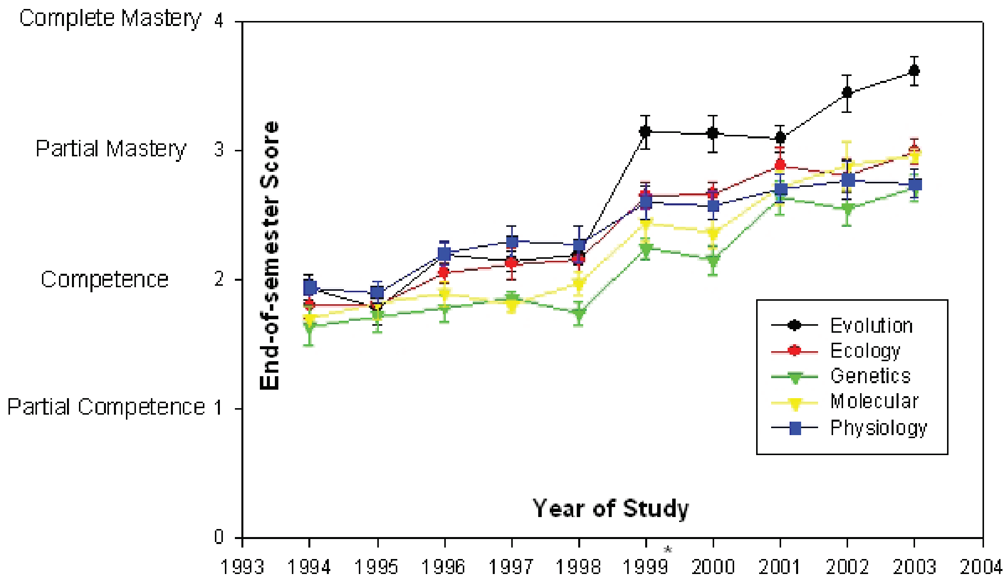

FIGURE 1. *Student responses to end-of-semester oral assessment, scored by course instructors on four-point scale (see text for questions, scoring rubrics, and content mastery statistics), showing changes from limited focus on evolution to detailed focus on evolution as organizing theme of general biology course, but with topics and syllabus otherwise unchanged. During the final two years (2002–2003), there was a special emphasis on case studies from human evolution. Total n=262 (per year: 1994 n=30, 1995 n=31, 1996 n=31, 1997 n=36, 1998 n=23, 1999 n=22, 2000 n=18, 2001 n=24, 2002 n=21, 2003 n=26). Error bars show one standard deviation.*

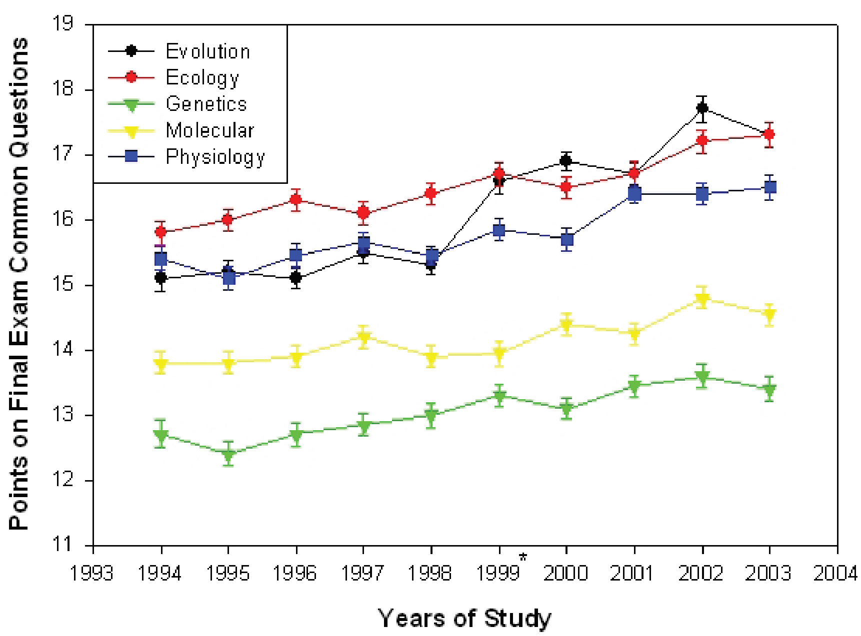

FIGURE 2. *Student performance in five content areas on common questions (used throughout the decade-long study; 0–20 points totaling 100 of 200 exam points; not all other questions stayed same), showing changes from limited focus on evolution to change (* in 1999) to detailed focus on evolution as organizing theme of general biology course, but with topics and syllabus otherwise unchanged. During the final two years (2002–2003), there was a special emphasis on case studies from human evolution. Total n=262 (annual breakdown as in Figure 1). Error bars show one standard deviation.*

ogy from 13.8 (0.17) to 14.55 (0.19), $p=0.042$. No significant differences were observed over the course of the ten-year study in indicators such as essay scores or final course grades.

(3) Survey of student attitudes

Table 2 summarizes statistics keyed to questionnaire statements. Adoption of an evolutionary emphasis correlates with clear, statistically significant ($p<0.05$) changes in student attitude (Figure 3), including acceptance of evolution as established scientific fact rather than as one among several equally likely explanations. Increased focus on evolution as a unifying theme led to students' being more willing to accept macroevolutionary change (speciation) rather than only microevolutionary change within species, and to accept evolution as a process that is not goal-directed. Notably, attitudes changed during each semester to be more accepting of evolution in humans, of behavior, and as an ongoing rather than merely historic process.

Cronbach's alpha test, used to judge internal consistency of and covariance between components of the longitudinal survey instrument (questionnaire), yields a value of $\alpha=0.58$ with all 25 statements as variables, showing marginal reliability of the test as a measure of a single, unidimensional construct (that is, attitude toward evolution). When four questions relating to religion and science were removed from the analysis (Q 2, 23, 24, 25), the statistic increased to $\alpha=0.73$, an acceptable reliability coefficient that demonstrates validity of the survey.

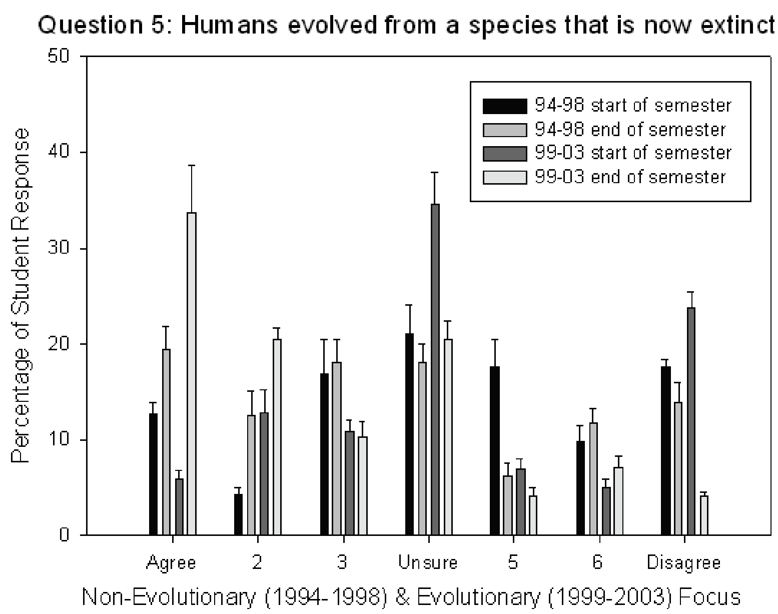

FIGURE 3. *An example of altered student attitudes resulting from the shift to an explicit evolutionary course focus: response to this statement (n=262, error bars=1 SD) shows students became (in all years, over the duration of the semester) more likely to accept the former existence of now-extinct hominid ancestors, but they were overwhelmingly more likely to accept ancestry of humans from extinct hominids following adoption of the new evolutionary focus.*

The time series analysis, used to note change over time concomitant with the shift in pedagogical focus, yielded an autocorrelation (Yt) of +0.72 (close correlation) but was minimally conclusive over the entire longitudinal study; however, the z-score value (1.81) from the runs test also showed a correlation of changing responses through the time of the study, especially in the year after the focus shifted (z=1.96). Results from control groups (same questionnaire administered to sections taught by other instructors, who also applied the evolution-centric focus but with less emphasis on human evolutionary case studies) showed minor differences (overall not significant, though this was deemed due to limited sample size). Additional findings of this questionnaire are available from the author.

TABLE 2. *Statistics of mean response change from pre- to post-semester in 1994–1998 (non-evolutionary course focus, NEF), pre- to post-semester in 1999–2003 (evolutionary focus, EF), and pre- to post-longitudinal study (LS) shift in course focus (1994–1998 versus 1999–2003), compared via unpaired t-tests (t), showing probability (p). Significant changes (p<0.05) shown in bold.*

Survey statement	NEF (t, p)	EF (t, p)	LS (t, p)
1 (divine creation)	4.18, **0.047**	2.59, **0.040**	3.42, **0.036**
2 (constancy of species)	6.63, **0.048**	**4.66, 0.042**	4.23, **0.039**
3 (human origin)	-3.54, **0.039**	-3.05, **0.019**	-3.29, **0.022**
4 (human ancestry)	-7.93, 0.248	-4.82, 0.136	-5.67, 0.221
5 (human evolution)	12.33, **0.045**	8.54, **0.044**	6.24, **0.041**
6 (shared ancestry)	8.14, 0.183	9.52, 0.064	4.57, **0.044**
7 (evolution evidence)	5.35, **0.047**	3.87, **0.038**	2.39, **0.026**
8 (evolution consensus)	9.54, 0.093	6.76, 0.059	5.56, **0.043**
9 (evolution details)	-16.84, 0.347	-9.04, 0.166	-6.77, 0.205
10 (evolution history)	8.09, 0.083	7.55, **0.047**	3.94, **0.038**
11 (transitional forms)	5.37, **0.005**	5.82, **0.045**	5.33, **0.041**
12 (origin of life)	17.88, 0.332	11.04, 0.150	9.77, 0.133
13 (microevol/adaptation)	-4.55, **0.018**	-2.62, **0.007**	-7.42, **0.004**
14 (macroevol/speciation)	-8.36, **0.040**	-5.09, **0.037**	-2.43, **0.036**
15 (continuing evolution)	-3.39, **0.023**	-3.82, **0.003**	-5.15, **0.034**
16 (common ancestry)	-1.91, **0.041**	-4.44, **0.039**	-2.30, **0.045**
17 (random evolution)	7.36, **0.033**	4.54, **0.027**	2.02, **0.038**
18 (physical evolution)	-4.05, **0.028**	-5.91, **0.020**	-3.29, **0.044**
19 (behavioral evolution)	-8.83, **0.031**	-3.22, **0.014**	-4.06, **0.036**
20 (purposeful evolution)	1.88, **0.191**	4.04, **0.174**	3.92, 0.246
21 (optimal design)	3.392, **0.028**	2.038, **0.021**	3.49, **0.033**
22 (human culmination)	7.04, 0.202	5.63, 0.149	8.66, 0.201
23 (value judgments)	3.69, 0.233	4.82, 0.212	7.70, 0.275
24 (sci/faith compatibility)	-4.63, 0.261	-5.03, 0.123	-3.09, 0.227
25 (sci/faith compatibility)	-5.92, 0.208	-4.22, 0.171	-6.72, 0.203

Discussion and Conclusions

Changes in attitude to evolution

Results demonstrate that a clear, consistent focus on evolution alters student attitudes toward greater acceptance of evolutionary explanations. Even in the first five years of the study (1994–1998), evolution was outlined in broad terms and treated in detail, from patterns and processes of evolutionary change to the history of life on earth, as a major block of the course. Specific topics including species concepts, models of speciation, and the Hardy–Weinberg equilibrium were dealt with in depth. Thus it was not the case that the shift from 1998 to 1999 involved a sudden or robust introduction to evolutionary thinking. Rather, the transition involved reframing and reorganizing content to make evolution a consistent unifying theme from the first day of class, so that students could see how it applies to all aspects of life.

The shift to reframe the course using evolution as conceptual glue was concomitant with adoption of a top-down approach (beginning with whole organisms and ecosystems). These were seen as collaborative rather than confounding influences. It may be worth examining in the future how the top-down approach, which by its nature employs an evolutionary perspective, shaped the results of how students perceived evolution: evolutionary thinking applies as well to cells and molecules as organisms, yet it could be easier for students to adopt an evolutionary mindset when they think first about relationships of organisms and later about smaller levels of biological organization. Nonetheless, because both changes occurred together, it is impossible to tease the factors apart in this study.

Changes in student performance

It was anticipated that the new "front and center" focus on evolution would improve student's knowledge of this underlying theme—indeed, this was the initial goal of the course reorganization—and results bore this out: students attitudes shifted. However, an unexpected further result of this shift revealed by empirical data was that students were better able to comprehend and explain other content areas of biology, such as ecologic interactions among species (for example, competition, predation, symbiosis), or physiologic or biogeographic concepts, that are, like all aspects of biology, indirectly related to and dependent upon evolution. In short, students exposed to evolution as a central organizing theme gained a better appreciation for how evolution works at varying levels: population, individual organism, and organism's components at the cellular and organ/system levels. This result was qualitative and quantitative as noted by multiple lines of evidence, including but not limited to peer-reviewed judging of oral interviews at the end of the course (Figure 1), written essay responses to common questions on the final exam (Figure 2), and student lab reports and comments in the affiliated laboratory course (no quantitative data provided here). According to these criteria, students proved demonstrably superior in their knowledge of general biological concepts as a result of the central course focus on the unifying theme of evolution.

As a "natural experiment" that allowed us to compare data collected in the context of assessing the achievement of learning objectives in the course, this study lacks some of the design features that we might have used to examine specifically the influence of evolutionary coverage on other areas of biological education. The initial intent of the pedagogical shift in course focus was to improve comprehension of evolution and NOS (Alles 2001;

Farber 2003) by presenting, in greater depth and detail and at the outset of the semester-long course, six full-class sessions dedicated to basic ideas, principles, and questions about evolutionary theory (current and historical) and NOS, including discussion of the strengths and limitations of science, how scientific inquiry proceeds, and how science differs from other ways of knowing (see Appendix 1 for detailed outline). Nonetheless, these data indicate a clear, statistically significant effect (at the 5% level) that students gained a better appreciation of other areas of biology as a consistent outcome of this change.

Previous work shows that teaching underlying knowledge effects improvement in specific subject areas. Schmid (2007) showed that performance in college science improved in direct correlation to the number of previous mathematics courses taken. Mastery of basic mathematical concepts and operations makes students successful in later courses (both math and science) that depend on quantitative reasoning (Fortmann and others 2007). A similar argument can be made for the primacy of evolution in biological education. Hence the main conclusion of this study is that evolution should not be considered as merely another chapter or unit in a treatment of biology, but should instead be the foundation that introduces every general biology course and ties all content together. Because of the focus on evolution in this class, we saw improvements in students' knowledge of several specialized subdisciplines of biology (genetics, physiology, ecology, evolution, and molecular biology). Given the centrality of evolution to biology, it should not be surprising that a better understanding of evolution would increase the understanding of these other biology disciplines. Appendix 1 provides a basic roadmap for the evolutionary emphasis adopted in this study. Following an extensive and intensive introduction to evolution and NOS, instructors of general biology courses are urged to return repeatedly to evolutionary thinking as a consistent refrain, emphasizing connections between diverse disciplines of biological study.

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Two anonymous reviewers offered constructive suggestions that improved this paper, as did Andrew Petto. I thank Douglas Allchin and Michael Dougherty for their assistance in planning, conducting, and analyzing this study, Dan Weese and Bob Herdegen for advice in producing the questionnaire, and C Beckie Smith for compiling questionnaire data.

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About the Author

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Appendix I

Specific aspects of evolutionary and nature of science (NOS) course content that were emphasized (midway through the ten-year study) in the new curricular focus on evolution as the underlying theme of all biology.

- Some items* were mentioned briefly in the first five years of the study (non-evolutionary emphasis), but these topics were made more central by presenting them (1) at the start of the course (first six class sessions), (2) in greater depth and detail, and (3) by making clear that this evolutionary theme was to be the organizing outline and unifying touchstone to which all further course content (ecology, molecular and Mendelian genetics, cell biology, biochemistry, physiology) would be related.
- Discussions constituted an important part of the course, with material typically presented as questions rather than traditional lecture topics. Students were repeatedly invited to pose questions about these items and some additional topics (not listed here) were occasionally discussed as a direct or indirect result of student questions.
- Contact the author for additional information, handouts, outlines, and lesson plans.

Class 1: Introduction to course

- What is biology?*
- Problems with defining life and living organisms*
    - Shared properties of life
        - Living vs non-living, abiotic vs biotic, organic vs inorganic
        - Hierarchical levels of biological organization, and so on.
        - DNA, growth/development, reproduction, metabolism, homeostasis, and so on.
    - Domains and kingdoms of life
    - Vitalism vs mechanism
    - Reductionism vs holism and emergence
- Basic themes of biology*
    - Evolution, flow of energy, homeostasis, structure determines function, interdependence of life
- Theories that unify biology as a science

Class 2: Introduction to science: What science is and what it isn't

- Science as a way of knowing*
    - Importance of curiosity and wonder
    - Our innate striving to understand and know more
- Aims of science (process to explain natural phenomena)*
- Basic "rules" of science that must be followed*
    - Science is solely naturalistic
        - Deals with natural, material, physical
        - Does not deal with supernatural, immaterial, metaphysical
    - Science is empirical (addressing measurable, experiential data)
        - Uses data derived from observation and experiment
        - Does not proceed merely by thinking or imagining
        - Uses explanations that are testable and falsifiable
    - Science is intersubjectively testable
        - Cannot address non-repeatable phenomena observed by single person
        - Different people can confirm or challenge findings of others
    - Science is open (no inherent limits to its growth and development); never-ending
    - Science is a self-correcting, progressive, dynamic process
        - Why is it a good thing that scientists often disagree?
        - Science can and must change in light of new and better evidence
    - Science is systematic

        - Tenets internally consistent and consilient
        - Organized around broad conceptual framework
- Parsimony and Occam's razor; why we seeking simplest possible explanation*
- Great predictive power of scientific explanations*
- Uncertainty in science; tentative nature of scientific explanations*
    - Why scientific knowledge continually changes
    - Science as a cumulative, collective enterprise
- "Truth" in science?*
    - Are there facts (things we know with certainty) in science?
    - Kinds of facts (by definition/axiom, by experience, by logic, and so on.)
    - No formal, final, absolute truth in science
- The "Big E" in science: evidence*
- Data as the sole ultimate authority in science*
- Can we "know" about things we don't directly observe? (for example, in the past or far away?)
- Non-science (for example, art, literature, philosophy, religion, sports) and pseudoscience
- How and when did science arise?
    - Natural philosophy vs modern science
- Limits of science (why we need more than science), practical and philosophical
- Science and faith
    - Naturalistic data vs revelation
    - Dogma and doctrine in science and religion
    - Is science really just a religion (scientism)?
    - Methodological vs philosophical naturalism
    - Why science can never prove/disprove divinity
    - Science as inherently/literally atheistic (can't rely on divine explanations), but not inherently anti-religious
- Why is science in some ways a subversive, revolutionary process?
    - Why are warning stickers always a good idea?
    - The delicate balance between openness and skepticism
    - Being skeptical vs denying empirical data
- Relation of science to society*
    - Science as both process and product
    - "Treasure hunt" vs social construction models of science and scientific findings
    - Kuhn's paradigmatic shifts; normal and revolutionary science
    - Subjectivity in science
        - Although science *per se* is objective, scientists are people, with biases
- Why science is valuable, and why rejection of science is dangerous

Class 3: How biologists work: Scientific tools and methods

- Revisit theories that unify biology as a science
    - Cell theory, gene theory, theory of heredity, theory of evolution
- What is a theory? Defining hypotheses, theories, principles, laws*
    - Hypothetico-deductive methodology
    - Which comes first, induction or deduction?
    - Stages of scientific investigation
    - Logical process of inferring patterns and drawing general conclusions
    - Supporting/disproving explanations on basis of empirical, measurable evidence
    - Rejecting and revising hypotheses
    - Popper's "imaginative preconception"
    - Bruno Latour's "ready-made science" vs "science in the making"
    - Testability, falsifiability, provability?
    - Why scientists seek to disprove (falsify) rather than to prove
    - Numerous examples/cases: are these valid scientific hypotheses?

        - How is "scientific method" used all the time in everyday life?
- Multiple methods of science (no single "scientific method")
    - Controlled experiment
    - Controlled observation
    - Correlation studies
    - Statistical analysis
    - Historical inference
    - Comparative methods
    - Models and simulations
    - Logical reasoning by analogy, and so on.
- Examples and case studies of scientific investigations (testing medicine on pet fish, growing lawns with fertilizer, and so on.)*
    - The importance of controls
    - Blind and double-blind studies
    - Sampling error and sample size
- The promise and peril of teleological reasoning
    - What is an acceptable explanation in biology?
        - Causal, mechanistic vs teleological explanations
        - Historical/evolutionary (teleonomical) explanations
        - Explaining in terms of purpose vs cause
    - Case study: why do birds build nests?
    - The difference between goal (*telos*) and function
- Why science is complex and often counterintuitive
- Is there a notion of "equal time" in science for competing ideas?

Class 4: Introduction to evolution

- Case study: When is a bee not a bee? (ubiquity of mimicry and process of adaptation)
    - How did many harmless insects come to resemble stinging bees and wasps?
    - How did many harmless snakes come to resemble harmful striped snakes?
    - Ubiquity of mimicry
    - Aposematic (warning) coloration vs crypsis (camouflage)
    - How might mimicry come about?
        - Batesian vs Müllerian mimicry
    - A conscious choice or not? "Intentional" or not?
    - Back to proximate vs ultimate causes
- The other "Big E" in science: evolution
- Why is evolution so controversial?
    - View WGBH segment on "Why is evolution controversial anyway?"
    - Class discussion
- Theory of evolution (universally accepted scientific explanation) vs evolutionary theory (active field of inquiry, with much yet to learn)
- Analogue of theory of gravity vs gravitational theory (which we still don't understand)

Class 5: How evolution works

- Evolution as change in gene frequencies
- Three main steps of variation, selection, and inheritance*
    - Darwin's simple scheme of descent with modification*
    - Algorithmic nature of evolutionary process
    - Selection as a non-random process
    - Melanistic peppered moths and panthers (jaguars)*
    - Example of the Heike (oni-gani) "demon spirit" crab
        - Natural or artificial selection?
        - Intentional or unintentional?
- Populations evolve, not individual organisms*

- Favorable (adaptive) features are context-dependent (specific to environment)*
- Why Darwin saw variation not as a flaw but as a strength in natural populations
- Evolution operates without foresight, solely in the "here and now"*
    - Preadaptation and exaptation
    - Just-so stories
- Selection*
    - Artificial vs natural selection
        - Breeding pigeons, dogs, pigs, horses, and so on.
        - Crop plant descendants of wild mustard, *Brassica oleracea*
    - Sexual selection
    - Directional (and introduce stabilizing, disruptive, and so on.)
    - Random vs non-random processes
    - Levels/units of selection? [more later]
- Difference between evolution (phylogeny, over multiple generations) vs development (ontogeny, over course of single lifespan)
    - Why non-living entities (planets, solar systems, and so on.) develop but do not evolve
- Debates about tempo and mode of evolution
    - Gradualism vs punctuated equilibrium, and so on.
- Evolutionary pattern and process
    - Introduction to tree diagrams and phylogeny/systematics
- Teleology again: Is evolution a predictable unfolding of preordained plan?
    - Gould's *Wonderful Life* and re-rolling the tape
- Spencer's "survival of the fittest" vs Allchin's "amplification of the aptest"
    - Preserving desirable or discarding undesirable (or both)?
    - Evolutionary vs physical fitness
    - Fitness as in "fitting" into set of environmental (biotic and abiotic) conditions
    - Is "survival of the fittest" circular reasoning?
- Why there is no "mutation on demand"*
- Why no organisms are perfect
- Mosaic evolution (blend of plesiomorphic and apomorphic features)
- Huxley's "unity of design and diversity of execution"
- Case studies of antibiotic resistance in pathogenic bacteria, and DDT resistance in insects

Class 6: Darwin's voyage on HMS *Beagle* and his development of the theory of evolution

- Brief history of Darwin pre- and post-voyage, and while on *Beagle**
    - Importance of Lyell, Hutton, and uniformitarianism
    - Importance of Malthus and unchecked population growth vs finite resources
    - Darwin's calculations about slow but exponential elephant population growth
    - Challenges comprehending "deep time" in our fast-paced world
- Why Darwin did not use the term "evolution" (others had used it with no mechanism)
- Who was Darwin's intended audience in writing *Origin*?
- Lamarck and inheritance of acquired characteristics*
    - Introduce concept of epigenetics and genomic imprinting
- Darwin's evidence from fossils, biogeography, similarities/differences among organisms
- Darwin's finches, then and now
    - Peter & Rosemary Grant's study on Daphne Major/Minor
    - Weiner's *Beak of the Finch*
    - Adaptive radiation
- Microevolution (adaptation) vs macroevolution (speciation); "megaevolution"
- Did Darwin really discuss speciation in the *Origin of Species*?
- Why is "Darwin's theory of evolution" "wrong on all counts"?
    - Darwin was not first to propose non-constancy of species
    - Idea not attributable solely to one man

            - If Darwin hadn't developed idea, someone else would have
            - AR Wallace developed the same idea independently!
            - Difference between scientific explanation and pejorative "Darwinism"
        - A theory in scientific sense, but not in vernacular sense
        - Darwin spoke of descent with modification, not evolution
        - Not a single theory but a suite of interconnected ideas, including
            - Natural selection
            - Artificial selection
            - Sexual selection
            - Common ancestry
            - Gradual, steady, incremental change
            - Importance of extinction
- Intelligent design
    - Evolution in action: can we see evolution occurring in the world today?
    - What about evolution of eyes and "irreducible complexity"?
    - "Transitional forms" and whales with legs
    - Gene families (for example, globins) and evolution
    - Chromosomal changes in humans and apes
- Frequent criticisms of evolution
    - Can we see evolution in action (occurring in the world today)?
    - What about evolution of eyes and "irreducible complexity"?
    - Intermediates: no "transitional forms" vs whales with legs
    - Does evolution violate laws of thermodynamics?
    - Adaptation within species doesn't lead to appearance of new species
    - If we evolved from monkeys, why are there still monkeys?
- What didn't Darwin know? [genetics, and so on.]
    - DNA, genes, and particulate inheritance
    - Gene families (for example, globins) and evolution
    - Chromosomal changes in humans and apes
- How did Darwin's work change the world?
- "Modern synthesis" of (roughly) Darwinian evolution and Mendelian genetics
- Neo-Darwinism
- Social Darwinism
- What is/are the unit(s) of selection? (gene, organism, group)
- Evidence for evolution*
    - Fossils/paleontology
    - Selective breeding of plants/animals
    - Comparative anatomy: homology, vestigial features, and so on.
    - Embryology/development
    - Molecular biology: chromosomes, genes, and so on.
    - Biogeography
- What would constitute valid empirical evidence *against* evolution?
- Human exceptionalism: what makes our species special?
    - Are humans still subject to evolutionary pressures?
    - Genetic vs cultural (memetic) evolution
- Much more about evolution to come, throughout every aspect of course

APPENDIX 2

Anonymous pre- and post-semester questionnaire used in study.

This is an anonymous survey, not a test. I am not looking for right or wrong answers, only your honest opinions. Please mark or fill in the box of the response that best matches your opinion of each statement. Read carefully and answer truthfully. Check "Unsure" if you have conflicting feelings. Do not put your name on this questionnaire.

Agree strongly	Agree somewhat	Agree a little	Unsure/ Don't know	Disagree a little	Disagree somewhat	Disagree strongly	
❍	❍	❍	❏	❍	❍	❍	1. God created all species as they appear today.
❍	❍	❍	❏	❍	❍	❍	2. God originally created all species, but they have since evolved and changed forms.
❍	❍	❍	❏	❍	❍	❍	3. Humans evolved from a non-human species.
❍	❍	❍	❏	❍	❍	❍	4. Humans evolved from chimpanzees.
❍	❍	❍	❏	❍	❍	❍	5. Humans evolved from a species that is now extinct.
❍	❍	❍	❏	❍	❍	❍	6. Humans share common ancestors with other species.
❍	❍	❍	❏	❍	❍	❍	7. There is reliable evidence to support evolution.
❍	❍	❍	❏	❍	❍	❍	8. Biologists disagree about whether evolution occurs.
❍	❍	❍	❏	❍	❍	❍	9. Biologists disagree about minor details of evolution.
❍	❍	❍	❏	❍	❍	❍	10. No one can be sure evolution occurred because no one was alive back then.
❍	❍	❍	❏	❍	❍	❍	11. There are transitional fossils indicating intermediate forms between species.
❍	❍	❍	❏	❍	❍	❍	12. Scientists can explain how the first life arose.
❍	❍	❍	❏	❍	❍	❍	13. There is evidence for evolution within species.
❍	❍	❍	❏	❍	❍	❍	14. There is evidence for the appearance of new species.
❍	❍	❍	❏	❍	❍	❍	15. Species continue to evolve today.
❍	❍	❍	❏	❍	❍	❍	16. All species could theoretically be traced back to a single ancestral species.
❍	❍	❍	❏	❍	❍	❍	17. Evolution is a purely random process.
❍	❍	❍	❏	❍	❍	❍	18. Physical features (like bones) can evolve.
❍	❍	❍	❏	❍	❍	❍	19. Behavioral traits can evolve.
❍	❍	❍	❏	❍	❍	❍	20. Evolution works toward a purpose/goal.
❍	❍	❍	❏	❍	❍	❍	21. Evolution results in optimal (perfect) species.
❍	❍	❍	❏	❍	❍	❍	22. Evolution culminated (ended) in the human species.
❍	❍	❍	❏	❍	❍	❍	23. Science can make ethical (value) judgments.
❍	❍	❍	❏	❍	❍	❍	24. Scientific and religious views are incompatible.
❍	❍	❍	❏	❍	❍	❍	25. Many people believe in biological evolution and at the same time believe in God.

Please return this survey to Prof. Werth when you are finished. Thank you!

Appendix 3

General biology textbooks used during the ten years of this study:

1994–1995	Levine & Miller, *Biology: Discovering Life*, 2nd ed. (Heath, 1994)
1995–1996	Wallace, Sanders, Ferl: *Biology: The Science of Life*, 4th ed. (HarperCollins, 1996)
1996–1997	Arms & Camp: *Biology,* 4th ed. (Saunders, 1995)
1997–1998	Raven & Johnson: *Biology,* 4th ed. (William C Brown, 1996)
1998–1999	Starr & Taggart: *Biology: The Unity and Diversity of Life*, 8th ed. (Wadsworth, 1998)
1999–2000	Guttman: *Biology* (WCB/McGraw-Hill, 1999)
2000–2001	Cain, Damman, Lue, Yoon: *Discover Biology* (Sinauer/Norton, 2000)
2001–2002	Cain, Damman, Lue, Yoon: *Discover Biology* (Sinauer/Norton, 2000)
2002–2003	Cain, Damman, Lue, Yoon: *Discover Biology,* 2nd ed. (Sinauer/Norton, 2002)
2003–2004	Cain, Damman, Lue, Yoon: *Discover Biology*, 2nd ed. (Sinauer/Norton, 2002)

For the study's last five years (evolutionary focus), students were also required to read and write essays about Allen & Baker, *Biology: Scientific Process and Social Issues* (Fitzgerald Science Press, 2001).

Despite the use of seven textbooks during the ten-year period, the syllabus was virtually the same for each half of the study, so that course resources were a minor influence on differences in student learning from year to year.

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FEATURE

People and Places: Biological Sciences Curriculum Study

Randy Moore

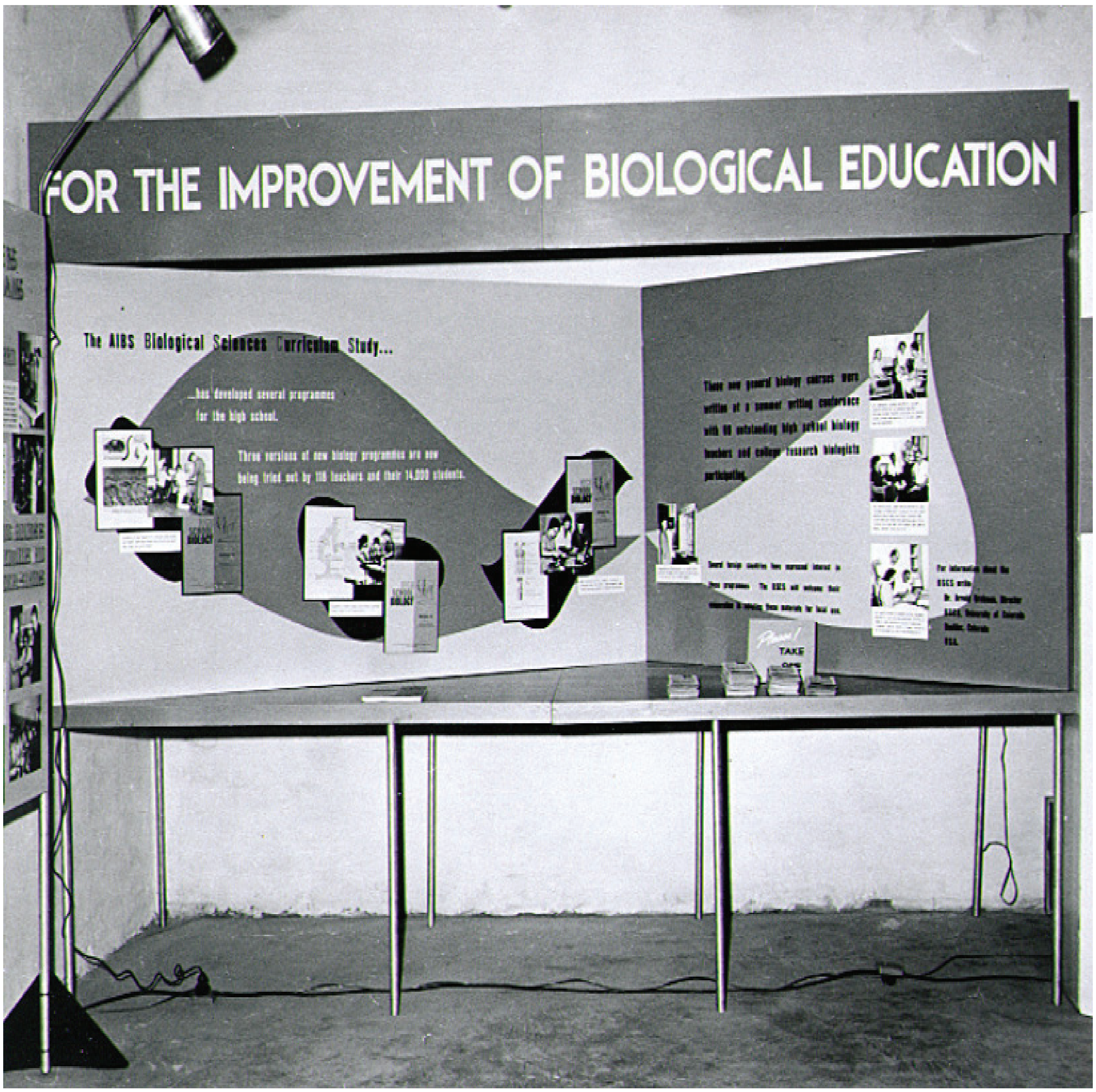

FIGURE 1. *The Biological Sciences Curriculum Study (BSCS) had humble beginnings, but by the 1970s its books were used in most US high school biology programs. This photo, taken in 1960, shows a BSCS exhibit that announced the first chapters of the new BSCS textbooks. Those books, which returned evolution to the biology curriculum, transformed biology books and science education. (Photograph courtesy of BSCS.)*

The history of the Biological Sciences Curriculum Study (BSCS) can be traced to the October 1957 launch of the Soviet satellite *Sputnik*, which awakened the American political and educational establishment to the importance of improving science education. The following year, Congress passed the National Defense Education Act, which encouraged the National Science Foundation (NSF) to develop state-of-the-art science textbooks. In the same year, NSF allocated $143 000 to establish the BSCS to educate "Americans in general to the acquisition of a scientific point of view." By 1959, BSCS had established its headquarters at the University of Colorado.

In the early 1960s, BSCS created new biology textbooks that, unlike other textbooks, stressed concepts rather than facts, and investigations rather than lectures. The three BSCS books published in 1963 became known by the color of their covers: *Blue* emphasized molecular biology, *Green* emphasized ecology, and *Yellow* emphasized cellular and developmental biology. Approximately 70% of the content of each book was identical, but the material was presented using different themes. Although BSCS wanted to avoid the criticism that it was trying to establish a national curriculum, their books–for all practical purposes–did exactly that, for in the 1960s, most schools used BSCS textbooks.

When John Scopes was convicted of teaching human evolution in 1925, publishers feared that discussing evolution in biology textbooks would hurt sales. As a result, biology textbooks published after Scopes's conviction did not include the word *evolution*. However, BSCS books were different. Instead of relying on professional writers to prepare their textbooks, BSCS recruited the best scientists and teachers in the United States. Not surprisingly, all of the BSCS books stressed evolution. Today, BSCS is credited with putting evolution back into the biology curriculum. BSCS books were an agent in the US Supreme Court's ruling that laws banning the teaching of human evolution are unlawful (for example, *Epperson v Arkansas*), as well as in cases involving issues such as instruction about human reproduction and the use of live animals in biology classrooms. Some states, such as Texas (in 1970) and Kentucky (in 1965), banned the BSCS books. Evangelists such as Reuel Lemmons of Austin condemned the textbooks as attacks on Christianity (Engelman 2001).

Today, BSCS is a non-profit corporation headquartered in Colorado Springs, Colorado, that continues to develop high-quality science curriculum materials for all grade levels, including high school biology, while also designing and leading professional development in support of effective science teaching and conducting research on both curriculum and professional development. BSCS materials have been printed in more than 25 languages for use in more than 60 countries. Since its inception, more than 20 million students have used BSCS materials.

References

Engelman L. 2001. *The BSCS Story: A History of the Biological Sciences Curriculum Study*. Colorado Springs (CO): Biological Sciences Curriculum Study.

About the author

Randy Moore is the HT Morse–Alumni Distinguished Professor of Biology at the University of Minnesota. His most recent book (with coauthor Sehoya Cotner) is *Understanding Galápagos: What You'll See and What It Means* (New York: McGraw-Hill, 2003).

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FEATURE

What Would a Religious Paleontologist Have to Confess? Robert Asher's *Evolution and Belief*

Brian Swartz

Does accepting evolution preclude believing in the God of the Bible? If not, and without contradiction, then how does one embrace both scientific and religious world views? In *Evolution and Belief: Confessions of a Religious Paleontologist* (2012), Cambridge zoologist Robert Asher attempts to answer these questions. As a scientist, Asher's research in mammalian paleontology is complemented by his deep philosophical, scientific, and religious considerations. These deliberations are captured nicely in his first popular work.

Asher's primary thesis distills to two points: (1) science focuses on "how" questions, not "why" questions; and (2) because of this difference, evidence for evolution does not support or deny the existence of a deity. That is, as Asher documents, evolution explains the history of life and how organisms come to share common ancestors. It does not explain any potential *who* or *why* behind it. In this way, his simple "confession" is that he sees no contradictions between his scientific views and his religious faith. However, despite clarifying the boundary between science and religion, his discussion of evolution falls victim to popular misrepresentations embraced by the "intelligent design" movement.

Striking a Balance Between Science and Religion

As Michael Ruse outlined in *Can a Darwinian be a Christian?* (Ruse 2001), resolution between science and religion will emerge when god concepts are defined appropriately. With a targeted definition, any ultimate plan or cosmic "why" behind the universe or evolution will be outside of scientific questioning. To achieve this, Asher emphasizes the distinction between *deism* and *theism*: the notion of God as a first cause versus a direct participant. Asher explains that in contrast to a deist, the theist "attributes to God not only the initial spark of life, but also specific human qualities." He notes that this type of theism relies on the naive notion of an anthropomorphic active god, which conflicts with science. However, as Asher explains, divine deeds need not resemble human actions. Thus, if one believes that theistic efforts manifest themselves through natural mechanisms set into motion 13.7 billion years ago (Ga), then it is possible to maintain non-overlapping scientific and religious world views.

Asher continues his attempt to distinguish religion and science by the types of questions they ask: religion deals with *agency* (primary, ultimate, "why" questions), whereas science tackles *cause* (secondary, proximate, "how" questions). It may still require faith to believe in a primary agency behind natural processes, but since that agency does not tinker (and therefore does not produce testable predictions), science and religion will forever ask and answer different questions. However, despite Asher's terminology, it is probably best to restrict the terms *agency* and *cause* to Thomas Aquinas's distinction between "primary" and "secondary" questions. It is misleading to suggest that science, in the magisterium of *cause*, address "how" but not "why" questions. Moreover, *proximate* and *ultimate* constitute a sliding continuum and do not dichotomize easily; an ultimate factor at one level becomes proximate at the next. A simple query such as "why did the fire alarm startle you?" entertains this full spectrum of considerations. The more proximate *how* explains the biochemistry of your nervous system, whereas the less proximate *why* details your ancestry to resolve why you have a nervous system in the first place.

To make his point about agency and cause, Asher draws upon an analogy by Thomas Aquinas. He asks, "Does a carpenter [the agency] hammer in a nail or is it his tool [the cause] doing the work?" If one believes that God does not intervene but manifests himself through nature as part of a cosmic plan, then as with the carpenter and hammer, agency and cause are two sides of a non-competing discussion. The problem, as Asher notes, is that people anthropomorphize nature and read human-like qualities into its workings. People certainly want to see characteristics of the Creator in the creation. Thus, if we believe that God acts through nature via a plan set into motion 13.7 Ga, then nature reflects this plan just as an edifice reflects the precision of its carpenter. Yet what are we to make of shoddy workmanship? We observe the full spectrum of horror, indifference, and beauty in the natural world, so how do these characteristics resonate with people if they reflect upon their creator? Related implications speak to the mechanics of prayer. If the creator does not tinker, then all prayer must be answered through nature. However, this is only possible if prayer-triggering mechanisms (and some fraction of answers) are natural components of his plan. In other words, the inclination to pray (and perception that a prayer has been answered) is a naturalistically-induced emotional and behavioral manipulation used to connect us with the Creator of the universe. No consideration here nullifies Asher's god concept, but these are the ramifications if one believes in a non-interventionist deity that strikes his hammer through natural processes.

Observing the importance and perception of supernatural intervention in the religious experiences of countless people, I admit that however well-defined, I am skeptical that this god concept will resonate with people. Are they more likely to embrace non-contradiction through a supernatural definition that alters valuable criteria, or are they inclined to stick with what feels comfortable despite rejecting scientific data? I am inclined to think the latter. I applaud Asher for calling out scientists who confuse agency and cause, but for science-deniers on the fence about evolution, I am concerned that this definition will discourage a change of heart and mind.

Evolution: The science and its social perceptions

The second theme in *Evolution and Belief* (about 8 of 12 chapters) documents the case for evolution and explains *how* organisms come to share ancestors. Asher includes the discussion to complete his argument and illustrate how one can be religious *and* accept evolution. However, it is here where I find the most objections. The misrepresentations are numerous, and are problematic because they perpetuate creationist caricatures of evolution, in particular the point that evolutionary biologists have too much faith in natural selection.

Asher's focus on natural selection manifests itself in numerous instances. For example, in the context of discussing the predictions of "evolution" or "common ancestry," he emphasizes selection. He mentions "how fossils match the predictions of natural selection" (p 140) or that the platypus and echidna "mix anatomical features otherwise found in reptiles and mammals in just the way one would expect if Darwinian natural selection was the mechanism" (p 54). The concern is that Asher does not specify why *this* process makes predictions that a hypothesis of "common ancestry" does not. This is problematic for two reasons: (1) natural selection is part of how evolution works, but evolution is not simply natural selection (a point that Asher later alludes to); and (2) this underscores criticisms articulated by the "intelligent design" community.

In other instances, Asher notes that "the phrase 'descent with modification' encapsulates Darwin's idea" about natural selection (p 4), and he explains repeatedly that "descent" is *the mechanism* of evolution. At face value this may seem okay, but students of history will be the first to point out: "descent with modification" was Darwin's term for *evolution*, not natural selection. The reason is simple and important: during Darwin's time, "evolution" described a process with a predetermined outcome (think of a fiddlehead fern unraveling in its predictable fashion) (Padian 2009). To avoid this implication, Darwin used his alternative phrase.

Moreover, equating "descent" with natural selection and suggesting that this is the cause of evolution misconstrues the history and structure of evolutionary theory. In this context, Darwin made two contributions: (1) he proposed a mechanism for natural selection to explain adaptation; and (2) he proposed the first completely genealogical hypothesis for evolution and a mechanism to explain it (his "principle of divergence") (Darwin 1859; Stauffer 1975).

Thus, even though "natural selection" was Darwin's term, the concept was not his idea. Darwin took the older "negative" notion of natural selection and spun it into a "positive" cumulative process through his classic mechanism of variation, heritability, and so on (Gould 1987). However, as Darwin knew, this explained *adaptation* and led to anagenesis, not diversity. This is why he remarked in his carriage ride of the mid-1850s, "I can remember the very spot on the road … when to my joy the solution occurred to me" (Darwin 1887:84). This "solution" was not the Malthusian insight of 1838 that led to natural selection, it was his principle of divergence that explained diversity.

Asher does explain that evolution includes "contingencies of natural variation, environmental change, adaptation, and constraint" (p 47), but this pluralistic message is lost in his general discussion. He remarks that "the recognition of constraint in evolution does not diminish the major role of natural selection as the engine" of evolution (p 85), but this misrepresents evolutionary theory. Asher is correct that no serious biologist would claim that selection is an irrelevant mechanism, but Richard Lewontin captured the point perfectly by noting that selection is a theory of "trial-and-error externalism" (Gould 2002:1027).

In organismic selection, there are two primary processes: (1) *internal* genetic and developmental machinery that produces variation in only certain directions; and (2) *external* mechanisms (for example, selection, through the struggle for existence) that "act" on this variation. Because variation is not always copious, small, or isotropic, evolutionary rate and direction results from an *interaction* of both internal and external components. In many cases, internal mechanisms bias evolutionary outcomes (for example, parallelism) (Wake 1991), and in others, external processes influence results (for example, convergence) (Donley and others 2004). Because of this duality, there is give and take, and "taking" on the part of one diminishes the relative influence of the other. This is what Stephen Jay Gould meant when he said that, "Organisms are not billiard balls, propelled by simple and measurable external forces to predictable new positions on life's pool table" (Gould 1980:16).

The interaction of process and pattern fits importantly into Asher's discussion of multilevel (that is, hierarchic) selection and punctuated equilibrium. In this section, he commits two mistakes that perpetuate creationist arguments: (1) he confuses *gradual* (that is, slow-steady-continuous) evolution with *graduated* (that is, step-like) evolution to suggest that transitional features conflict with punctuated equilibrium; and (2) he misrepresents the relationship between organism-level and higher-level selection, and their potential significance over geological time.

First, Asher's discussion of punctuated equilibrium emphasizes rate—that is, high at "punctuations" and low during "stasis"—and his analogy with learning languages underscores how fluency does not accumulate at a constant rate. Instead, Asher explains that learning advances in episodes of punctuations and stasis. Drawing upon this discussion, he notes that stasis has been viewed skeptically by mammalian paleontologists because of "an abundance of fossils that exhibit 'transitional' features" (p 110).

The problem here is that punctuated equilibrium is not predominantly about rate; rather, it is about *net* morphological change. In other words, with punctuated equilibrium (and with its competing hypothesis, phyletic gradualism), evolution occurs continually. The difference between these patterns is not continuous versus discontinuous evolution, the presence versus absence of "transitional features", or gradual versus graduated evolution; the distinction is that with a punctuated pattern, *net* morphological changes occur when lineages diverge.

This means that with punctuated equilibrium, evolution occurs gradually within lineages (the back-and-forth "wobble" of environmental tracking documents this [Dietl 2010]) and in a graduated (step-like) fashion between them. These graduated "steps" (that is, punctuations) are where net morphological changes arise. Moreover, because all characteristics are ancestral or derived at some level, just because they occur at splitting events does not mean that members of these lineages cannot exhibit combinations of ancestral and derived characters (in fact they often do) (MacFadden 2005; Mihlbachler and others 2011). Unfortunately, because creationists argue that punctuated equilibrium was invented to explain away the absence of "transitional forms," Asher's treatment of this scientific issue plays right into popular misconceptions about evolution.

Second, Asher's discussion of hierarchic selection (that is, selection above and below the level of individual organisms) furthers his emphasis on conventional, organism-level selection. He acknowledges that natural selection is a "means by which one generation of organisms contributes ... information to its descendants" and that rather than replacing conventional selection, higher-level selection is "an elaboration upon it" that explains macroevolutionary patterns (p 88). This is true! However, the question then becomes: do higher-level processes diminish the importance of conventional selection when evolution is viewed in the long run?

Even though we are physics at the lowest level, no one would argue that quarks and leptons predict mating behaviors in swans. This is because certain properties emerge at higher-levels that do not smoothly extend from lower ones. In the same way, if the big patterns of evolutionary history emerge from selection (and other processes) operating above the level of individual organisms, what does this say about the real importance of lower-level, organismic selection in the fullness of time? Lower-tiered components certainly persist through time (for example, subatomic particles, adaptations, and so on), but that does not mean they carry the same caliber of explanation at larger scales (Gould 2002).

Understanding all of this, we can recognize problems with the "intelligent design" (ID) community's caricature of evolutionary biologists. They say we think that evolution is about random mutation and natural selection (Behe 2001; Johnson 1991; Wells 2002), which is a tremendous oversimplification. However, Asher's reiteration of this notion, especially as a substitute for *evolution*, shows that he is not well-tuned to criticisms that lie at the heart of the creationism/evolution discussion. Some of the strongest ID attacks target natural selection, especially as it relates to macroevolution (Meyer and others 2007).

Thus, it is unfortunate that Asher simply appends "natural selection" to his rhetoric without detailing how this process makes predictions that an alternative mechanism (or simply "common ancestry") does not. Moreover, even though he mentions constraint, contingency, and higher-level processes, pluralistic thinking is not well integrated into a synthetic picture of how evolution works. In this way, through his pervasive emphasis of natural selection, he perpetuates the perception among science-deniers that biologists place too much faith in conventional selection as the cause for all things evolutionary.

Concluding Remarks

Despite these criticisms, Asher does a truly excellent job with many aspects of this book. It is commendable for a religious scientist to articulate so adequately how to embrace both scientific and religious world views. In this context, *Evolution and Belief* receives five stars. Even though the book's second theme falls victim to many problems that pervade most evolutionary discussions, Asher does a spectacular job documenting a wealth of cross-disciplinary data that support evolution.

In particular, his historical discussions of embryology and whale evolution kept me on the edge of my seat, and I was captivated by his storytelling even though there are already many popular accounts of these subjects (Berta 2012; Zimmer 1998). Moreover, this is the first popular book to my knowledge that teaches its audience to construct an evolutionary tree. Asher will have you downloading mitochondrial sequence data from GenBank and using computer software to reconstruct evolutionary relationships. This will be an exciting experience for most people.

However, considering his approach, I would be surprised if readers did not simply emerge from the exercise thinking, "how are a bunch of computer clicks supposed to convince me of macroevolution?" That is, Asher never explains why a pattern of nested sets (that is, groups subordinate to groups) is predicted by a hypothesis of common ancestry. And herein lies how I would characterize the second theme of *Evolution and Belief* (about 70% of the book): Asher does an excellent job emphasizing evidence, but he succeeds less well in his synthetic case for evolution. He excels in the first chapter and concluding summary where he articulates how to balance scientific and religious views, and insists that scientists "reach out to people where they are, not where we think they should be." However, to help the evolution skeptics, it is important to show them not just the evidence for evolution, but how it is packaged in the theory of evolution. Only with this knowledge will people understand the bigger picture of life's history, and why a religious worldview, if defined appropriately, does not conflict with scientific knowledge.

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REVIEW

Charlie and Kiwi: An Evolutionary Adventure

by Eileen Campbell, illustrated by Peter H Reynolds
New York: Atheneum Books for Young Readers, 2011. unpaginated

reviewed by Alan D Gishlick

Charlie has to write a report for school about a bird. Wanting to pick something a little surprising, and having a stuffed toy kiwi on hand, he chooses to write about the kiwi (genus *Apteryx*). But when he presents his report to his class, everyone says that it's not a bird. One student jokes, "It's supposed to be about birds, not fruit!" Charlie retorts that the kiwi is different—but when his teacher invites him to explain why, he realizes that he doesn't know. Fortunately, the bell rings. Charlie has just a day to research why the kiwi is a bird—a really cool bird—despite its differences from stereotypical birds like eagles and robins.

That's the premise for *Charlie and Kiwi*, the companion volume to the New York Hall of Science's Charlie and Kiwi's Evolutionary Adventure exhibit, which opened in 2009. Both the exhibit and the book seek to engage children from seven years old and up in learning about the basics of evolution—variation, inheritance, selection, time, and adaptation—using bird evolution as the main example. As a paleontologist who works on the evolution of avian flight, I was especially happy to see my specialty used for such a vital educational purpose.

So back to the story. At home, as Charlie labors late into the night on revising his report, his stuffed kiwi (named Kiwi) astonishingly offers a suggestion, tapping her beak on a photograph of Charlie's great-great-great-great-great-grandpa, the bird expert. (Could this be Charles Darwin? The sideburns are right…then again, Darwin wasn't a bird expert.) And Charlie finds himself travelling back in time to 1860, where he asks his ancestor how to prove the kiwi's really a bird. Grandpa Charles says, "Of course a kiwi is a bird. It's got feathers, a beak, and two legs."

But Charlie is not satisfied: after all, kiwis don't fly. "Some birds don't fly," Grandpa Charles responds, citing penguins or ostriches. (Kiwi nods.) Grandpa Charles explains, "We know that birds changed by looking at their ancestors, like this ancient fossil." Since they don't have a fossil of an ancient kiwi, Kiwi invites them to hop back in the time machine and go back thirty million years to New Zealand. There the largest predators are hawks and eagles. The ancestral kiwis hide during the day and come out at night, when the predators don't fly, and use their whiskers to help them find food in the dark.

But how did kiwis get this way? Grandpa Charles explains his theory. Maybe the ancestors of kiwis once did have wings and flew. But if there was one family of these birds that stayed on the ground more, since it was safer not to fly, their being a little bit different made their survival more likely. So the "Little-Bit-Different" family raised more chicks than flying birds did. Little by little, generation by generation, the Little-Bit-Different birds became more and more different—and better and better survivors in their environment. The result: "a very different kind of bird: the kiwi!"

"That's pretty cool," Charlie comments. But is it cool enough? Is it enough to convince his skeptical classmates? No: what's needed is a visit to the very first bird. Charlie, Grandpa Charles, and Kiwi then go back in time 150 million years, where they meet feathered dinosaurs. Grandpa Charles is initially puzzled. After all, earlier in the book, he was assuming that feathers and beaks were characteristic of birds. Now he is confronted with animals with feathers but with teeth instead of beaks.

Why would dinosaurs have feathers? Grandpa Charles and Charlie think about it. Feathers have more uses than just flying. Perhaps they gave the feathered dinosaurs a little extra glide in their leaps to help them catch food. And the more food they could feed their babies, the more surviving children they would have. A little change in each generation could lead to bigger changes, and after millions of years, the first feathered dinosaurs would look very different from their descendants, the birds. "So the first birds were dinosaurs—with feathers!" Moreover, Kiwi is not only a bird but also a kind of dinosaur: "Nothing's cooler than that!"

The next day, when Charlie continues his presentation to his classmates, telling them that "every bird is different, but all part of one big, amazing family … [that] came from the same ancestor: the dinosaur," nobody laughs. Instead, they say, "Dinosaurs. Whoa." As well they might! It would have been good to explain, as the exhibit explains, that only certain dinosaur lineages—therapods—are ancestral to birds, and to emphasize the diversity and the convergence of the lines of evidence for the dinosaurian ancestry of birds—but only so much is possible in so much space and for such a young audience.

Charlie and Kiwi explains Darwin's theory of evolution by natural selection in an easily understood if simplified manner. The scientific information as presented is reasonably accurate and well-suited for the intended audience and reading level. But the lessons are conveyed without didacticism. The characters are believable and entertaining. The illustrations by Peter H Reynolds, the author-illustrator of such books as *Ish* and *The Dot*, which won several awards, are cartoonlike and colorful while still illustrating the scientific information presented. (It won't hurt that Reynolds's illustration style will be recognized by fans of the popular Judy Moody and the Stink books, which he illustrates.) Overall, this is a fine book telling a story of evolution for young readers.

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REVIEW

Darwin's Disciple: George John Romanes, A Life in Letters

by Joel S Schwartz
Philadelphia (PA): Lightning Rod Press / American Philosophical Society, 2010. 806 pages

reviewed by John M Lynch

Correspondence has always been central to the scientific enterprise, and nineteenth-century scientists have left us with a rich seam of letters to mine in our efforts to understand their work, lives, and milieu. Some of these letters have been published in posthumous "life and letters" volumes, often lovingly assembled by spouses, children, or close colleagues. To the modern historian, these often suffer from excessive editorial interference. Other letters remain unpublished, languishing in public and private collections scattered worldwide. Given the value of letters as historical source material, recent decades have seen projects (often transnational) aimed at collecting, transcribing, editing and publishing the correspondence of notable scientists such as Charles Darwin, Thomas Henry Huxley, Alfred Russel Wallace, and John Tyndall. Joel Schwartz has made a modest, yet valuable, contribution to this collective enterprise in making available the letters of George John Romanes.

A British physiologist who studied the nervous system of invertebrates under such luminaries as Michael Foster and John Burdon Sanderson, Romanes became a supporter of Darwinism, albeit one who argued that there were problems with the theory. Noting that Darwin never showed how natural selection could produce new species (as opposed to adaptations), he proposed a theory by which physiological "peculiarities" involving the reproductive system lead to hybrid sterility between individuals occupying the same area, thus causing isolation that would then allow natural selection to promote diversification (Romanes 1886). While natural selection was by no means an accepted idea at this time, Romanes's idea received significant resistance from the Darwinians, whom he believed were being inflexible in their opposition.

In other matters, Romanes was a more orthodox Darwinian. After coming to the attention of Darwin in 1874, he began research into the material basis of mind. His *Animal Intelligence* of 1882 aimed to extend Darwin's argument in the *Descent of Man* and to further establish the continuity between the mental capacities of humans and other animals. He also formulated failed experiments to establish Darwin's theory of pangenesis and the inheritance of acquired characteristics, both of which he accepted in the face of August Weismann's theory of germ plasm. In a letter to his wife, Ethel, he wrote:

> [S]ince coming here [to Madeira] I have heard of no less than three additional cases of cats which have lost their tails afterwards having tailless kittens. I wish to goodness I had been more energetic in getting on with my experiments about this, so I have written to John to get me twelve kittens to meet me on my return. It will be a great thing to knock down W[eismann]'s whole edifice with a cat's tail. (p 66, letter of 3/19/1893)

> Unless he has already procured ordinary kittens, tell John [their butler] to get them either Angora or Persian. They will cost more but will be much better. (p 67, letter of 3/22/1893)

While cutting tails off kittens in an attempt to disprove Weismann is unlikely to endear him to modern sensibilities, such was Romanes's status that *The Times* described him as "the biological investigator upon whom in England the mantle of Mr. Darwin has most conspicuously descended." Simply put, Romanes was the Darwinian *non plus ultra* of the era.

Romanes was a "rare example of an educated Victorian whose religious beliefs were undermined by scientific reason" (Smith 2004–2012). Though initially an orthodox believer, by the time he met Darwin he began to deny the rationality of theism and intelligent design. By the following decade, he had begun to examine the limits of naturalism and adopted a form of monism that saw mind as a factor in evolution. In so doing, he was not alone, mirroring the doubts of such biologists as Wallace (with whom he disagreed about spiritualism) and St George Jackson Mivart (who incidentally also accused the Darwinians of inflexibility). Before his death, he "certainly came to believe that his rational rejection of religion … was faulted by an undue reliance on reason to the exclusion of emotional sources of truth" (Smith 2004–2012). There is, however, no evidence that a deathbed conversion occurred.

Like many of his contemporaries, Romanes wrote not just for the emerging scientific elite but also for a general audience, and he was a regular contributor to the periodical press. Wanting to continue outreach to the public but aware of his frail health, he endowed Oxford's annual Romanes Lecture in 1891, the second occurrence of which provided a venue for Huxley to deliver his famous discourse on evolution and ethics. Romanes died in 1894, exactly three weeks after Weismann delivered his own Romanes Lecture (*The Effect of External Influences upon Development*). Two years later Ethel published the *Life and Letters of George John Romanes*. Like many such volumes, the selection of letters was not exhaustive, and the accompanying narrative and editorial apparatus was somewhat tendentious, seeking, for example, to solidify Romanes' return to orthodox belief.

Aiming to provide a "faithful record" of an "eventful life" (p xvii), historian Joel Schwartz has assembled letters from archives in the UK and US. While the collection is not exhaustive—though the full Darwin/Romanes correspondence is included—Schwartz has succeeded in his task. Letters are transcribed with minimal editorial apparatus (for example, insertions and deletions are not indicated as with some other correspondence projects). Schwartz provides useful short introductions to each period of Romanes's life and indeed to the individual letters—these can profitably be read on their own to provide a capsule biography of the man. I for one would have preferred to see the endnotes as footnotes and for there to be a biographical register to guide the novice student of Victorian science. But these are mere quibbles. Schwartz presents the reader with an opportunity to examine the life of a Victorian who not only was a skilled scientist but also struggled with—and I offer only the slightest sampling—vegetarian dinners (p 35), the ethics of suicide (p 44), his own poetry (p 36), and his own lack of belief (p 26 and *passim*).

Recently, biologist Donald Forsdyke (2001) has attempted to establish Romanes's relevance as a precursor to his own "Physiological Selection Theory," though there are historical problems with this claim (see, for example, Lynch 2004). What Schwartz's volume makes abundantly clear is that Romanes—occupying as he did a central place in the early history of Darwinism—should be seen as a fascinating character on his own merits. This volume deserves to be on the shelf of anyone—historian or not—with an interest in nineteenth-century biology.

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REVIEW

Controversy in the Classroom: The Democratic Power of Discussion

by Diana E Hess
New York: Routledge, 2009. 197 pages

reviewed by Andrew J Petto

Anyone involved in promoting evolution in education knows that evolution remains *socially* and *politically* controversial—despite the fact that the relevant sciences have long ago reached a consensus that evolutionary models provide the best framework both for understanding the history and diversity of life on earth and for generating interesting and productive research questions in fields from agriculture to zoogeography. Too often, however, the scientific community has failed to engage the sociocultural and political environment in which scientific models should be applied (for example, Lewis 2009), taking an authoritative approach instead. Chris Mooney (2010) has called this approach "decide–announce–defend", and despite the best scientific evidence in support of evolution (and other scientific ideas), it is clear that public acceptance of policy (and curriculum) proposals put forward in this way is limited. We only need to look at the past three decades of polling on the creationism/evolution issue and recent legislation on climate change education to see these results.

For better or worse, our public schools are intimately entwined in the democratic process. To succeed in establishing and maintaining evolution or climate change education in the public schools requires engagement of the democratic process, and Diana Hess's book explores examples in which teachers have successfully engaged students in productive democratic discussion of socially controversial issues in the classroom. Her main thesis is that having students learn to engage in high-quality deliberative discussions about socially and politically controversial issues is essential to the health of our democracy. She points out a lesson that often escapes defenders of modern science (including evolution, climate change, and related curriculum): it is the sociocultural and political context that makes a topic controversial, and it is in this milieu that the controversy must be engaged.

> Topics are not controversial by nature. Instead, they are socially constructed in ways that cause them to be more or less controversial. This is why it is common for issues that are considered closed in one nation or region to be controversial in others. For example, the question of whether evolution (or other ideas about the origin of life) should be taught in public schools is a matter of bitter controversy in some parts of the United States but does not generate the same level of controversy in much of Europe. (Hess 2006:114)

This book focuses on the arena where most of us in the creationism/evolution and climate science controversies are concerned: the public schools as a place where these social controversies play out.

One important concept explored in this book is the way that interest groups and media can "tip" a concept from a closed or settled status to a controversial one. Readers of *RNCSE* are familiar with the term "manufactroversy", and others have described the public fuss about evolution as a "nontroversy". However, Hess's examples and discussions of "tipping" strategies reveal important lessons about the social dynamics of creating apparent controversy even when issues are considered closed by the relevant disciplines.

In the creationism/evolution and climate science controversies, as in many others, the goal of the tipping efforts is to convince the public that it is a "matter on which several views are or can be held" which Hand describes as a characteristic of an active controversy (Hand 2008, quoted on p 122). NCSE members recognize this assertion immediately in the various denialist campaigns against evolution and climate education—the concept that there is more than one scientific interpretation of the "evidence" underlies calls for "fairness" and demands for "academic freedom" in preparing and delivering curriculum.

Most of the book deals with controversies that do not have a direct bearing on creationism/evolution or climate change issues. Furthermore, Hess is clear that there is a different dynamic for engaging concepts that are considered settled by the relevant disciplines but whose closed status is being challenged in public discourse. However, there is much for the natural sciences to learn here from experience in the social sciences classroom. The strategies and practices for engaging socially controversial issues in the classroom (and, by extension, in society) are useful suggestions for how to promote successful dialog about these issues. One outcome of a successful dialog for the perceived controversies related to NCSE's mission might be to separate those aspects of the controversy that have to do with values and beliefs of discussants from the scientifically settled aspects of scientific models (for example, see Lockwood 1996).

Controversy in the Classroom is a valuable resource for anyone interested in promoting rational conversations about controversial issues in the classroom—and ultimately in society. The creationism/evolution and climate science controversies are only two of those that get played out in the public schools, and we need a more successful strategy if we are to make any progress in helping students (and future citizens) learn to engage in dialog, rather than "counting coups" in catchphrases and sound bites. The "democratic" in the subtitle refers to the value of informed *political* discourse that illuminates and promotes understanding. Hess is not proposing a postmodern free-for-all in the classroom, but a model for developing a well-structured and well-informed discussion of relevant issues in the classroom when there is disagreement among citizens about any important topic. Since it is in the political arena where both creationism/evolution and climate science discussions generally take place, it would be beneficial to those active in promoting these scientific positions to adapt and apply some of the strategies examined in this book to "scientific controversies" in popular culture.

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REVIEW

Darwin the Writer

by George Levine
New York: Oxford University Press, 2011. 244 pages

reviewed by Michael Roos

A common assumption among even the most educated modern readers is that it isn't necessary to read Darwin in order to understand and appreciate the import of his ideas. An enlightened contemporary human can get along just fine, we presume, without having read *The Voyage of the Beagle*, *On the Origin of Species*, or *The Descent of Man*, so long as we know the essentials of the theory and how it produced us and the rest of life. At one time, not so long ago, I would have counted myself in this group. For many years, I quite contentedly read lively modern summaries of evolutionary theory by the likes of Richard Dawkins, Jerry Coyne, Kenneth Miller, and others, satisfied I was getting all of Darwin that was necessary and having a reasonably fine time in the process. Ultimately, however, I reached a point where something like guilt set in. As my absorption of the truth of evolution grew ever deeper, so did my sense that it is fraudulent to call myself a Darwinist without having read the original texts. So I girded my loins and prepared for battle.

Yes, I have to admit, I approached Darwin's texts not without a real sense of trepidation, expecting to have to slog through hundreds of pages of dry and dreary pre-modern scientific writing unfriendly even to a serious and avid 21st-century reader such as I. However, what I discovered, much to my surprise, was not the dull, difficult, and depressing writing of the sad man Darwin is so often depicted to be, but instead found works that, although awkward at times, revealed a genuine love of language and metaphor, an engaging sense of wonder and awe before the world, and a humble, likable author possessed of an ear for the well-tuned sentence—in other words, a real writer. Darwin's great works are now ones that I, as a student of the best literature of all ages, look forward to re-reading often.

If you haven't already discovered this fact for yourself (or even if you have), George Levine's fine new book, *Darwin the Writer*, will certainly assist you in recognizing the beauty of Darwin's language and convince you of the importance of actually reading Darwin before you start conversing in any depth about his ideas. A distinguished scholar of Victorian literature, Levine has had a longstanding almost emotional connection to Darwin. He is deeply passionate about the man's ideas and perhaps even more so about his language. In fact, Levine argues that Darwin's continual relevance in the 21st century is as much dependent on the quality of his writing as it is on the quality of his ideas. We need only remind ourselves of the degree to which Darwin's theory was limited by his own Victorian prejudices and the scientific tools available to him, especially so when it came to an understanding of heredity and genetics. So, for a thorough and up to date explanation of the science of evolution, numerous modern scientific writers other than Darwin serve us better. It is Levine's task, however, to show us that reading Darwin today is more than a mere journey back to the quaint and innocently ignorant beginnings of his theory, in other words, more than a historical exercise.

Darwin the Writer is an extension of Levine's previous books on Darwin, beginning with *Darwin and the Novelists* (1988) and continuing through the excellent *Darwin Loves You* (2006). In the first book, with a relatively narrow audience of literary scholars, Levine's aim was to demonstrate the degree to which evolutionary concepts infiltrated and eventually permeated 19th-century literature and culture. Then, in *Darwin Loves You*, he sought a much wider readership and directly challenged the notion that Darwinian theory has, in Max Weber's famous terminology, "disenchanted" the modern world by having stripped it of its spiritual meaning. Here, in a heartfelt, impassioned, and finally convincing treatise, Levine revealed how enchanted Darwin himself was with the evolutionary world that he uncovered and how meaningful a truly Darwinian view of the world can be. Instead of stripping meaning from the world, Levine argued, a Darwinian view, in fact, recognizes how all of life's elements are charged with meaning and significance, a recognition that allows us to become newly enchanted with the world in a far richer and deeper way than any religious meaning could ever provide.

Now, in the new book, Levine intends to show us how much of Darwin's enchantment with the world is inherent in the very language of his great texts, especially *The Voyage of the Beagle* and *On the Origin of Species*. Levine begins by insisting that *On the Origin of Species* is the most important book in English literature written in the 19th century. Certainly, if he had declared Darwin's book the most important scientific treatise of its time, perhaps even of all time, there are few who would disagree. But to claim that its literary stature outshines works such as George Eliot's *Middlemarch*, Dickens's *Bleak House*, Wordsworth's "The Prelude," or Tennyson's "In Memoriam" gets our attention, to say the least. Levine wants us to know that Darwin's book remains "something more than its ideas." This is not to say that Levine minimizes Darwin's ideas; for, as he admits, the quality of the ideas fed the quality of Darwin's writing. Both good science and good writing require precision, and Darwin was obsessive in his attempt to be precise.

In the end, Levine's most important point, and a point likely to take many readers aback, is his insistence that Darwin's vision, especially in *On the Origin of Species*, is a comic one—comic, that is, in the literary sense, in its movement through a full awareness of the pain and suffering in the world to a final recognition of the triumph of life—affirmation and celebration of life in all its wondrous forms. Of course the book's famous last paragraph serves as Levine's best evidence, the "grandeur" of Darwin's "tangled bank." Darwin achieves this through what Levine calls a "double movement" in his prose, in which Darwin takes himself (and his readers) through intuitive feeling, allows us all to struggle with the feeling, and leads us out into the light of new scientific knowledge.

After chapters on Darwin's skillful writing in *The Voyage of the Beagle* and *On the Origin of Species*, Levine presents a particularly fascinating exploration of Darwin's proficient use of surprise and paradox, making the case, along the way, that Sherlock Holmes stands as one of the great Darwinian characters of literature, and this path leads Levine to make an even more surprising and paradoxical connection between Darwin and Oscar Wilde in the next chapter. The book concludes with a somewhat less surprising but no less insightful chapter—focusing on the similarities between Darwin's propensities toward the grotesque and the generally bleak vision of Thomas Hardy, although, in this case, Levine chooses one of Hardy's less overtly bleak novels, *The Woodlanders*, as his point of illustration.

Although Levine's erudition is impressive and he requires his readers to wade through pages of endnotes, he is nevertheless a most engaging writer, and his passion for Darwin is evident in every sentence. Reading one of his books can feel like absorbing the essence of twenty or more books by different authors—in other words, a very rich experience. The fact that he goes to great lengths to sing the praises of fine Darwinian commentary by the likes of Gillian Beer, Robert J Richards, Adrian Desmond, and James Moore, among others, only serves to underscore Levine's humility as a scholar. In this, Levine clearly follows the master himself, Darwin. But George Levine has his own uniquely important contributions to Darwinian scholarship and deserves to stand alongside those other distinguished commentators. While this book is perhaps less broadly significant in impact than was *Darwin Loves You*, it is a worthy successor, and I highly recommend it.

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About the author

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REVIEW

Proving Darwin: Making Biology Mathematical

by Gregory Chaitin

New York: Pantheon Books, 2012. 144 pages

reviewed by Jeffrey Shallit

This is an infuriating little book.

It's poorly written—if the author knows what a run-on sentence is, he doesn't care. It's repetitive and padded with a thirteen-page paper of John von Neumann (1968) that is easily found on the web (for example, at http://tinyurl.com/7kwxgud), so that the book's 123 pages suggest more content than is really there. The author, Gregory Chaitin, is relentlessly self-promoting, and likes to drop the names of his famous and infamous friends, including Stanislaw Ulam, Jack Schwartz, Sydney Brenner, Stephen Wolfram, Marvin Minsky, and David Berlinski (a senior fellow of the Discovery Institute's Center for Science and Culture!). He portrays himself as a scientific rebel, and favorably cites the bogus cold fusion claims of Italian inventor Andrea Rossi (Wolchover 2012). The book makes some false claims about biologists and exaggerated claims about the importance of the mathematical results it contains, and Chaitin takes sole credit for a theory that was largely developed earlier by others.

Nevertheless, despite all these flaws—and more problems, which there is not enough space to describe here—the book is written in an engaging and enthusiastic style, and does contain one rather interesting idea, which I will explain below. Readers interested in pursuing more details can easily find Chaitin's papers on the web (Chaitin 2010, 2011, 2012), so there is really no good reason to buy this book.

First, let me tell you a little bit about the author. In 1965, at the age of 18, while still an undergraduate at City College in New York, Chaitin submitted two papers on the foundations of what is now called "Kolmogorov complexity" or "algorithmic information theory"; one was published in 1966 and the other in 1969. Chaitin has spent the rest of his career mostly on working out the implications of these ideas.

However—and this is common in the history of mathematics and science—the basic ideas of algorithmic information theory had been discovered earlier by Ray Solomonoff and Andrei Kolmogorov. Because of priority, and because Kolmogorov was already world-famous for his work in probability theory, the name "Kolmogorov complexity" became entrenched in the literature for this field. Chaitin certainly deserves credit for his independent discovery, especially at so early an age, and since then he has found many additional results of interest, such as his amazing number, Omega (Gardner 1979). However, while algorithmic information theory is discussed briefly in the book under review, the reader will not find the theory's co-inventors Solomonoff and Kolmogorov mentioned anywhere. This is unfortunate. (For an unbiased appraisal of each person's relative contribution, see Li and Vitanyi 1997:89–92.)

But back to the main subject of the book. For many years people have attempted to model biological evolution using computer programs. Indeed, there is an entire field devoted studying this, called "artificial life", with yearly conferences and an academic journal published by MIT Press. (Oddly enough, the term doesn't seem to appear anywhere in the book under review.) However, a significant emphasis in artificial life thus far has been the construction of software models of organisms that evolve in various ways, such as Tom Ray's Tierra (Ray nd), and Karl Sims's evolution of locomotion strategies (1994a, 1994b). In this milieu, experiments are key, and proof of a claim consists of coding up your simulation, running it, and seeing what you get.

Chaitin's approach is very different. He wants to construct a model of evolution that permits one to *rigorously prove mathematical theorems* about what happens in the model.

Chaitin's model of evolution is so simple it can be described in a couple of paragraphs. An organism is modeled by a computer program P that, when you run it, must eventually halt and print out an integer I. At each step of the simulation, a mutation is applied to P, obtaining a new program P′ that prints out some other integer I′. If I′ is bigger than I, the new program P′ is deemed to be more fit; P is then killed off and P′ replaces it. For Chaitin, this is how evolution proceeds.

How are Chaitin's mutations applied? Randomly and algorithmically. More precisely, the mutations themselves are also computer programs, and at each step, *every possible mutation program* is considered, with a probability distribution that strongly favors "simple" mutation programs being chosen and disfavors more complicated ones. Specifically, we assign a certain probability of being chosen to every program of length n, for all integers n. At each step we choose such a program Q according to our probability distribution, run P through it, and get a new program P′ = Q(P). This is the model.

Chaitin's main result, which he can rigorously prove, is that in such a model, after at most about $n^2(\log n)^2$ steps, we will obtain, with high probability, a program to compute the busy-beaver function BB(n), which is the function sending n to the largest possible integer printable by a n-bit program The significance of the evolution, in Chaitin's model, of programs that compute the busy-beaver function lies in the fact that busy-beavers are hard to find, both because the search space (of all possible n-bit programs) is so large and because it is in general impossible to determine whether an arbitrary program will halt. He contrasts this result with a model based on pure random choice, which will take about 2^n steps to get the same result; this is much longer than his evolutionary model. Finally, in a model he calls "intelligent design"—which means that at each step, the optimal mutation is chosen—about n steps suffice.

A pure mathematician or theoretical computer scientist may well find this result interesting—and I do! But if it is supposed to be relevant to biological evolution, there are a number of obvious objections. First, when we get P′ by mutating P, it could well be that P′ is not a *useful* computer program. It could, for example, go into an infinite loop and never print out anything at all. And of course, we know from fundamental results of Alan Turing that there is no program that will, in general, tell us whether P′ is useful in this sense. To get around this, Chaitin blithely assumes we have an "oracle": a purely theoretical construct in computer science that ignores Turing's theorem and gives answers to uncomputable problems. We have a similar problem when we run our mutation program Q, so we need an oracle to handle *that*, too.

But as soon as we assume we have an oracle to solve the halting problem, we could solve the busy beaver problem *directly*, simply by running all programs of length N, and weeding out those that don't halt! To get around this, Chaitin needs yet *another* rule: the oracles can't be used arbitrarily, but only in the way he specifies. The result is that his model is rather arbitrary and says little, if anything about the actual physical process of evolution.

Furthermore, Chaitin's model is unrealistic in other ways. Evolution occurs in populations, not single individuals. In a population we get competition for scarce resources, and we can get sex and horizontal transfer. Furthermore, mutations do not seem to be algorithmic in Chaitin's sense; they seem to be restricted to a few very basic kinds of changes, such as point mutations.

Then again, Chaitin is not a biologist. Readers will be astonished to learn that "every cell in our body has the complete DNA for an entire human being" (p 17); I guess those red blood cells and gametes aren't worth chopped liver. As well, we are told that "conventional biologists ... suspect that life on Earth was either seeded by accident ... or deliberately planted" (p 14). Funny, I know a lot of conventional biologists who don't suspect either one.

So contrary to the title of his book, Chaitin has not proved Darwin mathematically. Nor has he invented a whole new field, "metabiology"; indeed, papers by Nehaniv and Rhodes (1997, 1999, 2000) have already explored some analogous ideas. Instead, he's created an unrealistic but intriguing mathematical model quite divorced from biological evolution in the real world, and proved some theorems about it. This is the stuff of an interesting talk at a departmental colloquium, not a whole book.

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REVIEW

Evolution and Medicine: How New Applications Advance Research and Practice

edited by Randolph M Nesse
London: Henry Stewart Talks, 2007. Two CDs, approximately 27.5 hours

reviewed by Niall Shanks

Famously, the population geneticist Theodosius Dobzhansky remarked that nothing in biology makes sense except in the light of evolution. Darwin's take on evolution, however, had few if any ties to medical or physiological issues. The rediscovery of Mendel's work on genetics at the dawn of the 20th century would set the scene for a slow process of evolutionary change in the realm of ideas that would effectively alter all this. Notable in this regard was Sir Archibald Garrod's observation of alkaptonuria, an inborn error of metabolism, back in 1908.

The conceptual fusion of ideas about evolution with ideas about genetics resulted in the new evolutionary synthesis (1925 to 1955). Here was an approach to evolutionary issues firmly rooted in population genetics. Since the 1980s, there has been an even newer synthesis involving developmental biology, resulting in contemporary evolutionary developmental biology (evo-devo for short).

In the 1990s there was an explosive growth in the publication of books attempting to tease out the implications of these new evolutionary insights for medicine—a field traditionally resistant to the intrusion of evolutionary considerations (with such noted exceptions as the evolution of drug resistance). Randolph M Nesse, along with George C Williams, published *Why We Get Sick: The New Science of Darwinian Medicine*, which aimed to get the message about the need to rethink medical puzzles in the light of evolution to a broader, popular audience.

Evolutionary medicine (for the issues go far and beyond anything envisaged by Darwin himself) is very important to an educator for the following reason: the discussion of medical matters takes us to the heart of the human condition, and to see these matters informed by evolutionary biology is perhaps to inform us that evolution is not just a theory about dinosaurs and things long dead. It is instead something that matters for a rational discussion of our own health and wellbeing. "Intelligent design", for all its blather about biochemistry, has nothing whatsoever to say about these matters (save, perhaps, that the putative designer wasn't as smart as we have been told to believe); and old style creationism simply places the burden of human disease on either the will of God or our innate sinful natures.

Enter the Henry Stewart Talks on evolution and medicine. Here we have a series of talks by leading evolutionary biologists and medical theorists on the relevance of evolution to medical theory and practice. Taken together there are 37 talks of average length just over

45 minutes, for a total of 27.5 hours of talks. The talks are in audiovisual format, accompanied by numerous helpful diagrams and illustrations. (I will not attempt to summarize the individual talks—a couple of lines apiece will hardly do them justice.)

Reviewing these talks, I found myself asking who the intended audience might be. As noted above, evolutionary medicine is one of those places where the theoretical rubber hits the road of human experience. It would be nice to think that these talks could be used in the high school setting. Perhaps one or two of them might be used to form the basis of class discussions. However, it may be asking too much of science teachers to take on the matters at hand in high school, when there are so many other scientific holes to fill first. Professional educators themselves (including high school teachers) might make good use of the talks in the sense that they will provide new perspectives on old topics of interest—the relevance of the talks then becomes pedagogically useful, but primarily indirectly.

Professional biologists, and their students taking college-level biological science classes, will definitely benefit from judicious use of these talks. Having taught evolutionary biology to pre-med students, it is my judgment that it is here that the talks could be most valuable. It might be a good idea in principle to change the way medicine is taught to incorporate evolution into the curriculum. Given that this is currently not a reality, giving pre-med students a grounding in these matters would be a valuable service.

Luckily for the educator considering the use of these talks, they come in the form of ten modules, and these constitute a splendid feast of chewable morsels on what is a large and comprehensive smorgasbord of evolutionary ideas.

The first module (three talks) is on the fundamentals of evolution and medicine and constitutes a good introduction to the matters at hand. The second module focuses on evolutionary genetics, and includes a lecture on race and medicine (six talks). These are self-contained and would not need too much background preparation in the classroom. The third module shifts the focus of the discussion to the study of infectious disease (five talks), and provides a good basis for a discussion of drug resistance and hospital-acquired infection. The fourth module (four talks) focuses on evolved defense mechanisms and strategies to cope with pathogenic and parasitic invaders. This section brings to the fore the important topic of evolutionary immunology. The fifth module is on the topic of novel environmental factors (five talks). Covered here are such issues as evolution and diet, the health implications of our Paleolithic inheritance, and diseases of civilization.

The sixth module (three talks) focuses on the issue of evolutionary tradeoffs, compromises, and constraints. The discussion here ranges from evolutionary obstetrics to the nature of aging and senescence. The seventh module (four talks) shifts the discussion to issues about sex and reproduction, and covers topics relating to pregnancy, gender differences and the role of endocrinology in a discussion of human life histories. The eighth module concerns cancer as a disease with an evolutionary dynamic (two talks). The ninth module (three talks) examines specific body systems, including lung tissue and lung disease. The final module (three talks) concerns mental disorders, and touches on such issues as behavioral genetics and the evolutionary biology of depression. Finally there is a question-and-answer session moderated by Nesse.

All in all, a very well-structured series of talks of use to a variety of educators. If I have a quibble, it concerns the absence of a module focusing specifically on pharmacogenetics and pharmacogenomics. Given the role played by drugs and other xenobiotics in medicine, a module here would have been useful and timely.

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Niall Shanks was the Curtis D Gridley Professor of History and Philosophy of Science at Wichita State University. He was the author of *God, The Devil and Darwin* (New York: Oxford University Press, 2004), and (with C Ray Greek) *Animal Models in the Light of Evolution* (Boca Raton [FL]: Brown Walker, 2009). He died on July 13, 2011. Rebecca A Pyles is his literary executor.

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