Model-Based Instruction:

Fostering Change

in Evolutionary Conceptions and in Epistemic Practices

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In this chapter, we present ideas that might guide the development of instruction that promotes conceptual change in evolution. Specifically, we argue the following:

1. Conceptual change in the domain of evolution requires more than just changes in explanatory models of speciation and population change; it also requires changes in the epistemic practices used to generate and evaluate these models. In short, achieving conceptual change in the learning of evolution requires simultaneous changes in both theoretical concepts and epistemic practices. Therefore, effective instructional methods should foster both appropriate theoretical conceptions (i.e., a proper understanding of evolutionary models) and the appropriate epistemic practices used by scientists to evaluate their models.

2. Model-based inquiry instruction represents a very promising method for achieving these dual goals. We outline our model-based inquiry project, PRACCIS (*P*romoting *R*easoning *a*nd *C*onceptual *C*hange in *S*cience), an approach to model-based instruction that scaffolds growth in both content understanding and the epistemic practices of science.

3. We review research on evolution instruction and discuss several promising evolution curricula that employ model-based inquiry.

4. We argue for the adoption of new instructional methods to better promote the dual goals of understanding evolutionary models and understanding the epistemic practices of

science. Specifically, we recommend a much stronger focus on macroevolution (as opposed to microevolution), as well as a stronger focus on engaging students in reflection on their epistemic practices.

Components of Conceptual Change: Change in Conceptions and Change in Epistemic Practices

Thomas Kuhn (T. S. Kuhn, 1962, 1977) argued that the history of science reveals two distinguishable kinds of change in episodes of revolutionary scientific change (see Zammito, 2004). The first is change in the explanatory theory itself (e.g., the change from the geocentric Ptolemaic theory to the heliocentric Copernican theory, or the change from Newtonian physics to relativistic physics). This is the kind of change that conceptual change researchers have focused on—changes in the content of people's conceptions of the world.

The second kind of Kuhnian change occurs in the epistemic methods and standards used in scientific reasoning. For Kuhn, proponents of rival theories disagree not just about which is the correct theory, but also about the very standards and norms used in theory evaluation itself. For example, for one group of scientists, the crucial standard guiding theory choice might be to prefer theories that can explain disparate sets of data, and these scientists may give more weight to carefully controlled laboratory experiments. For a second group, the key standard might be a preference for detailed causal descriptions, and the preferred methods may be ecologically valid field studies. As one theory replaces another, Kuhn argued, it is not just claims about entities and processes that change. The very methods used to gather data and the practices used to evaluate theories change, as well, and often in very deep and fundamental ways. Other philosophers and historians of science have agreed that the history of science has seen major shifts in epistemic aims and practices (e.g., Laudan, 1977, 1984).

Although conceptual change researchers have extensively investigated fundamental changes in explanatory models as students learn science, they have paid much less attention to the possibility that science students learning a new theory may need to learn radically new epistemic practices, along with the new scientific theories. Just as the elements of a novice student's naïve theory might display stark conceptual divergence from those of the scientific theory under study, their naïve ways of reasoning about evidence and theories is also likely to differ substantially from that of scientists. Research on conceptual change has focused almost exclusively on evaluating and promoting change in students' theoretical conceptions, neglecting their use and understanding of the epistemic practices of science that go along with particular theoretical orientations.

Programs designed to promote conceptual change in science typically employ evidence to help motivate and guide the development of new conceptions (C). Program designers hope that as students encounter new evidence that supports new theories, the students will develop and accept the new theories. However, such procedures seem to assume implicitly that students value evidence in deciding what theories to accept, and that their evidence-evaluation strategies are relatively mature. If, however, students initially do not see fit with evidence as an important criterion in deciding what theory to accept, then instructional designers will not be able to design instruction that straightforwardly relies on evidence to promote theory change. Instead, designers will need to promote change in epistemic practices at the same time that they are promoting change in theories. That is, designers will need to design instruction that promotes an appreciation of using evidence to guide theory choices at the same time that they are trying to help students develop the new theories. For these reasons, Chinn and Samarapungavan (2009) argued that effective conceptual change programs should begin to analyze situations in which both theories and epistemic practices must undergo simultaneous change.

Psychological Evidence for Dual Processes of Conceptual Change during Evolution Learning: Changes in Conceptions and Changes in Epistemic Aims and Practices

The extensive literature on conceptual change has amply demonstrated that students' prior ideas can sharply diverge from the concepts of accepted theories, and these can be extremely resistant to change (Chinn & Brewer, 1993; Driver, Leach, Millar, & Scott, 1996). This is certainly so in the domain of evolution, where many students share many of the beliefs of creationists—that species have an essence, that species are significantly homogenous, that variation and selection are irrelevant to speciation and adaptation, and so on (e.g., Bishop & Anderson, 1990; Shtulman, 2006). Successfully learning evolutionary theory requires developing alternative conceptions—about variation within species, natural selection, and other concepts that are absent from or inconsistent with their prior understandings.

Besides changing their theoretical concepts through learning, we argue that science students learning evolutionary theory must also undergo changes in their epistemic practices. One source of empirical evidence for this claim is psychological and educational research focused on the development of reasoning about evidence during the school years. First, this literature suggests that students may have some difficulty even distinguishing theories from the evidence that might support or contradict them (e.g., D. Kuhn, 1989). Making this distinction consistently and accurately constitutes a crucial learning achievement, one that undoubtedly involves the development of new epistemic categories.

Second, a substantial subset of the students who *do* grasp the distinction between theories and evidence fail to align theories with evidence in normative ways. For example, they do not seek rigorous consistency with all the evidence (Reif & Larkin, 1991; Sandoval & Millwood, 2005), and they typically evaluate evidence in highly biased ways, ignoring evidence that contradicts their theories and distorting evidence to fit their favored account (Chinn & Brewer, 1993; Gilovich, 1991). Although scientists are also undeniably subject to a range of biases in the interpretation of evidence (Solomon, 2001), their training and the institutional norms of science (e.g., use of statistical methods; peer review) tend to engender a stiffer regard for evidence in comparison to science students. For example, expert scientists are more likely to attend to anomalies and to change their views in light of anomalous data (for detailed arguments, see xxx)(Donovan, Laudan, & Laudan, 1998; Galison, 1987; Haack, 2003).

For these reasons, we suggest that as students learn to engage in scientific inquiry, they experience significant changes in their appreciation of the epistemic practices involved in theory-evidence coordination. An important implication of this is that when engaging in inquiry-oriented instruction to promote conceptual change—an approach in which students use evidence to develop better theories—educators must take into account that students are undergoing major changes in their understanding of theory-evidence coordination at the same time that they are trying to grasp the components of new scientific theories. It would thus seem prudent for educators designing instruction to avoid presupposing that students will understand or evaluate evidence as scientists do.

In the domain of evolution, conceptual change requires very large shifts in epistemic practices alongside the challenging conceptual shifts needed to understand variation, populations, natural selection, and so on. Chinn and Buckland (in press) have argued that creationists and evolutionists differ strikingly not only in their theories about the origins and development of species but also in their epistemic practices. Our analyses of the epistemic practices of two groups of contemporary creationists—young earth creationists (YECs) and intelligent design creationists—revealed marked divergences with the practices of both pre-Darwinian creationists of the 1800s and contemporary evolutionary scientists (who differed less from each other). A list of the key differences in epistemic practices between YECs and scientists are summarized below (see also Chinn & Brewer, 2000). As we will argue after presenting this list, the differences we discuss exist in the actual—not ideal—practices of scientists and YECs; so our analysis aims to avoid an idealized view of the practices of either group. See Chinn and Buckland (in press) for extensive discussions.

- *Core aims of inquiry*. For evolutionary scientists, the preeminent aim of theorizing is to account for empirical data. For YECs, the most important epistemic aim is affirming the truth of the Bible and disseminating that truth to others.
- *Explanations*. Evolutionary scientists develop increasingly detailed explanations which both account for an accumulating body of empirical data and cohere with the larger corpus of scientific theory. YECs, in contrast, seek explanations compatible with scriptural texts, which they view as sources of truth, and they consider such sources as epistemically primary in all cases of conflict with well-established scientific theories.
- *Methodological naturalism*. Scientists seek natural rather than supernatural explanations. We believe that this commitment arises from a history of successful practice rather than from an *a priori* belief that science does not allow supernaturalism (Chinn & Buckland, in press); indeed, scientists in Darwin's era *did* regularly develop explanations with supernatural causes. YECs theories are deeply committed to supernatural causes and entities, and YECs reject claims of the historical success of scientific naturalism.
- *Methods*. Evolutionary scientists expose their theories to data through use of a wide variety of sophisticated and rigorously tested methods. YECs do not seek to test their theories of

creation against empirical data, but rather seek to undermine evolutionary explanations, and find ways in which evidence can be reinterpreted to accord with scriptural claims. YECs also reject historical, as opposed to experimental, methods, such as the inference of speciation from the historical distribution of fossils.

- *Empirical evidence*. Evolutionary theory explains many diverse lines of evidence, including paleontological, anatomical, bio-geographical, ecological, genetic and behavioral. In contrast, young-earth creationism is radically inconsistent with the large majority of this data, and prominent YECs routinely cite evidence long-since proven to be false.
- *Disinterestedness*. Although scientists regularly fall short of the ideal of an impartial evaluator of evidence, impartiality is nonetheless one of the central norms of the scientific community. The history of science (and of evolutionary science) shows that scientists regularly select their preferred theory on the basis of the evidence even when this choice runs against their personal interests, biases, and allegiances. In contrast, the YECs' *a priori* commitment to the truth of creationist theory, as expressed by a literal reading of Christian scripture and regardless of the empirical evidence, demonstrates a theoretical inflexibility which diverges sharply from the practice of scientists.
- *Human capacities*. Scientists view humans as capable of acquiring knowledge of the world, at least under the right kinds of circumstances. For YECs, "original sin" and "the fall of mankind" so undermine the reliability of human reason and knowledge-forming practices, that empirical inquiry cannot be considered as epistemically trustworthy.
- *Debate tactics*. During debates amongst scientists, evidence and theory is coordinated in an argumentative context with a robust but flexible set of inferential and discursive rules, disallowing, for example, the misleading use of evidence. In contrast, YECs who engage in

public debates routinely use biased debate tactics, using misrepresentation and obfuscation focused on the scoring of points with audiences that are ignorant of the details of theory and evidence.

Our analysis of the differences between scientists and YECs does not, we believe, rest on an unfair caricature of YECs or on an idealized view of scientists. In arguing that YECs adopt the stances we outline above, Chinn and Buckland (in press) cited extensively from writings of leading YECs. In arguing that scientists adopt, on the whole, the stances we describe above, we do not assume that scientists reason in an ideal way. On the contrary, we agree with those who identify widespread imperfections in the reasoning of scientists, such as biased interpretation of evidence and confirmation bias in seeking out evidence that supports (rather than contradicts) hypotheses. Nonetheless, despite these flaws, we contend that scientists as a community do uncover and treat seriously data that conflicts with established theory, a process which leads to substantial changes in scientific theories over time. As Haack (2003) has argued, despite all their biases in reasoning, scientists on the whole exhibit a regard for evidence that is significantly greater than those (including creationists) who do not utilize scientific practices. Further, institutionalized practices of scientists (e.g., peer review, use of statistics, study replication) are geared to make it more difficult for scientists to ignore unwanted data or to explain away data in nonnormative ways. To be sure, science is messy, contentious, and error-fraught. But, as Mayo (1996) has argued, science is organized around identifying and avoiding a great many sources of error, making the growth of knowledge possible in spite of the many imperfections of individual scientists and the many errors they have made. In the long run, scientists are sufficiently attuned to evidence—even if imperfectly—that their theoretical claims about the world accord reasonably well with a broad array of data, and thus merit acceptance. We thus argue that even though the epistemic practices of scientists are imperfect, they are markedly different from those of YECs.[1]

The epistemic practices of YECs that distinguish them from scientists may well be widely shared by students who espouse creationist ideas during evolution learning. For example, children of creationist families seem likely to share the core commitment of supporting the Bible as literal truth, rather than that of developing theories that fit the evidence—wherever the evidence should lead. They also seem likely to reject methodological naturalism and to distrust the products of human reason and inquiry wherever they yield conclusions contrary to articles of religious faith. Commitments such as these are likely to affect the types of explanations that students develop, their interpretations and evaluations of evidence, as well as the criteria they use to decide which explanations and evidence should be preferred.[2]

In short, conceptual change in the domain of evolution requires change not only in ontological conceptions of species, populations, variation and extinction, among other concepts; it also requires changes in students' epistemic practices related to scientific theory and evidence. Indeed, changes in theoretical conceptions would not in general be expected to occur without concomitant changes in epistemic practices. For example, a student who does not value empirical evidence as relevant to developing theories is unlikely to gain much from an evolutionary curriculum that provides ample evidence for theoretical claims.

Smith and Siegel (M. U. Smith & Siegel, 2004) have argued that on topics like evolution, which involve deeply held beliefs, one is ethically constrained to expect only that students understand the theory and come to appreciate its evidential and explanatory features, even if they do not personally endorse it as correct. This is a particularly complex and nuanced issue, one that cannot be adequately explored here. We do note, however, that an important learning outcome of evolutionary instruction is that students develop an appreciation of the reasons that scientists used in developing their theories and that they understand why scientists believe that the epistemic practices that they employ are reliable means of achieving valid theories.. Furthermore, we suggest that deep and comprehensive conceptual change is at the ideal a rational process, by which the theory best supported by the evidence and the practices most conducive to successful inquiry, come to be accepted and adopted, and not merely understood. Certainly, if students experience conceptual change in epistemic practices, they will be more likely to adopt theories based on evidence, and this would make acceptance of evolutionary theory, as well as understanding it, more likely.

Instructional Approaches to Promoting Both Kinds of Conceptual Change

If our argument to this point is correct, conceptual change in the domain of evolution (and many other science domains) requires instructional methods that promote simultaneous growth in both conceptual understanding of evolution and in epistemic practices. This means that educators cannot simply trust that exposing students to the compelling array of evidence in support of evolutionary theory will be sufficient to reveal to them the strength of the grounds in its favor. This is because many students' epistemic practices may not be organized around properly coordinating empirical evidence with theories, at least not in a way that allows the weight of the evidence to drive theory choice.

We argue that a particularly productive approach to promoting both kinds of conceptual change is model-based reasoning (Duschl & Grandy, 2008; National Research Council, 2007). This instructional approach is based on recent conceptualizations of scientific thinking by several philosophers of science (Giere, 1988, 1999);(Magnini, Nersessian, & Thagard, 1999). On this view, science involves the construction and modification of evidence-driven models, which serve to represent particular phenomena in specified respects. For example, evolution involves a variety of models of evolutionary change, such as species divergence as a result of genetic drift, speciation via geographical isolation and differential survival of sub-groups, sexual selection as an explanation of traits, selection-driven changes in distributions within idealized populations, game-theoretic models of changing behaviors, and so on. These models constitute an overlapping set of explanatory resources, and share many theoretical constructs and processes.

Curricula oriented around the promotion of model-based reasoning aim to achieve both content understanding as well as skill at constructing and revising models based on evidence. On the one hand, students' construction of a model (e.g., such as a model of photosynthesis) involves learning about the relevant scientific content (e.g., about the entities and processes involved in photosynthesis). On the other hand, students simultaneously learn about processes of constructing and evaluating models, the criteria used to decide between alternative models, and the ways in which models can be revised in light of evidence. Teachers therefore explicitly set both content goals and reasoning goals in a model-based unit. We argue that these features make model-based reasoning ideally suited for a topic such as evolution, which requires attention to both concepts and practices.

There are some instructional methods employing model-based methods that do not, in our sense, count as properly model-based reasoning curricula. For instance, several studies have investigated how students revise models of genetic inheritance based on evidence of the offspring of parents of specified phenotypes and genotypes (Hickey, Kindfield, Horwitz, & Christie, 2003; Johnson & Stewart, 2002). However, in these studies the instructional focus was principally on understanding of genetics rather than epistemic practices. In contrast, White and Frederiksen (White & Frederiksen, 1998) engaged students in modeling in the domain of physics and tracked both changes in reasoning and changes in students' physics understanding. Other model-based curricula of this sort have been developed by Krajick, Reiser, and colleagues (J. Krajcik, McNeill, & Reiser, 2008; Reiser, et al., 2001). The model-based methods that we advocate have as their goals both the development of epistemic practices and the development of conceptual understanding.

In collaboration with Ravit Duncan, Richard Duschl, and William Pluta, we have developed a model-based curriculum entitled PRACCIS (*P*romoting *R*easoning *a*nd *C*onceptual *C*hange in *Science*). To illustrate model-based methods, we describe our PRACCIS curriculum, but we emphasize that other model-based projects that use many of our methods are being implemented in the U.S. and other countries (Schwarz & White, 2005; Windschitl, Thompson, & Braaten, 2008).

The PRACCIS curriculum consists of units spanning an entire year for seventh-grade life science classes, covering many of the learning areas considered appropriate at this level. Our model-driven instructional methods center on the dialogic discourse and epistemic practices of coordinating explanatory modeling with evidence (Chinn & Malhotra, 2002; Duschl et al., 2007).

Across each of the learning units and throughout the course of the year, the focus of PRACCIS is on the development of students' abilities to construct and revise models, to coordinate models and model revisions with evidence, and to engage in effective written and oral argumentation in support of this coordination. All of our instructional activities directed at promoting modeling and argumentation skills are embedded within particular content topics that students learn as a regular part of their curriculum. Examples of such topics include cell organelles and membranes, photosynthesis, cellular respiration, mitosis, taxonomy, food webs, and invasive species. Within each of these domains, the goal is to promote understanding of the important theoretical ideas while providing the epistemic practices of science, including modeling, evaluative and critical reasoning, and collaborative argumentation, a central place in the learning environment.

The epistemic practices that have been the central focus of PRACCIS are (a) constructing models, (b) developing and revising models in response to evidence—especially multiple lines of evidence, (c) providing strong reasons for decisions involving model design, model preference and model revisions, (d) comparing and choosing among alternative models based on evidence and arguments and providing strong arguments for these choices, (e) thinking with and about multiple models, including making predictions with rival models and explaining a single set of data using different models, and (f) evaluating the quality and strength of evidence.

While the content goals of PRACCIS vary according to the topic of the unit, they are focused on the achievement of conceptual change through substantive engagement with students' prior misconceptions, and these goals co-exist with goals regarding epistemic practices. For example, the content goals in the photosynthesis unit include understanding the accepted theoretical model of photosynthesis, as well as the relevance of this model to a variety of situations. Goals of epistemic practice included developing familiarity with the presence of multiple incompatible explanatory models for a phenomenon, and the construction and use of public reasoning criteria for ranking models as better or worse.

Although we have not yet developed a model-based unit on evolution as part of the PRACCIS project, the curriculum does include units on topics that are traditionally regarded as requiring substantial conceptual change, including photosynthesis, cellular respiration, and diffusion. We have also developed units for other conceptually challenging topics including cell membrane transport, mitosis, molecular and Mendelian genetics, the human respiratory system, food webs, and ecology. The PRACCIS modules typically vary in length from 1 to 4 weeks – although we believe that longer, six- to eight-week modules may be ideal for promoting both inquiry and content goals, teachers are generally more willing to adopt shorter units. Our instructional approach is therefore intended to provide a modular tool kit for promoting scientific reasoning that does not require commitment to very long inquiry units. This tool kit includes materials about multiple topics, including models and associated evidence, useful representations for scaffolding students' scientific reasoning, a panoply of embedded formative assessments, and guidelines for developing additional materials.

Learning units are organized around a driving question (J. S. Krajcik & Blumenfeld, 2006). In some modules, the driving question is practical (e.g., How does lead get into cells? How can the photosynthetic rate of plants in a space station be increased?). In others, it is directly explanatory (e.g., Which is the best food web given a body of evidence? How is a particular disease spread?) Regardless of the question type, all units are centered on problems whose solution requires students to develop a good scientific model of a phenomenon and to actively engage in the kinds of epistemic practices distinctive of successful science.

All modules are designed to involve both hands-on activities and reasoning encounters with research reports that include tables and figures needing interpretation. Hapgood et al. (2004) refer to these as first-hand and second-hand investigations. One goal of module design was for student model-based reasoning to be grounded both in data that they had collected and in previously collected data reported by scientists in simplified research reports. Like real scientists, students work collaboratively to develop models that explain their own data, data reported by other students, and data previously reported by scientists. For some modules these hands-on activities involved extensive simulations (such as a simulations of catch, release and re-catch procedures for estimating fish population); in other modules, the hands-on activities involved real investigations (such as assessing how lung volume and aerobic fitness were related in data collected from all seventh graders in a school).

In sum, each unit is designed to engage students in activities that promote criteria-driven reasoning with models and evidence, encourage the collaborative assessment of models embodying popular misconceptions against those which express the normative concepts of the domain, and assess students' growth in the use of strategic practices of effective inquiry.

Instructional schemes. The instructional units of the PRACCIS program each center around what we call reasoning seminars—small-group and whole-class discussions in which students engage in collaborative argumentation using evidence to construct, revise, compare, and evaluate explanatory models. This format involves teacher- and peer-led discussions in which students engage in constructive argumentation, adducing reasons and evidence to support or oppose various alternative dialectical positions. Collaborative Reasoning also incorporates a very useful set of recommended teacher strategies to scaffold students' reasoning.

Scaffolds to support students' reasoning. The PRACCIS team has developed a variety of methods to effectively scaffold argumentation and model building and evaluation. One central scaffold was the use of *public criteria for good models and reasons.* In this approach each class develops their own publicly posted lists of criteria, one set for good models and another for good reasons and justifications. Students and the teacher then work throughout the year to refine and improve their criteria in light of argumentation about the usefulness of various reasoning practices. The criteria constitute an evolving public statement of class beliefs about good models and good reasons and are subject to further refinement during the course of the year. The criteria are also used by teachers for purposes of evaluating students' work. Figure 1 presents the criteria for "good models" developed by one class.

The emphasis on criteria represents one of the ways in which the PRACCIS curriculum explicitly and deliberately prioritizes epistemic practices for students. The criteria play a focal role for many of the other inquiry-oriented activities undertaken by students. Classes return to their criteria repeatedly throughout the year as they evaluate models and weigh reasons, improving them in light of new conceptions of practice, and this familiarizes students with shifts in science that are oriented around practice rather than around theory. The focus on reflecting on and applying criteria for constructing models and arguments cues students to the centrality of reasoning and evaluative practices in theory development, as well as on the development and application of norms of scientific practice. .

A second core scaffold we have employed is one called the model-evidence link scaffold (see Figure 2) (cf. Suthers et al., 2003). Using this scaffold, students (a) draw lines between evidence and models (indicating the particular kind of relationships the student identifies, including evidence that supports, strongly supports, contradicts and is irrelevant to one or more models) and (b) provide elaborated reasons for the kind of link they selected (see Figure 2). This scaffold is incorporated into instructional modules throughout the year and is intended to heighten students' focus on considering evidence when examining theories. By requiring students to distinguish between evidence that *strongly supports* a model, as opposed to only *supporting*, the model, the scaffold encourages students to reflect on the quality of evidence, as well. A focus on evidence and careful attention to the quality of evidence are central to the epistemic practices of science; thus, this scaffold is designed to promote the use of these practices during units in which students construct and evaluate models using evidence.

Promoting and Assessing Change in Scientific Conceptions and Epistemic Practices

Model-based instruction such as that developed by PRACCIS has the potential to promote change in epistemic practices as well as scientific conceptions. Change in students' scientific conceptions is promoted through a variety of class, group, and individual activities directed at improving models through reasoning about evidence. Students' models (and their day-to-day model modifications) provide teachers with formative-assessment data regarding their students' ongoing conceptions. When students' models diverge from scientific models (for example, when students incorporate soil as essential for the photosynthesis reaction), new evidence can be brought to bear to challenge these conceptions. Discussions can also directly address conceptual issues, such as how theoretical constructs like food and energy should be defined, as well as issues of fit with evidence.

At the same time, PRACCIS (as well as some other model-based instructional programs) also seeks to promote change in students' epistemic practices. The class criteria for model goodness serve as one critical marker of changes in epistemic practices, as criteria for evaluating models are an important feature of scientific practices (Newton-Smith, 1981). In individual and group activities, students regularly explain their reasoning, which affords teachers the opportunity to track growth in individual students' criteria. For instance, they may find that students' initial justifications for models are that the models are clear and easy to understand; later, students focus more on fit with evidence as a core criterion for evaluating models. Students' writing provides information about critical epistemic practices such as their aims (e.g., the extent to which they view the aim of science as explaining data) and the kinds of evidence they consider persuasive (e.g., whether students view only experimental evidence as relevant to scientific models). .

Instructional Approaches of Prior Research

In this section, we examine educational work on instructional methods to promote conceptual change in evolution. We specifically consider whether instructional approaches discussed in the literature address both kinds of conceptual change (in theoretical concepts and in epistemic practices) that we have argued are needed in this domain.

Given the importance of evolution as a core biological concept and the difficulties in promoting conceptual change in this domain, there is relatively little empirical research investigating methods for instruction. In addition, much of the extant research provides relatively little information about the instructional methods employed (e.g., Bishop & Anderson, 1990; Scharmann, 1994; Trowbridge & Wandersee, 1994). Although these papers often report pretest-posttest changes or differences between different instructional methods, they do not describe the instructional methods in enough detail for us to clearly determine the instructional methods (modeling or other) employed. As noted by Passmore and Stewart (2002) there is a need for richer descriptions of the actual instructional practices investigated in research projects so that researchers can begin to understand specific features that promote conceptual change in evolution.

We distinguish between three instructional approaches to engaging students in using scientific models in science classrooms. One approach (the model-application approach) explains models to students and engages students extensively in applying these models to explain new phenomena and make predictions in new situations. A second approach asks students to evaluate the comparative explanatory power of evolutionary and non-evolutionary (including creationist) models. A third approach (the model construction or revision approach, including PRACCIS) engages students in using evidence to construct or revise models. All three approaches have been used in evolution instruction documented in educational research.

Some evolution instruction projects explain key evolutionary models to students and then engage students in activities likely to help them understand how models apply to different situations (Jacobson & Archodidou, 2000; Nehm & Reilly). These approaches encourage students to think about how evolutionary models are related to examples of evolution or to evidence that supports evolution. Thus, opportunities are afforded for students to critically assess their understanding of evolutionary concepts in collaborative peer interaction, involving elaborative and reflective discursive activities that foster active involvement. We think that these approaches represent a promising route (Chinn & Samarapungavan, 2009) to promoting understanding of evolutionary models.

It seems to us that the model-application approaches are unlikely to promote changes in students' epistemic practices. Students whose epistemic practices diverge sharply from those of scientists may understand evolutionary theory better as a result of model application activities, but their experiences would provide them with little reason to reconsider their own epistemic practices. Because model-application methods do not engage students in inquiry practices of constructing, comparing, and evaluating models, there would appear to be little reason for students to reflect on or revise their epistemic standards for deciding what theories to adopt. Although whole-class and small-group discussions involving evidence may be emphasized, little attention is directed at the principles and grounds considered by learners to be persuasive in these discursive contexts.

The second set of model-based methods of teaching evolution does appear to have strong potential to engage students in reflection about epistemic practices. These methods usually employ a historical approach in which students compare and contrast the speciation theories of (for example) Darwin, Lamarck, and Paley (e.g.,. Jensen & Finley, 1996; Passmore & Stewart, 2002). Indeed, the Lamarckian inheritance of acquired traits (e.g., a lost tail or a stretched neck) is an alternative conception that many students spontaneously adopt. Similarly, Paley's argument from design corresponds to the creationist conceptions that many students also espouse. As students explore these historical cases, there is the potential for students and teachers to discuss not only the opposing theories and their fit with the evidence, but also the epistemic aims and practices employed by these historical figures. Although it is unclear the extent to which any of the existing instructional implementations in the literature engage students extensively in discussions about the epistemic commitments of creationists and scientists, such discussions could be a potent means to driving student thinking forward (a similar point is made by Nelson, this volume).

This historically-enriched approach could be extended by including examples of scientists (such as Lyell) who were creationists prior to Darwin's publication of *Origin of Species,* but who were eventually persuaded to adopt at least some evolutionary beliefs. In our previous analysis (Chinn & Buckland, in press), we discussed ways in which the epistemic practices of these scientists differed from those of contemporary evolutionary scientists in that they shared some of the epistemic commitments of modern creationists. These scientists did consider fit with Biblical tenets to be one criterion for theory choice. Yet their greater ultimate commitment to an open appraisal of the evidence and a commitment to adopt theories that best fit the evidence eventually led them to accept the Darwinian account. Inclusion of these historical figures could foster further discussion of circumstances in which standards and practices come into conflict, and epistemic practices change.

Other approaches to evolution instruction employ a model-construction-and-revision method (Alters & Nelson, 2002; Demastes, Good, & Peebles, 1995; Jensen & Finley, 1996; Passmore & Stewart, 2002). One important set of studies revolves around the use of BGuILE (Reiser, et al., 2001; Sandoval & Reiser, 2004; B. K. Smith & Reiser, 2005), a computer-based system for engaging students in constructing natural-selection explanations accounting for changes in the population of a species on a Galapagos island. The data support an explanation in which a drought affects the availability of seeds, such that finches with stronger beaks are more successful at eating the harder seeds that remain. The model-construction approach of BGuILE aims to promote growth both in the ability to construct natural selection explanations and in the epistemic abilities to coordinate explanations with evidence. Studies using this approach have investigated the quality of students' natural-selection explanations, the quality of students' ability to use evidence to develop and support explanations, and even, to some degree, students' understanding of the epistemic practices of science. The researchers have reported gains in many students ability to develop evolutionary explanations, though some students struggle with coordinating theories with evidence (Sandoval & Millwood, 2005; Sandoval & Morrison, 2003; B. K. Smith & Reiser, 2005).

Another excellent example of instruction employing model construction and revision is Passmore and Stewarts' (2002) nine-week evolution curriculum. Passmore and Stewart criticized prior research as overly dominated by a focus on evolutionary concepts; in contrast, their instruction provides multiple opportunities to use evidence to develop and revise evolutionary models. They emphasize the importance of students learning components of scientific practices, (as defined by Kitcher, (1993), including the language used, the statements made about nature that the scientist accepts, the questions counted as important, the methodological views specific to the research of the field of science, the canons of good observation and experiment, and the standards for assessing the reliability of others. In their curriculum, students revised a Darwinian model to accord with a rich, multi-case dataset. Students also constructed modified Darwinian explanations to account for phenomena that had never previously encountered, such as mimicry in butterflies and sexual selection in pheasants. Passmore and Stewart (2002) also provided a number of illustrations of students who were engaged in the curriculum demonstrating sophisticated reasoning using evolutionary models.

Future Directions in the Design of Learning Environments that Promote Conceptual Change in Evolution

The work by Reiser and his colleagues on BGuILE and by Passmore and Stewart provide outstanding exemplars that can be built upon in the continued design of learning environments that promote both theoretical and epistemic kinds of conceptual change in evolution. In this section, we consider two sets of issues raised by the use of model-based instruction to promote this change. The first set of issues addresses helping students develop an understanding of evolutionary models. The second addresses promoting conceptual change in epistemic practices.

Promoting Conceptual Change in Evolutionary Models

As discussed by Catley (2006), many of the current instructional efforts directed at conceptual change in evolutionary models focuses on microevolution—that is, the changes in the distribution of traits within a species, not involving species change. In contrast, we agree with Catley that instruction should include a strong focus on macroevolution—the evolutionary changes leading to the formation of new species. Many current curricula neglect the difficulties involved with the understanding and possible acceptance of macroevolution. Indeed, many creationists accept microevolution but not macroevolution (Chinn & Buckland, in press). Hence, several key beliefs at issue in evolutionary theory are not addressed by curricula that focus on microevolution. Macroevolution poses difficulties for understanding as well as accepting evolutionary theory. A student who understands how natural selection can produce longer finch beaks may yet be baffled about how such processes could possibly produce new species. Similarly, without the opportunities to work with a rich and extensive body of evidence that supports macroevolution, students will fail to understand why evolutionary theory offers an explanation that powerfully unifies disparate bodies of data. Without understanding these data and the evolutionary models of speciation, students will fail to understand central components of evolutionary theory, and they will similarly fail to understand how the application of the epistemic criteria of science would lead scientists to accept macroevolution.

An important issue regarding evolution instruction is whether it should explicitly allow students to contrast creationist models with scientific models. As we have noted, one type of instructional intervention encourages such contrasts (often in the context of considering historical theories of the 1700s and 1800s) (e.g., Jensen & Finley, 1996; Passmore & Stewart, 2002). This allows students to consider the explanatory power of creationist theories in comparison with alternative evolutionary theories. However, others have argued that students should not be encouraged to contrast creationist models of speciation with scientific models, because this encourages the idea that religion and science are in competition with each other (e.g., M. U. Smith, Siegel, & McInerney, 1995). Instead, according to this view, religion should be viewed as compatible with evolutionary theory, as evidenced by those religious people who accept evolution and those evolutionists who are religious. On this view, science provides natural (i.e. non-supernatural) explanations of the physical world, and addresses a set of matters different from those addressed by religion. On this view, only atheists and religious fundamentalists find religious and evolutionary views to be in conflict (see statement by Kevin Padian in Jones, 2009).

We agree that many people find evolutionary theory and religious belief to be compatible. But we suggest that it is simply wrong to say that religious beliefs in the US (for example) are typically compatible with evolution. The many fundamentalist YECs in the US hold beliefs about the physical and biological worlds that are radically at odds with the beliefs of evolutionary scientists. Even further, we hypothesize that many non-fundamentalist Christians who view their religious beliefs as compatible with evolution believe that God intervenes in the world, actively shaping events, including the direction of speciation and the resulting biological forms of organisms. For example, such a Christian may believe the emergence of humans was intended or willed by God, who shaped evolution so that humans would be guaranteed to emerge in their current form. Any such belief is simply incompatible with an understanding of the randomness of evolutionary processes and can be maintained only by misconstruing evolution as a directed, teleological process.

These misunderstandings about evolutionary theory highlight the importance of helping students understand the random and contingent aspects of evolutionary theory. Accordingly, it would seem valuable for students to contrast teleological models of speciation with non-teleological models. This could be done by asking students to contrast the accepted evolutionary model with teleological models in which evolution is viewed as moving in a particular direction, such as toward inevitable greater complexity or toward the inevitable emergence of humans. These could be evaluate against a body of data that supports randomness and contingency in evolutionary processes.

There is as yet very little research on the effects of different options for organizing modeling curricula, or on instruction involving teleological versus Darwinian evolutionary models. We hope that contrasting different model-based approaches will become a focus of future research on teaching evolutionary theory.

Promoting Conceptual Change in Epistemic Practices

We think that another area in which model-based instruction on evolution can be improved is through greater attention to the epistemic features of scientific practice. To be sure, model-based approaches to evolution instruction have sought to enculturate students into the epistemic practices of constructing explanations that fit the available evidence (Jensen & Finley, 1996). A smaller number of projects (Stewart & Rudolph, 2001) have also encouraged students to use accepted scientific criteria such as developing explanations with internal consistency and explanations that are compatible with explanations in other areas of science (such as the consistency of evolutionary theory with geological theories of the age of the earth). These approaches engage students in the use of some of the epistemic practices of science.

However, it seems to us that researchers have not explicitly considered that many students may enter instruction with commitments to epistemic practices that are starkly at odds with the epistemic practices of scientists. As we argued earlier, students who espouse creationist views seem likely to also evince epistemic practices that diverge sharply from those of scientists. The challenges of achieving both understanding and belief that make it difficult to learn the concepts and principles of evolutionary theory have parallels in learning the epistemic practices of science. Just as some students have difficulty understanding evolutionary concepts, they may have also difficulty understanding the epistemic practices of science. Thus, students may fail to understand why scientists value theories that explain a broad scope of evidence, or why one would even want to adopt the goal of developing explanations that account for evidence, rather than which conform with prior beliefs. Further, just as students may understand evolutionary theory without believing it, they may gain some understanding of the epistemic practices of science without believing that they are reliable means of attaining knowledge. Students using teacher-sanctioned epistemic practices for developing evolutionary explanations may consider these practices to be faulty, and they may use them only within the confines of the science class, without genuinely internalizing and adopting them.

There is thus a need for research that investigates different approaches to achieving understanding and appreciation of the epistemic practices of evolutionary science among students whose epistemic practices are at odds with those of science. There is little research on how instruction can deal with the dual difficulties of understanding the epistemic practices of science and coming to recognize these practices as creditable means to achieving knowledge—especially among students whose creationist epistemic practices differ so starkly from those of scientists.

One possible instructional approach may be to encourage more explicit reflection on and, perhaps, debate about epistemic practices. Instructional research in this area might encourage students to explicitly discuss what the aims of a theory of speciation should be, and what kinds of evidence and arguments are legitimate. The PRACCIS technique of having individuals, groups, and classes explicitly discuss criteria for model goodness could provide a forum for such discussions, as students discuss, for example, whether acceptance of models should depend on consideration of their consequences (such as a fear that widespread belief in evolutionary theory would lead people to behave selfishly or immorally) or only on the evidence that might support or undermine them. Such discussions may lead students to reflect on the epistemic practices of science as well as on the theories that these epistemic practices support.

Conclusions

In this chapter, we have argued that conceptual change in the domain of evolution involves changes in both theoretical models of evolution and in epistemic practices used to generate and evaluate these models. We have also argued that model-based instructional methods provide one general means of promoting growth in both theoretical understanding of science and in the epistemic practices of science, and we have outlined our own model-based approach (PRACCIS) to promoting both conceptual understanding and epistemic growth. As we have argued, we believe that PRACCIS and other similar model-based reasoning curricula provide the instructional resources needed to promote conceptual change in both conceptual understanding and epistemic practices. We have also reviewed promising instructional interventions that engage students in the construction, revision, and application of models. Finally, we have argued that there is a pressing need for several new lines of research in these areas, including research that contrasts alternative instructional techniques.

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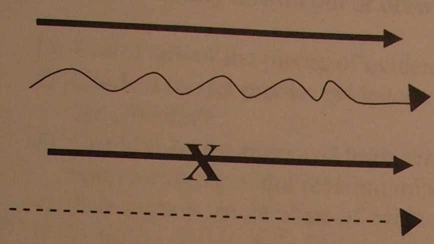
List of Figures

Class Criteria

Clearly answers the question
Provides visual aides (pictures) + words (suggested)
Easy to read and understand + organized
Gives most information possible (all you have) – correct info
No unnecessary words – keep it simple
Supported by/based on evidence – shows data – background, research
Steps/stages in order (if appropriate)
Explains why or how – answers questions
There's an example of how it works (if appropriate)
Audience = classmates
None of the evidence contradicts the final model
Realistic, makes sense
Make sure evidence is correct



The evidence **supports** (or could support) the model.

The evidence **STRONGLY supports** the model.

The evidence **contradicts** the model (shows it is wrong).

The evidence has **nothing to do with** the model.

Please draw arrows from each of the 4 pieces of evidence below to Models A and B. Each piece of evidence should have 2 arrows (one for Model A and one for Model B). When drawing the arrows, point them to the part of the model they support or contradict.

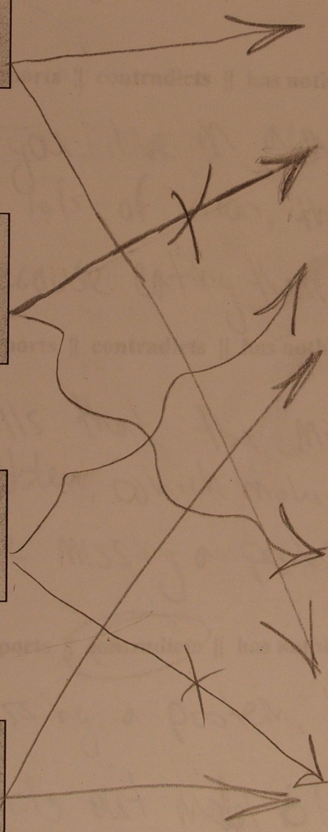
Evidence

(1) Usually more than one family member has HC.

(2) HC is more common in countries in which people eat a lot of red meat, beans, and spinach.

(3) People with HC are missing an important protein in their liver

(4) Often people with HC get better if they take special pills that do not allow iron to be absorbed.



Model A- Genetic disorder

Hemochromatosis is caused by a mutated gene. The affected individual inherits the bad gene from his/her parents.

People with the mutated gene cannot regulate the amount of iron they absorb from food.

They absorb too much iron from food and the excess iron accumulates in their liver.

Model B- Dietary disorder

Hemochromatosis is caused due to bad diet.

The affected individual eats foods that have a lot of iron in them- such as red meat.

Because these people are eating too much iron their body cannot remove it from their blood fast enough. The excess iron accumulates in their liver

[1] In Chinn and Buckland (in press), we also compared and contrasted proponents of intelligent design (which we call Intelligent Design Creationists, abbreviated as IDCs) with YECs and with evolutionary scientists. We note some significant differences between IDCs and YECs. For example, IDCs state that accounting for empirical evidence is one of their goals, and IDCs (unlike YECs) do not reject historical (as opposed to experimental) methods of science. However, writings of leading IDCs provide strong evidence that their preeminent goal is to promote a theistic worldview rather than follow where the evidence leads. Like YECs, IDCs ignore the vast array of evidence that evolutionists take to support evolutionary theory, and they do not gather data and conduct tests of their own. Rather, their main method is to demand that evolutionary scientists explain the evolutionary history of the complex biological structures (such as the flagellum) for which IDC's cannot generate an evolutionary account. When evolutionary scientists do produce such explanations, IDC's generally either ignore them or shift their demands to a new complex structure. Chinn and Buckland note other similarities, as well.

[2] There are some who argue that there are no significant epistemic differences between evolutionary scientists and creationists; each side is equally biased and ideological. Creationists make this argument, and so do some sociologists of science (see Chinn & Buckland, in press, for details). Some educators sometimes write as if different groups have different scientific world views and epistemic practices which cannot be viewed as better or worse than each other (e.g., Brayboy & Castagno, 2008); this might be taken to imply that creationism, too, is a world view no less reputable than evolutionary theory.

We believe that science educators should reject any such epistemic equivalences. Evolutionary theorists and YECs make starkly incompatible claims about the physical and biological world. For example, evolutionary scientists hold that the earth is billions of years old and that species evolve, at least in part through natural selection. In direct opposition, YECs hold that the earth is several thousand years old and that species did not evolve but were created directly by divine intervention. If one believes that the epistemic practices of YECs are in no way inferior to those of evolutionary scientists, then it seems to us that there is no reason to accept that the earth is old rather than young. On the contrary, it is reasonable to accept that the earth is old because it is reasonable to accept the evidence accumulated by scientists as well as the processes scientists have used as a community to explain this body of evidence.