

Was Apatosaurus a Vegan? Dinosaur Knowledge Rocks When Learning About Evolution

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Abstract

We present the results of an experiment involving a curriculum designed to foster conceptual changes, generative understandings, and coherent evolutionary explanations. This middle school curriculum highlights dinosaur knowledge due to its intrinsic interest to students and its compatibility with the objectives of integrating several concepts (e.g., variation and heredity) into a coherent natural selection schema. The domain also allows one to communicate an understanding of the process of evolutionary change across geologic time. Students in a class that received the curriculum exhibited significantly greater gains than did a control class, across a range of problem types. Further, the subjects in the conceptual change classroom appear to be less prone to generating the kinds of explanations that directly conflict with Darwinian patterns of reasoning.

Introduction

Transfer is one of the most widely investigated phenomena in both cognitive science and science education. Arguably, the most important goal of education is to foster the transfer of knowledge and skills. Similarly, any learning theory worth its salt must include mechanisms of transfer. From some perspectives, studies of transfer have often yielded dismal results (Detterman, 1993). However, as one might expect, increasing any salient similarity between training and the transfer materials increases the probability that transfer will occur (Bassok & Holyoak, 1993) as does selecting a source domain in which the subjects have substantial prior knowledge (Kaufman, Patel, & Magder, 1996).

Evolution is a central unifying theory in modern biology, contributes to a foundation for learning across biological sciences, and provides a basis for understanding the interrelationships among all organisms. However, evolution remains a polarizingly controversial and poorly understood subject that typically receives a minimal amount of class time (Working Group on Teaching Evolution, 1998). In addition, evolutionary concepts are often taught as a set of discrete ideas, rather than as a central integrative topic (Sharman, 1994). Several recent studies have documented a range of misconceptions and erroneous beliefs in students' understandings of evolutionary concepts and their resistance

to instructional effects. Many individuals regard evolution as a need-driven, adaptive teleological process, whereby organisms change traits in response to some environmental pressure (Bishop & Anderson, 1990). Some see evolution as Lamarckian, in which an organism passes on to its offspring characteristics that are acquired during its lifetime (Samarapungavan & Wiers, 1997). These teleological and Lamarckian beliefs conflict with Darwinian theory of evolution by natural selection theory, an essential component of modern biological understanding.

Why is evolution such a difficult topic for students to master? In our view, the development of evolutionary competence is predicated on the following four factors (Kaufman, Ranney, Thanukos, & Brem, 1999). 1) Conceptual Knowledge: evolutionary knowledge involves the complex integration of concepts from several biological disciplines, including genetics, ecology, and paleontology. 2) Reasoning and argumentation: evolutionary reasoning makes formidable demands on the process of coordinating evidence and hypotheses; part of the problem concerns the unique nature of evolutionary explanation, which often requires reasoning about historical narratives rather than proximate (Kaufman, et al, 1998). 3) Epistemological commitments: students' views concerning the nature of science and of the biological world affect their understandings of evolution (Rudolph & Stewart, 1998). 4) Discourse practices: as in all sciences, there are ways of constructing explanations and using communication that are sanctioned or eschewed by the domain; students have considerable difficulty mastering mechanistic causal explanations and often use scientific terms, such as adaptation, inappropriately.

What are the ultimate objectives of an introductory evolutionary curriculum designed for middle school students? As with other sciences, the goals are to promote robust conceptual understanding and durable transfer. That is, we do not want students to learn merely about the evolution of dinosaurs, insects or other sets of organisms. We want students to begin to "own" Darwinian patterns of reasoning and apply them flexibly in multiple contexts. Ohlsson's (1993) notion of an abstract schema allows us to sharpen our intuitions about transfer. Such a schema encodes the structure of an explanation, rather than its content. The

following schema, adapted from Ohlsson, illustrates the notion of a Darwinian explanation pattern:

- There exists a species that varies randomly on a set of heritable characteristics.
- An environmental pressure (from imperceptible to catastrophic) will favor individuals (regarding survival) with certain traits.
- The selection mechanism operates such that these individuals are more likely to reproduce and pass on their traits to offspring.
- Therefore, more individuals in the next generation will possess the favored trait and the relative distribution of the trait will increase.
- Over many generations (i.e., hundreds or thousands), these small changes in traits accumulate and may eventually substantially modify the characteristics of the species.

This natural selection schema is potentially applicable to any organism and can be articulated by instantiating the appropriate slots (e.g., favored traits, and environmental pressure). The schema embodies both core conceptual knowledge and the relational argument structure that constitutes natural selection. Mastery of this explanation form across several domains would constitute strong evidence for transfer. Of course, a mere syntactic mapping is not all that is required; the use of this abstract schema requires substantial biological knowledge and development of the aforementioned factors that comprise evolutionary competency.

We sought to develop a curriculum that (a) specifically targets conceptual knowledge and reasoning/argumentation, and (b) engages students' prior knowledge in a domain of student interest. Chi and colleagues (Gobbo & Chi, 1986; Chi, Hutchinson, & Robbins, 1989) demonstrated that young children have substantial dinosaur knowledge and can employ this knowledge to make inferences about the organisms' diets, habitats, and locomotion. In addition, many middle school students have a basic mastery of the concepts required to learn natural selection (e.g., inheritance, biodiversity, variation, and prey/predation), but they lack an organizing schema for understanding evolution (Ash & Brown, 1996). It was hypothesized that knowledge of dinosaurs would represent a generative source domain in order to impart a robust understanding of evolution. Further, the study of dinosaurs exemplifies the historical/narrative dimension of evolutionary reasoning and the process of evidence gathering from the fossil record. In general, greater subject matter knowledge increases the likelihood of transfer since both entities (i.e., dinosaurs) and ecological processes (e.g., predator/prey relations) are familiar in this context. There is less need for negotiating new terminology and other unfamiliar surface features. This domain may also serve to foster epistemological commitments regarding the transitional state of knowledge, since new fossil finds and concomitant hypotheses are regularly brought to the public's attention.

Method

Participants

Two seventh grade classes from an urban, ethnically diverse, public school participated. The experimental and control classes included 21 and 27 students, respectively.

Procedure

Pretest: In the first of the study's three phases, each class was given a dinosaur knowledge test followed by two evolutionary knowledge tests. The dinosaur test consisted of 39 questions that evaluated students' abilities to identify dinosaurs from pictures, draw inferences about the dinosaurs' diets from both pictures and dinosaur names, match dinosaur names to descriptions of dinosaurs, order events on a timeline, and, respond to Likert items about dinosaurs. The evolution tests assessed students' understandings of related concepts. The two tests respectively consisted of seven Likert items, followed by eight short essay questions (/problems). The evolution tests assessed students' knowledge of heredity, variation, selection pressure, survival advantage, and mutation. The test questions involved a variety of animal contexts including birds, humans, and dinosaurs. There were three types of essay questions, involving natural selection, conditions of adaptational change, and common ancestry. An example of an essay problem addressing natural selection is "Apatosaurus was a dinosaur that had a long neck (longer than modern giraffes). The ancestors of all Apatosaurs had short necks (similar to necks of horses). Please explain how Apatosaurs came to have long necks." The conditions of adaptational change questions can best be answered by discussing functional adaptation and the time scale for such adaptations to appear. An example of this type of problem is: "If there were a sudden drought that killed off most edible plants, could a cow start to eat other animals instead of plants? Explain why or why not." The common ancestry questions addressed the salient similarity and differences among ancestral and contemporary species. The following problem is an example: Ostriches are large birds that cannot fly. The Rhea and the Emu are in the same family of birds – they are very closely related genetically. Interestingly, Ostriches are found in Africa, the Rhea live in South America, and the Emu live in Australia. How can you explain that these birds, which cannot fly, are found on different continents? "

Instruction: In the next phase of the study, the two classes participated in divergent eight-day evolution units. In the experimental class, hands-on activities, illustrations, and lectures were constructed to illustrate scientists' conceptions of dinosaur life. (Each lesson included at least one hands-on activity, an interactive discussion, and independent thinking assignments.) The curriculum addressed a range of topics: heredity, variation in the environment, mutation, extinction, and variation among individuals in a population. Explicit examples were provided to model how students could transfer evolution concepts to other animal species. This curriculum was created and taught by the teacher-researcher, a Masters

student who had prior experience teaching the students in this classroom (Lewis, 1999). This instructor used a constructivist pedagogy, largely modeled after Minstrell's instructional approach (van Zee & Minstrell, 1997). Minstrell is noted for introducing a new topic with a "benchmark lesson." He attempts to discover what students know about a topic, and tries to evaluate which of the different facets of the larger concept are understood or misunderstood.

The control class was taught by its regular teacher. He had over 25 years of teaching experience and taught in a traditional didactic manner while relying on the textbook. Students were responsible for taking accurate notes and answering the questions that appeared in the text. The control class drew on a range of organisms to illustrate the process of how life changes over time and evidence for these changes.

Posttest: The final phase of the study measured what students learned by again assessing dinosaur and evolution knowledge. The dinosaur test was essentially identical to the original test except for the order of questions. The evolution posttest used analogous (structurally isomorphic) and questions that were identical to those on the pretest. The evolution posttest was thus designed to assess the students' basic learning and their ability to transfer evolutionary knowledge to novel contexts.

Analyses: The Likert questions were initially scored on a seven point scale, based on the "correctness" of answers, and then scaled to fractions of a single point. The essay questions were scored and weighted for difficulty, according to a modified version of a rubric created by Kaufman, et al (1999). The coding criteria are similar to those used by Ferrari and Chi (1997) and Ohlsson (1990). For example, on the natural selection questions, explanations were coded for clear expressions (i.e., not merely jargon usage) of 1) variation, 2) selection pressure (environmental contingencies), 3) survival advantage (adaptive characteristics) and 4) heredity. A subset of the 16 questions was rescored by a second reader, resulting in an interrater reliability of 94%.

Results

The results indicate that both control and experimental classes exhibited various gains. A multivariate repeated measures analysis of variance was performed, with the three tests serving as the dependant variables and class as the independent variable. The analysis revealed a main effect for class ($F(1,46)=6.24, p<.05$) with the experimental class performing better than the control class. There was also a significant temporal effect, indicating that subjects performed better on the posttests ($F(1,46)=100.79, p<.001$). In addition, there was a significant time by class interaction ($F(1,46)=19.46, p<.001$) with the experimental class exhibiting a larger gain.

The overall results, presented in Table 1, reveal that both classes had considerable and comparable prior dinosaur knowledge, averaging 70% ($F(1,46)=1.19, n.s.$) on the

dinosaur pretest. The evolutionary knowledge pretest indicated even more similarity between the experimental and control classes, averaging 67% ($F(1,46)=.28, n.s.$) over the Likert questions and 23% ($F(1,46)=.002, n.s.$) over the essay questions. Both classes improved on the evolution posttests, averaging 77% of the Likert questions' points ($F(1,46)=37.26, p<.001$) and 39% of the essay questions' points ($F(1,46)=67.70, p<.001$)

Not surprisingly, the experimental class demonstrated a significantly greater increase on the dinosaur posttest than the control group ($F(1,46)=9.660, p<.005$). More importantly, the experimental class showed a greater gain on both the Likert ($F(1,46)=7.60; p<.01$) and the essay ($F(1,46)=6.43; p<.02$) evolution tests. In concert with the view of dinosaur knowledge as an anchor for learning, an exploratory regression analysis to determine the predictors of the evolution essay posttest showed the dinosaur pretest to be the best predictor, accounting for over 30% of the variance.

Further exploration (Table 2) of the three essay questions that most involved natural selection reveal very modest pretest performance; the mean score for the experimental class was 12% ($SD = 9\%$), while that for the control class was 16% ($SD = 10\%$). However, during the posttest, the mean for the experimental class grew to 35% ($SD = 16\%$), while the mean for the control class was 22% ($SD = 19\%$). Table 2 also illustrates the breakdown of these three essay responses into the four natural selection criteria. The results indicate that students generated responses that accounted for selection pressures 36% of the time, whereas students only discussed the role of heredity in natural selection 8% of the time. The experimental class demonstrated several notable gains regarding the criteria (particularly, mutation/variation, which grew from 11% to 54%), whereas the gains of the control class were generally more modest. Consider the following student responses, regarding why apatosaurs/giraffes had longer necks than their ancestors:

A7 Pretest

They need to reach the food at the top of trees and they evolved with longer and longer necks.

A7 Posttest

"There was a random mutation and one baby had a long neck some of its baby will have long neck too. Then soemthing in there environment or surrounds change i.e. Food is higher in the trees making it good to have a long neck because food is harder to get the ones with the short necks die leving only ones with long necks. They mate and then there are more long neck and this keeps happing."

A13 Pretest

I think that apatosaurs came to have longer necks by evolution. Over time, they got bigger and bigger.

A13 Posttest

RANDOM MUTATION! Giraffes may have had offspring that, purely by luck, had long necks. Maybe food on the floor of the forest was

diminishing and the long necked giraffes got food from high up. The short neck giraffes probably died of starvation. Then when only long necks were left, long necks had to reproduce. If longnecks mated they'd produce other long necks, until present day giraffes were known for their long necks.

The pretest responses often invoked the notion of "need" with no real sense of mechanisms. On the posttest, the subjects expressed more sophisticated understandings of

evolutionary concepts and at least rudimentary mastery of the appropriate form of a natural selection explanation. In spite of the differential learning successes exhibited by the experimental class, their explanations were still rather modest or inconsistent, as evidenced by their evolution posttest essays and their natural selection question responses. These results are consistent with other studies (e.g., Ohlsson, 1990; Bishop & Anderson, 1990) that documented persistent difficulties in students' (from middle school to college) reasoning about natural selection.

Table 1. Mean percentages and standard deviations (parentheses) for all tests and classes.

	Dinosaur Pretest	Dinosaur Posttest	Evolution Pretest Likert	Evolution Posttest Likert	Evolution Pretest Essay	Evolution Posttest Essay
Exp. n=21	73 (17)	85 (14)	68 (8)	84 (10)	23 (12)	45 (18)
Cont. n=27	68 (17)	70 (17)	66 (12)	72 (14)	23 (11)	35 (16)
<i>Total</i>	<i>70 (16)</i>	<i>76 (16)</i>	<i>67 (11)</i>	<i>77 (13)</i>	<i>23 (11)</i>	<i>39 (17)</i>

Table 2. Percentages of natural selection essay responses with respect to aspects of the coding criteria.

	Experimental		Control		Totals
	Pretest	Posttest	Pretest	Posttest	
M/V	11	54	20	15	25
SP	25	41	28	48	36
SA	6	27	12	20	16
HE	6	19	4	4	8
<i>Mean</i>	<i>12 (9)</i>	<i>35 (16)</i>	<i>16 (10)</i>	<i>22 (19)</i>	<i>21(12)</i>

Code: M/V: Mutation/Variation, SP: Selection Pressure, SA: Survival Advantage, HE: Heredity.

Table 3. Percentages of some non-Darwinian essay responses.

	Experimental		Control	
	Pretest	Posttest	Pretest	Posttest
Lamarckian	4	3	4	7
Teleological	10	7	10	18
Amechanistic	24	14	21	24
<i>Total</i>	<i>38</i>	<i>24</i>	<i>35</i>	<i>49</i>

Students often exhibit patterns of reasoning that are inconsistent with Darwinian explanations. When possible, non-Darwinian response patterns were classified as Lamarckian, Teleological, or Amechanistic (absence of mechanism), as shown in Table 3. Note that there were many responses that were not fully consonant with a Darwinian explanation, yet were not classifiable according to

this coding scheme. Lamarckian explanations implying the passing of acquired traits to progeny. For example, a student from the experimental class explained, "I think that maybe the cheetahs hunted animals that started to get fast and run away. The cheetahs had to adapt and run faster to catch their food. As their prey began to lead them on chases, their speed increased. Over time, their muscles probably just got bigger

and stronger (because they worked them so much). Now, cheetahs run very fast, and can catch gazelles and impalas and zebras and antelope." Teleological explanations suggest that need causes evolutionary change. A control class student envisioned changes in the eating habits of a cow if there were suddenly no grass to eat: "I think that they would just get so hungry they would start with insects and move their way up to fish." Another student, during the control class's posttest, explained that giraffe necks are so long "Because the giraffes had to stretch their necks to reach the trees for food." A mechanistic explanation indicates that evolution simply happens. In explaining why cheetahs became faster, one control class student stated "they had adapted to the prey getting faster. Through evolution." While some non-Darwinian explanations merely reflect an inability to express ideas maturely or the absence of specific biological knowledge, they may also indicate an inability to construct reasonable Darwinian arguments with their existing knowledge of evolution.

Table 3 also illustrates ways in which the two classes, while performing rather similarly on the pretest, differ when it comes to posttest response patterns. The experimental class's non-Darwinian responding went from 38% to 24%, while the control class's non-Darwinian responding moved in the opposite direction, from 35% to 49%. One of the central goals of the experimental curriculum was to foster effective Darwinian reasoning, and the results suggest modest success in that regard. Further, the results suggest that instruction may even foster more problematic patterns of reasoning.

Discussion

Recently, innovative curricula have targeted different facets of student difficulty regarding understanding evolution. The present study suggests that a conceptual change evolution curriculum anchored in the domain of dinosaur knowledge can promote the integration of core concepts and foster more effective Darwinian reasoning. Dinosaurs seem to be a good choice as an anchor for a contextualized curriculum. Dinosaur knowledge has been established to be relatively high among middle school students, and the results of this study suggest that having dinosaur knowledge may provide students with an advantage in learning about evolution.

Although the results of this curriculum are promising, the gains are still modest. Further research is needed to exclude the possibility that the differences between groups are not the result of extraneous factors. For example, the gains may be explained by the novelty of dinosaurs, the experimental teacher's enthusiasm, or the relative advantage of constructivist teaching methods over conventional didactic instruction. Nevertheless, this study suggests that employing an intrinsically motivating curricular source domain that engages a student's prior knowledge can facilitate the development of evolutionary competence. The dinosaur curriculum was designed to foster generative conceptual knowledge and coherent evolutionary reasoning. The other two pieces of the evolutionary competence puzzle,

epistemological commitments and discourse practices, were less central in the curriculum. These core features of evolutionary competence are clearly interdependent. For example, a student who appreciates the "correct form" of a natural selection explanation, but lacks a suitable descriptive vocabulary (i.e., one who can't "talk the talk") is unlikely to generate a coherent explanation. The standards of coherence for evolutionary explanations are particularly exacting, and coherence-building interventions are worthy pursuits in fostering critical thinking (Ranney & Schank, 1998).

Teleological reasoning was noted in many of the students' explanations. Teleological causation in explanations is hardly unique to evolution. It may underlie intuitive theories of biology in children as well as adults (Carey, 1995). Biological processes can be thought about in mechanistic or teleological terms. While it is advantageous for students to have a principled, mechanistic, understanding of scientific concepts, teleological or goal-oriented explanations are often presented in textbooks and lectures to orient students to the functions of a particular bodily mechanism. Teleological explanations are also commonplace in everyday discourse. Considerable research indicates that young children develop rudimentary theories in which biological functions are often expressed in intentionalist terms, such as striving to fulfill "wants" and "needs" (Hatano & Inagaki, 1996; Carey, 1995). This phenomenon is not unique to children. Medical students sometimes generate teleological explanations in reasoning about the function of the heart and circulatory system (Kaufman, Patel, & Magder, 1996).

Teleological thought is rooted in productive forms of knowledge and provide coherent explanations for nonintuitive phenomena that surrounds us. It is a challenge is to effectively exploit this knowledge in formal education in order to develop mechanistic understandings of biological processes. For example, teleological reasoning may promote an understanding of structure-function relations in young children; Ash and Brown (1996) developed a curriculum that fosters transitions from more rudimentary forms of teleological thought towards adaptationist reasoning that approximates mature natural selection explanations.

Our results suggest that some students began to demonstrate proficient Darwinian explanation patterns. However, most students continued to experience difficulties incorporating notions of variation and heredity into their responses—and subjects were somewhat inconsistent across problems. Anchoring in a given domain represents a starting point, but experience applying the schema in different domains is likely a prerequisite to mastery.

Learning about evolution in a familiar domain can certainly facilitate the development of disciplinary discourse, though more needs to be done to foster proficient "evolution speak". Tabak and Reiser (1999), using BGUILLE (the Biology Guided Inquiry Learning Environment) and working with middle school teachers, also try to advance productive discourse strategies in learning about natural selection, striving to scaffold students so that they can progress from lay explanations to increasingly sophisticated scientific explanations. The process involved establishing scientific norms, providing specific prompts (e.g., to elaborate incomplete explanations) and reshaping response patterns in

a manner that approximates scientific discourse. Fostering effective disciplinary discourse practices is essential in the development of evolutionary competence.

The concept of biological evolution represents a critical challenge for students to master, and given that it is a foundational concept in the biological sciences, it warrants special attention. A growing body of empirical work has systematically diagnosed a range of student difficulties pertaining to evolution, and researchers will certainly continue to develop ever more promising instructional strategies to support coherent evolutionary reasoning and argumentation.

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References

- Ash, D. & Brown, A. (1996). *Thematic Communities guide shifts in biological reasoning: children's transition towards deep principles of evolution*. Paper presented at the Annual Meeting of the Educational Research Association, New York, April 1996.
- Bassok, M. & Holyoak, K.J. (1993). Pragmatic knowledge and conceptual structure: Determinants of transfer between quantitative domains. In: D. K. Detterman and R. J. Sternberg (eds.), *Transfer on trial: Intelligence, cognition, and instruction..* Norwood, NJ: Ablex.
- Bishop, B. & C. Anderson (1990). Student Conceptions of Natural Selection and its role in Evolution. *Journal of Research in Science Teaching*, 27, 415-427.
- Carey, S. (1995). On the origin of causal understanding. In D. Sperber, D. Premack, & A. J. Premack (Eds.), *Causal cognition: A multidisciplinary debate*. (pp. 268-308). Oxford: Clarendon Press.
- Chi, M., Hutchinson, J., & Robin, A. (1989). How Inferences About Novel Domain-Related Concepts Can be Constrained by Structured Knowledge. *Merrill-Palmer Quarterly*, 35, 27-62.
- Detterman, D.K. (1993). The case for the prosecution: Transfer as an epiphenomenon. In D.K. Detterman and R.J. Sternberg (eds.), *Transfer on trial: Intelligence, cognition, and instruction*. Norwood, NJ: Ablex.
- Ferrari, M & Chi, M.T.H. (1998). The nature of naive explanations of natural selection. *International Journal of Science Education*, 20 1231-1256.
- Gobbo, C. & Chi, M. (1986). How knowledge is structured and used by expert and novice children. *Cognitive Development*, 1, 221-237.
- Hatano, G & Inagaki, K. (1996). Cognitive and cultural factors in the acquisition of intuitive biology. In D. R. Olson & Torrance, N. (eds.) *The Handbook of Education and Human Development: New models of learning, teaching, and schooling*. New York: Blackwell.
- Kaufman, D.R. Patel, V.L., & Magder, S (1996). The Explanatory Role of Spontaneously Generated Analogies in a Reasoning about Physiological Concepts. *International Journal of Science Education*, 18, 369-386.
- Kaufman, D.R., Ranney, M, Ohlsson, S. Reiser, B.J., & Shapiro, L. (1998). Symposium: Multidisciplinary Perspectives on Evolutionary Reasoning. Presented at the Twentieth Annual Meeting of the Cognitive Science Society. Madison, WC. August 1-4, 1998.
- Kaufman, D.R., Ranney, M, Thanukos, A., & Brem, S. (1999). How to Spin an Evolutionary Tale. Presented at the Twenty-First Annual Meeting of the Cognitive Science Society. Vancouver, B.C. August 19-22, 1999.
- Lewis, E. (1999). *Dinosaur Knowledge as a Fruitful Anchor for Learning Evolution Proto-Concepts*. Masters Thesis, Cognition and Development, Graduate School of Education. University of California, Berkeley. Berkeley, CA.
- Ohlsson, S. (1990). *Young Adults' Understanding of Evolutionary Explanations: Preliminary Observations*. (Office of Educational Research and Improvement Rep.). Pittsburgh: University of Pittsburgh, The Learning Research and Development Center.
- Ohlsson, S. (1993). Abstract schemas. *Educational Psychologist*, 28, 51-66.
- Ranney, M., & Schank, P. (1998). Toward an integration of the social and the scientific: Observing, modeling, and promoting the explanatory coherence of reasoning. In S. Read & L. Miller (Eds.), *Connectionist models of social reasoning and social behavior*. Mahwah, NJ: Lawrence Erlbaum
- Reiser, B. J., Sandoval, W. A., & Tabak, I. (1998). *Teachers' support of students' biological inquiry: Making use of artifacts of students' reasoning*. Paper presented at the Annual Meeting of the American Educational Research Association, San Diego, CA.
- Rudolph, J. & Stewart, J. (1998). Evolution and the Nature of Science: On the Historical Discord and Its Implications for Education. *Journal of Research in Science Teaching*, 35 (10), 1069-1089.
- Samarapungavan, A. & Wiers, R. (1997). Children's Thoughts on the Origin of Species: A Study of Explanatory Coherence. *Cognitive Science*, 21 (2), 147-177.
- Shankar, G., & Skoog, G. D. (1993). Emphasis given evolution and creationism by Texas high school biology teachers. *Science Education*, 77, 221-233.
- Sharman, L. C. (1994). Teaching evolution: Designing successful instruction. *Journal of Science Teacher Education*, 5, 122-129.
- Tabak, I. & Reiser, B.J. (1999). *Steering the course of dialogue in inquiry-based science classrooms*. Paper presented at the 1999 Annual Meeting of the American Educational Research Association. Montreal, Canada.
- van Zee, E. & Minstrell, J. (1997). Using Questioning to Guide Student Thinking. *The Journal of the Learning Sciences*, 6, 227-269.
- Working Group on Teaching Evolution, National Academy of Science (1998). *Teaching about evolution and the nature of science*. Washington, DC: National Academy Press.