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 biol-
ogy 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 Kendrick (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 Biology** (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](image)

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

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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 seek 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*
Werth

An Evolutionary Focus Improves Students’ Understanding of All Biology

- 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 the 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.

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<th>Agree somewhat</th>
<th>Agree a little</th>
<th>Unsure/Don’t Know</th>
<th>Disagree a little</th>
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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.
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.
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:


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.