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ABSTRACT

Recent education reform documents emphasize the need for students to develop a rich understanding of evolution's power to integrate knowledge of the natural world. This paper describes a nine-week high school course designed to help students understand evolutionary biology by engaging them in developing, elaborating, and using Charles Darwin's model of natural selection. The aspects of evolutionary biology that informed course design are described and the curriculum development is discussed. Three major components of the curriculum implementation--examination of models, elaboration of the Darwinian model, and extension cases--are explored. (WRM)

RESEARCH REPORT

NATIONAL CENTER FOR IMPROVING STUDENT LEARNING AND ACHIEVEMENT IN MATHEMATICS AND SCIENCE

A COURSE IN EVOLUTIONARY BIOLOGY:
Engaging Students in the "Practice" of Evolution

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NATIONAL CENTER FOR IMPROVING STUDENT LEARNING & ACHIEVEMENT IN MATHEMATICS & SCIENCE

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Cindy Passmore and James Stewart work collaboratively with other Center researchers on The Modeling for Understanding in Science Education (MUSE) project. More information on this project will be posted at www.wcer.wisc.edu/ncisla in the Spring 2000.

A COURSE IN EVOLUTIONARY BIOLOGY: *Engaging Students in the "Practice" of Evolution*

Recent education reform documents have emphasized the need for students to develop a rich understanding of evolution's power to integrate knowledge of the natural world (American Association for the Advancement of Science, 1993; National Research Council, 1996). However, in spite of the efforts of science education reformers in publicizing the importance of evolution, a recent book on teaching evolution (National Academy of Sciences, 1998) lamented that, "many students receive little or no exposure to the most important concept in modern biology, a concept essential to understanding key aspects of living things—biological evolution" (p. viii).

In general, in education literature, the understanding of evolution has been limited to the understanding of individual concepts (e.g., variation, differential survival, natural selection, adaptation). Although the importance of understanding these concepts should not be downplayed, it is equally important for students to be able to use these concepts to think about evolutionary change. Such a level of understanding can be achieved by students' participation in activities that mirror aspects of the practice of evolutionary biology. Our approach to promoting understanding— engaging students in realistic inquiry— has formed through years of curriculum development and research into student learning, problem solving, and reasoning (see Cartier, & Stewart , BioQUEST Notes, Vol. 10 (2).

In this report, we describe a 9-week high school course designed to help students understand evolutionary biology by engaging them in developing, elaborating, and using Charles Darwin's model of natural selection. The first section provides an overview of some of the aspects of evolutionary biology that informed the design of our curriculum and is followed by a description of how this view was translated into a 9-week high school course. Finally, to provide a feel for the way the curriculum was implemented, we describe three major components of the course.

Evolutionary Practice

We start with the assumption that students need to learn the key knowledge claims of a discipline as well as the processes by which such claims are generated and justified (see Kitcher 1993 for an elaboration of the concept of a scientific practice). We have found that a fruitful way to help students develop greater understanding of scientific practice (science "content" and broader nature of science issues) is to engage them in realistic inquiry. We recognize that different disciplines inquire in unique ways, and, therefore, careful consideration of the disciplinary context under study is an important step in curriculum development work.

On a general level, the practice of evolutionary biology is concerned with reconstructing how life on Earth has changed and with proposing mechanisms that account for the ways those changes might have occurred. The first of these goals, the reconstruction of the past, creates challenges for evolutionary biologists because, unlike many disciplines that focus on directly observable and replicable processes, evolutionary biology is concerned with processes and events that span a significant amount of Earth's history. This extended temporal span necessitates a historical view, one that has, in large part, resulted from biologists' acceptance of Darwin's writing on descent, with modification. Because organisms are now recognized to be related through a common ancestry that has a many-million-year history, a primary activity of evolutionary biologists is to make inferences about past speciation events in order to establish phylogenetic relationships for the "tree of life."

In addition to working with extensive periods of history, evolutionary inquiry also leads to the second goal of evolutionary biology, the creation of explanatory models that can account for patterns observed in the historical reconstructions. These models serve both as a way of explaining natural phenomena and as a framework to guide additional inquiries. In order to serve their explanatory function, these models interact with two distinct domains: (a) the empirical phenomena for which the model purports to account and (b) the existing structure of evolutionary practice, which includes among other elements, related models, disciplinary specific language, methodological norms, and metaphysical assumptions about the natural world. Any particular model is deployed to explain and/or explore a limited empirical domain and is itself embedded in a context of practice that is in many ways unique to the model.

Although evolutionary biologists utilize an array of explanatory models there is one that is central—Darwin's model of natural selection. Natural selection is a mechanistic model that can be used to explain the changes in the heritable characteristics of populations over successive generations. This model interacts with a family of related models, including models of speciation as well as those in population genetics, and is based on a set of shared assumptions about the natural world (e.g., belief in a naturalistic mechanism that acts on existing variation among individuals in a population) championed by Darwin and accepted by evolutionary biologists since Darwin.

Another key aspect of evolutionary practice, and one that sets it apart from other disciplines in biology, is the form that acceptable evidence takes. Because many evolutionary phenomena do not lend themselves to easy manipulation, what counts as appropriate evidence in the field is different from what is acceptable in highly experimental fields like genetics and physiology. Much of the evidence available to evolutionary biologists is necessarily indirect as it is often impossible to make predictions about evolutionary events and then run experiments to confirm those predictions. Instead, evolutionary explanations depend on historical data and the probabilistic nature of its explanatory models. For example, although evolutionary processes might currently be at work and observable, the effects of these processes at the species level are generally not observable. Therefore, the evidence for evolutionary change comes from the fossil record, examination of homologous structures, and (increasingly in recent years) molecular information—all indirect sources of evidence.

Although the preceding is not an exhaustive account of the practice of evolutionary biology, we do believe that in order to develop a course on a subject, consideration of what goes into the practice of that discipline is an essential step. The recognition that the cognitive goals of evolutionary biology include both historical reconstruction and the modeling of observed patterns has important implications for evolution education, as does the recognition that the evidence considered acceptable is often indirect.

Curricular Approach

The practice of evolutionary biology sketched above provided the basis for designing our 9-week course. Because it is impossible to include all aspects of the practice of evolutionary biology in an introductory course, we focused on introducing students to the reasoning patterns of evolution by engaging them in developing, using, and extending Darwin's natural selection model. By focusing on natural selection, we were also able to provide a setting in which examination of argumentation, language use, and methodology would occur naturally as students collaborated to explain phenomena.

On a general level, our approach was to provide cases that "serve as realistic contexts that define a problem space and help students organize their learning of a body of known information" (Waterman, 1998, p. 4). Because evolutionary phenomena do not lend themselves to manipulation by high school students, the use of case materials (which included readings and data that could be used to build explanations and which defined the phenomena for student discussions) was instrumental. Through the use of cases, students were involved in extended explorations, each designed to promote understanding of particular aspects of evolutionary biology. The first set of cases involved students in an examination of the disciplinary context of evolutionary biology by providing them with materials about three explanatory models. The second case provided a large set of data from which an evolutionary explanation could be constructed using natural selection. The two final cases provided rich scenarios that required students to extend the natural selection model.

Course Description: Major Components

The first days of class were dedicated to establishing norms of classroom discourse in order to provide students with a common language and the analytical tools with which to examine and critique arguments. Students first participated in activities designed to help them distinguish between observations, inferences made from those observations, and the underlying assumptions (prior knowledge and beliefs) that affect inference making. The students then used these distinctions to examine and critique knowledge claims made during this activity and throughout the course.

Students were then given activities that supported students' exploring the metaphysical assumptions of models proposed by William Paley, Jean Baptiste Lamarck, and Darwin. By examining these models, students compared and contrasted Darwinian and non-Darwinian assumptions and gained a stronger working knowledge of the strength of Darwin's model. They then spent the remaining weeks of class applying Darwin's model of natural selection in order to explain phenomena in a hypothetical, but data-rich case and extending it to explore two other real-world data-rich cases.

EXAMINATION OF MODELS: PALEY, LAMARCK, DARWIN

This portion of the class involved students in the analysis of three models (Paley's model of intelligent design, Lamarck's model of use inheritance, and Darwin's model of natural selection), each of which, in its own way, accounted for species diversity. These models were chosen (a) because they were based on disparate assumptions and, therefore, lend themselves to comparison on that level and (b) because the models of Paley and Lamarck relate to common student misconceptions.

In order for students to compare the underlying assumptions of these models it was necessary for them to be familiar with the models. Students were asked to read an edited version of the author's original work and participate in class discussions in which the proposed mechanisms were elaborated. Students also experienced the phenomenon that inspired each author's model. For example, they examined fossils discussed by Lamarck, dissected an eye to examine the structure/function relationships that so fascinated Paley, and were visited by a pigeon breeder who brought several of the pigeon breeds described in Darwin's *Origin of Species*.

Once students had developed an understanding of each author's proposed mechanism and the observations on which it was based, they worked to identify the underlying assumptions of each argument. The first set of assumptions concerned the authors' view of species—Did the author view species as fixed or malleable, and what role did he attribute to variation within species? The second assumption concerned the author's view of the "force" responsible for production of new species. In this instance, students needed to consider what that force acted on, whether it was internal or external, and whether organisms played a conscious role in their own evolution.

Following this discussion, the comparison of models began. First, students assessed the explanatory power of each model: They used each model to explain phenomena other than that described in the original paper. For example, they used Paley's model to explain the presence of fossils, and they used Lamarck's model to explain the structure of the eye. In some cases the model could easily account for new phenomena; in others, the students recognized the model's limitations.

Second, students were asked to compare and critique the authors' underlying assumptions, allowing students to understand that it is good scientific practice to critique a model based on the assumptions made by the author even if that model could account for diverse phenomena in its own context. Comparison of the assumptions of the three models enabled students to distinguish those beliefs that underlie the model of natural selection (that a naturalistic mechanism of species change acts on existing variation among organisms) from those that underlie Paley's model (notions of supernatural influence) and those that underlie Larmarck's (notions of individual need).

ELABORATION OF THE DARWINIAN MODEL

Once introduced to natural selection, students developed a Darwinian explanation (a narrative that describes variation in the population, a description of the selective advantage of a trait, and a discussion of the role of inheritance in accounting for changes that occurred in the frequency of particular traits) for a simple adaptation. After composing Darwinian explanations and explicitly considering the components of an appropriate explanation, students were given a data-rich case to explore. This case was designed to provide a scenario in which students could investigate a change in a trait over time, use the natural selection model to explain that change, and support their argument with appropriate evidence.

The case materials were based on hypothetical organisms, for which a large amount of data was supplied. The phenomenon to be explained was the change in a seed-coat character-

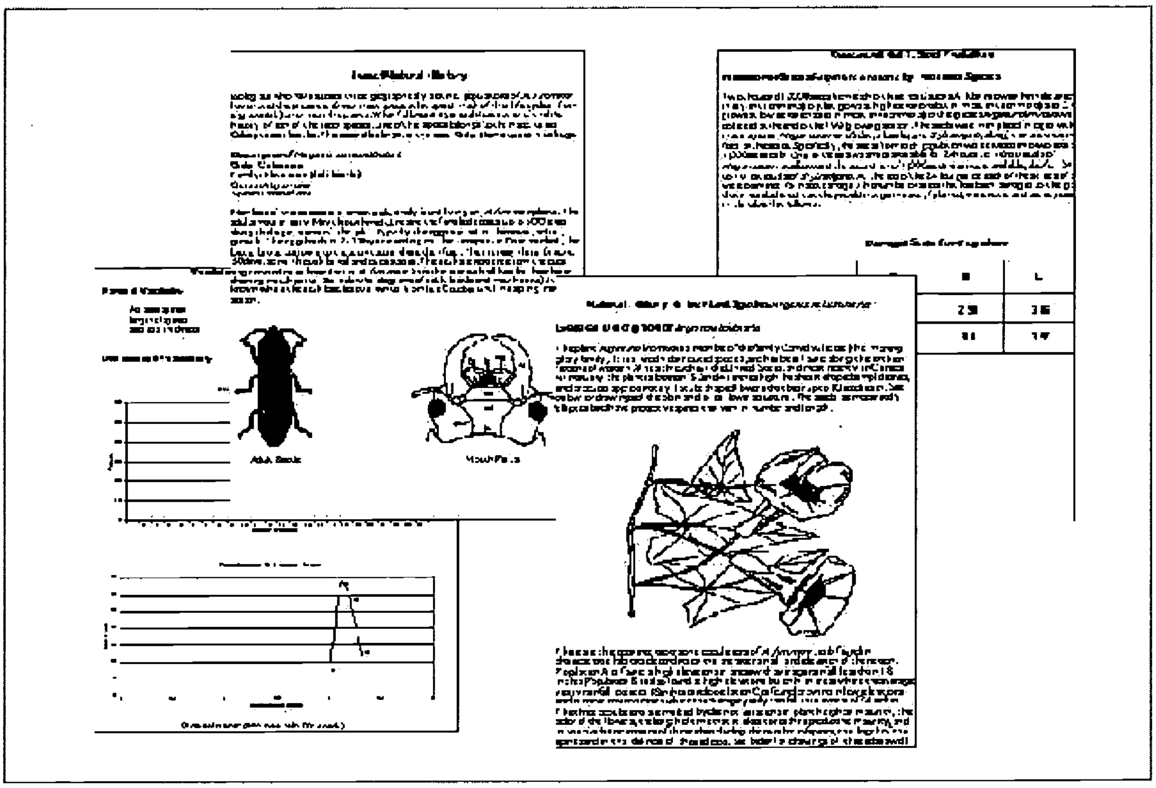

FIGURE 1. SAMPLE CASE MATERIALS

istic in different populations of a hypothetical plant. Students were given descriptions of the ancestral population, natural history information on contemporary populations, predation information, and data that allowed them to establish the heritability of the trait. Sample case materials are shown in Figure 1.

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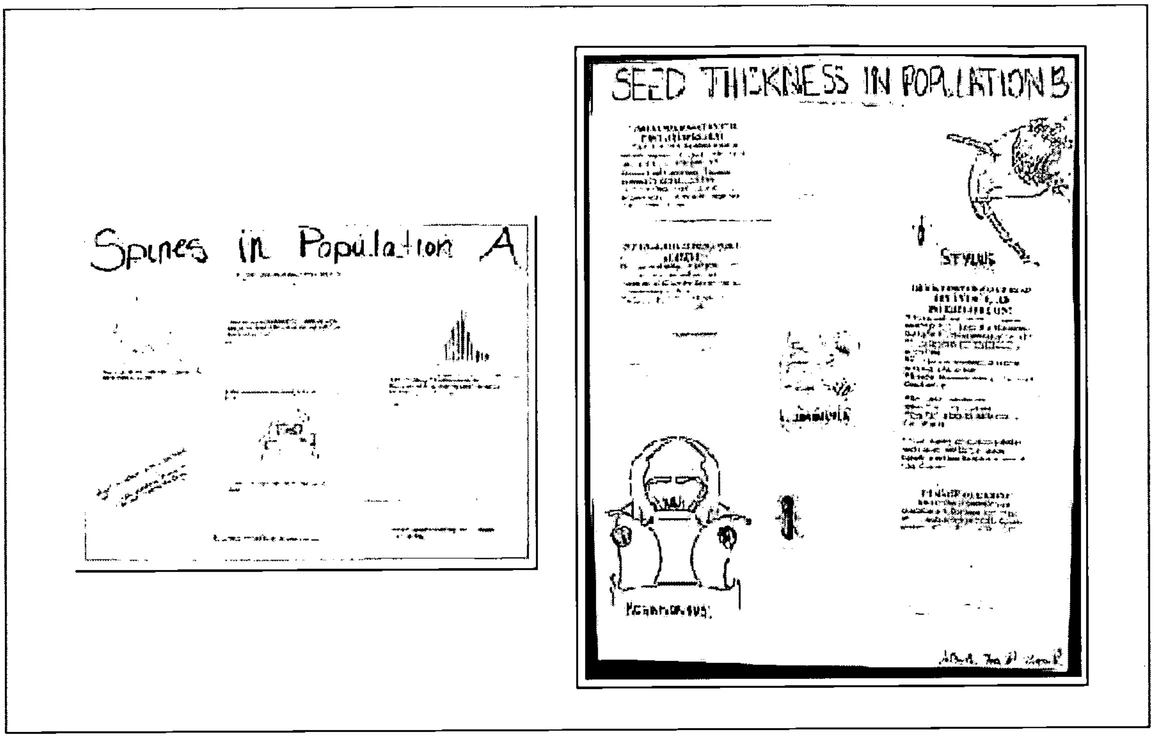

FIGURE 2. EXAMPLES OF STUDENT POSTERS

The students worked in groups to create a scientific poster that used the natural selection model to explain the change in one of two traits (seed-coat thickness or number of seed-coat spines) over time. Students were asked to develop an explanation using the natural selection model as well as to tie data from the case materials to each component of the model. The case ended with a poster session during which students presented their posters and critiqued each other's explanations. Sample posters are shown in Figure 2.

EXTENSION CASES

The cases used in these activities were similarly data rich, but they differed from the seed case in that these were based on real organisms and that the range of available data was constrained (e.g., no description of an ancestral population). These two cases were intended to push students into extending their understanding of the applicability of the natural selection model by asking them to construct explanations for situations in which the selective advantage of the trait in question was not immediately clear. The first case required students to explain the similarity in color between viceroy and monarch butterflies. What quickly became an issue for students was the lack of explanation for the bright coloration in the monarch. The second case asked them to explain differences in coloration between male and female ring-necked pheasants. Applying the model of natural selection to these less than straightforward cases necessitated a rich understanding of the model and the assumptions upon which it is based.

This portion of the class provided students with opportunities to work in groups and to meet periodically with other groups to compare explanations and present preliminary ideas. The culminating activity for the monarch/viceroy case was a round-table discussion, and the final work on the pheasant case was organized into a research funding competition.

Monarchs and viceroys. Once the students had finished writing their explanations for the monarch/viceroy case, they read and critiqued one other group's explanation. Students then met as a large group to discuss the case generally, describing the overall arguments and citing specific pieces of data to support their claims. The level of interaction between students was high on these two days. At the beginning of their discussion about a general explanation for the similarity in color between the monarch and viceroy there seemed to be agreement that the viceroy was brightly colored to gain the advantage of resemblance to the poisonous monarch. There was a consensus that the monarch's habit of eating milkweed plants as a caterpillar resulted in toxicity of the adult butterfly.

As the discussion progressed and students began to address the types of data that different groups brought to bear on their explanations, the interactions became more interesting: Not everyone assigned equal importance to pieces of data. For example, the case contained information on the habitat, range, and population densities of the monarch and viceroy in a meadow. This range map showed that the distribution of the monarchs and viceroys overlapped and that there were larger numbers of monarchs than viceroys in this area. The discussion students had about the relevance of this data provides interesting insights into their thinking about natural selection:

LINDA: I thought it was very important, about how we talked about the density of the monarchs and the viceroys because it said there was only .3 individuals per square meter of the viceroys and 2.2 individuals per square meter of the monarch and if it were, like for example, if the number of viceroys were higher or the monarchs were lower, then the blue jays wouldn't necessarily learn that the monarchs were poisonous and the coloring the way the monarchs looked wouldn't act as a warning. It would act as more of, like, an attraction. you know, 'cause they wouldn't know the difference between the viceroy and the monarch.

JASMINE: So, you're saying there wouldn't be as many monarchs, so they wouldn't have the chance to eat as many and find out and experience.

ANDREA: Well, yeah, if there were more, like, viceroys instead of monarchs, they wouldn't learn as quickly that the monarchs are poisonous because if they were the same color, the color would, like, attract them instead of repelling them 'cause there's more monarchs, which is important 'cause they learn that the monarchs are poisonous, you know.

This discussion shows sophisticated reasoning about selective advantage. The focus on population density data appeared to be useful to some students in imagining how predators would begin to associate bad taste with bright coloration. Later in the class period, the students had an extended conversation about blue jay's ability to learn and remember. It was clear that they were concerned with the apparent disadvantage of bright coloration in terms of predation for individual monarchs, but they could imagine how bright coloration could be advantageous to the population as a whole if the predators began to associate brightness with distastefulness. This differentiation between an advantage for an individual organism versus an advantage for the entire population is central to evolutionary reasoning.

The students also dealt with issues of species interaction when they recognized the potential problem for the monarchs if there were more harmless viceroy mimics: "They'd just keep eating them" (the brightly colored butterflies) if it were "the other way around" (there were more harmless butterflies than harmful). This appreciation for the complexity of species interactions in evolutionary terms indicates a high degree of understanding of explanations for evolutionary phenomena using the Darwinian model.

The following day the students discussed the origin of bright coloration. They began their discussion by considering how the trait could be advantageous before it was widespread throughout the population. Jen noted that "I don't see how in the beginning bright color could be an advantage."

This led one student to consider how the variation might have looked in the past in terms of the population as a whole:

MARK: Well, I don't think you can think of it as just one, one butterfly either, I mean even if it [evolution] is slow it is, I mean there's probably a lot, I have no idea, but—

DOUG: Because butterflies have a lot of offspring.

These students went on to note that initially there could have been multiple butterflies that were "brighter" in color: Even if the trait of brightness originated with one pair of butterflies, butterflies lay so many eggs that there would potentially be several brighter butterflies in a batch of eggs. These questions of the initial advantage of the trait led them to further consider the ancestral population and question how to define the starting point of evolutionary change:

ANNA: What about, I feel like we're saying that everything had to evolve from a dull color, what if it originally was bright, that just how it was. Just like every species has variation that was just that's what it was, it was bright for no particular reason.

MARK: But it had to evolve from something.

Here they began to talk about other animals and what they knew about ancestral traits. Mark brought the conversation back to defining starting point:

MARK: But it had to evolve from something sometime.

ROB: Do you think monarchs were always poisonous?

MARK: As long as they've been eating milkweed.

ROB: You think they always laid their eggs on milkweed?

TIM: They had to develop the ability to eat poisons without dying and pass on that trait to their offspring.

DOUG: Well, how do you define a monarch? That's the question.

The class became very animated at this point—students were debating ways to define a population in the past in order to describe a change that occurred. Again the interactions described here would not have been possible without a clear understanding of the natural selection model. These two transcripts indicate that students are capable of sophisticated reasoning about evolutionary events when they work from a well-articulated model.

Pheasants. The pheasant case was organized as a research funding competition. Students were given the task of developing a Darwinian explanation for the bright coloration of the male ring-necked pheasant supported with evidence drawn from the case materials. Once they had formulated an explanation, they were asked to develop a research question that would allow them to investigate some component of their explanation. They then presented their explanations and research questions to the class in a competition for research funds. The nonpresenting groups acted as judges and interacted with the presenting groups in an attempt to understand the proposal. Once all groups had presented, the students discussed the merits and shortcomings of each proposal and then as individuals decided which proposal to fund.

All but one of the Darwinian explanations the students developed for the bright coloration of the male pheasant were consistent with a sexual selection scenario. The one group that did not present a sexual selection explanation attributed the bright coloration of the males to an increased ability to protect the nest: Bright-colored males could distract predators better than dull-colored males; therefore, their offspring would be more likely to survive. These explanations, *developed by the students themselves*, required them to extend their knowledge of the Darwinian model. In contrast to traditional evolution instruction, which often presents mimicry, warning coloration, and sexual selection to students as additional concepts to be memorized, this instruction encouraged students to grapple with phenomena themselves, create plausible explanations, and, in so doing, develop deep understanding of the explanatory power of natural selection.

With each of the research questions proposed, the students attempted in some way to establish the selective advantage of the trait and to devise a wide variety of ways to test the advantage. Three groups proposed exploring the role of female choice in conferring a reproductive advantage to brightly colored male pheasants. Another group wanted to investigate the possible linkage of bright coloration to other advantageous traits, such as increased fertility or immunity to common disease. A fifth group wanted simply to establish the exact developmental timing of the acquisition of bright plumage. They thought that if they could establish a correlation between timing of sexual maturity and development of bright plumage, their idea that bright coloration aided in courtship would be supported. If, however, they found that these two events occurred at completely different developmental times, the students realized that their sexual selection idea would need to be revised: They believed that the disadvantage of bright coloration in terms of predation could only be outweighed if the development of bright plumage coincided with the mating season, thereby providing a reproductive advantage. As in the discussion surrounding the monarch case, students interacted in sophisticated ways while defending their research proposals.

We argued earlier that an important goal of evolutionary biology is to infer historical or phylogenetic relationships. In the pheasant case, students were using an established phylogeny to support their claims about the way pheasants might have changed over time. They used this information on closely related species in order to determine a likely scenario for the way the ancestral population might have appeared—slight differences between the sexes. The instrumental use of this phylogenetic information illustrates one way in which students can use historical reasoning and thus bring this important feature of evolutionary thought to bear while creating explanations for natural phenomena.

Summary

When students are given opportunities to use their knowledge to explain interesting and appropriate evolutionary phenomena, the potential for their meaningful understanding of evolutionary concepts is enormous. In this report, we have described a course designed to engage students in the use of natural selection model, which provided a rich context for students not only to reason about evolutionary concepts such as variation and differential survival, but also to use those concepts to explain changes in populations over time. In designing this course, we attempted to redefine the expectations for students in evolutionary biology and to provide a picture of what curriculum designed with these goals in mind could entail. Students in this course were able to reason and argue from data, to develop their own explanations for natural phenomena, and to evaluate the hypotheses of their peers—a sharp contrast to students in traditional courses who often walk away from these classes with a mental list of memorized facts and an "understanding" of evolution as a belief system rather than as reasonable scientific explanation of phenomena and species change.

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