# Next steps in evolution education: A literature review and suggestions for the future

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## Abstract

Biological evolution is unlike other topics in science. For many students, it is emotionally-charged and conceptually difficult, and yet it is vital to making sense of biology. Considerable research has addressed the unique challenges of teaching evolution, but it has left many questions unanswered. In this thesis, I will provide an overview of the literature on strategies for teaching evolution with an emphasis on those for which there is empirical support. Conclusions that may be drawn from this literature and limitations of the studies will be discussed. Based on the findings, I will argue that the best approach to evolution education is one that combines diverse strategies, focuses on essentials, and begins early, with regular reinforcement of key concepts throughout the K-12 curriculum. Suggestions for implementing such an approach are also discussed.



## Résumé

L'évolution biologique est différent des autres sujets de sciences. Pour de nombreux étudiants, il est émotionnellement chargé et conceptuellement difficile, et pourtant il est essentiel pour comprendre la biologie. Beaucoup de recherches ont abordé les défis uniques de l'enseignement d'évolution, mais il a laissé de nombreuses questions sans réponse. Dans cette thèse, je vais donner un aperçu de la littérature sur les stratégies d'enseignement de l'évolution en mettant l'accent sur ceux pour lesquels il y a de soutien empirique. Conclusions qui peuvent être tirées de cette littérature et les limites de ces études seront discutés. Sur la base des résultats, je ferai valoir que la meilleure approche à l'enseignement d'évolution est une synthèse de diverses stratégies qui se concentre sur l'essentiel et commence tôt dans la curriculum de K-12, avec renforcement régulier des concepts clés. Suggestions pour la mise en œuvre d'une telle approche sont également discutés.

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## Introduction

Biological evolution is unique among topics in science. Unlike other subjects, it tends to be divisive and emotionally charged. Perhaps because evolution conflicts with some cherished religious beliefs, many people deny that it even occurs. Despite a longstanding consensus among scientists that evolution does occur, controversy in the public domain persists (Wiles, 2010). Polls in the U.S. suggest rates of acceptance as low as 35%, while rates for Canadians are considerably higher, but still quite low, at 61% (Angus Reid, 2010).

Evolution is also a conceptually difficult topic for many people. Numerous misconceptions about evolution have been identified in both students and teachers and these prove to be exceptionally resistant to change (Nelson & Alters, 2002; Nehm & Schonfeld, 2007; Anderson, 2007).

To address the unique challenges of evolution education, a robust body of relevant literature has been generated, particularly over the past decade. I have reviewed this literature with the aim of identifying the best supported strategies for improving acceptance and understanding of evolution. Key research questions include the following: 1) which strategies are the most effective for improving acceptance and understanding of evolution? 2) what weaknesses or limitations exist in our current approach to teaching evolution? 3) how might extant literature be applied to improve our current approach to evolution education? The review included literature from diverse fields, including evolution education, educational theory, cognitive science, persuasion, and aesthetics, in order to generate a broader perspective on our current approach to teaching evolution.

Smith (2010) provided an excellent review of the literature in evolution education. Rather than simply describing the same studies, I will focus on the conclusions that can be drawn from this research and from research in other fields. I will use the data to highlight weaknesses in our current approach to evolution education and argue for a new approach--one that starts earlier in life, pays greater attention to non-cognitive factors, like attitude toward science and social influences, and emphasizes content quality over quantity. Finally, I will argue that the successful implementation of this approach requires greater curriculum guidance and pedagogical support for teachers.

*The Importance of an Early Start*

Starting early is important because there are competing cultural forces that may interfere with future learning. Even very young children may be exposed to anti-evolutionary thinking through family members, distorted representation in the media, or even through creationist museums and amusement parks. The prevalence and persistence of anti-evolutionary thinking in North American society provides ample opportunity for children to acquire and integrate misconceptions throughout their development.

It shouldn't be surprising then that students beginning college-level courses generally have numerous, varied misconceptions about evolution that are exceptionally resistant to change (Nelson & Alters, 2002). While some recent strategies have aimed to promote conceptual change by addressing students' initial conceptions, their success has been limited. For many students, evolution education at the high school or college level may simply come too late. This literature review will reveal the importance of early start. I will discuss selected studies that illustrate how evolutionary misconceptions develop early in life and may interfere with further learning.

*Addressing both cognitive and non-cognitive factors*

Strategies aiming to improve students' learning of evolution have largely focused on cognitive factors. These are certainly important and will be discussed, but they are not the only important factors. When it comes to controversial topics, like evolution, affective influences on learning may be especially important. The success of advertising attests to the power of associative learning and sensory and affective appeal in shaping attitude and opinion. Though persuasive strategies are typically used to promote products, there are few worthier applications than the promotion of a unifying and fundamental concept in science. In the case of evolution, an attractive presentation serves the best interests of the science consumer. I will suggest ways in which principles of persuasion may be applied to the teaching of evolution.

*Content: quality over quantity.*

Finally, I will discuss a growing body of literature that indicates that students learn more when they are taught less. Learning is deeper and more durable both when content is reduced and when students take a more active role in their own learning. Dense content overwhelms students' information-processing capabilities and leads to confusion. Extensive topical coverage must generally be achieved through lecture-style teaching and is necessarily superficial. Most active learning pedogogies, as well as many non-cognitive strategies, take more time per concept than traditional lecture-style methods. Thus, content reduction is essential because it directly improves learning and allows for the implementation of superior pedagogies.

There is now sufficient evidence, gathered from numerous studies approaching the problem from diverse directions, to develop a more effective approach to teaching evolution. This approach will incorporate active learning methods, focus on essential concepts, and consider cognitive, sensory, and affective aspects of learning. Given the unique cultural and cognitive barriers to understanding evolution, foundation building must start at the earliest age possible, with reinforcement of essential concepts throughout K-12 education.

## The Importance of an Early Start

Evolution is typically not addressed in science curricula until high school. There are some exceptions to this rule. Notably, the province of Quebec prescribes treatment of evolution at elementary school levels. While this effort is laudable, elementary school teachers may be ill-prepared for the task and unsure as to whether or how they will approach the topic (Asghar, Wiles & Alters, 2007). It is crucial that evolution not only be taught early, but taught well, through age-appropriate lessons and effective methods.

Early introduction of evolutionary concepts is essential for a number of reasons. First, evolution is key to understanding biology. It provides a framework that unifies much of scientific knowledge. Second, misconceptions about evolution may be acquired or developed by children at a very young age. The prevalence of such misconceptions makes repeated exposures and reinforcement of these ideas very likely. These misconceptions interfere with future learning about evolution. Finally, as this literature review will show, evolutionary misconceptions are extraordinarily difficult to unlearn. When it comes to misconceptions about evolution, an ounce of prevention may be worth a pound of cure.

*Evolution is key to understanding biology.*

The American Association for the Advancement of Science provides a nice description of evolution’s uniquely important role: "The modern concept of evolution provides a unifying principle for understanding the history of life on earth, relationships among all living things, and the dependence of life on the physical environment. While it is still far from clear how evolution works in every detail, the concept is so well established that it provides a framework for organizing most of the biological knowledge into a coherent picture." (AAAS, 1990, p.64). The U.S. National Academy of Sciences similarly acknowledges this vital role: “The theory of evolution has become the central unifying concept of biology and is a critical component of many related scientific disciplines." (1999, p. 1-2).

Despite its central importance to understanding science, evolution is widely neglected at all levels of science curricula, especially at elementary levels (Asghar, Wiles, & Alters, 2007; Lerner, 2000; Alters & Alters, 2001; Gross, Goodenough, Haack, Lerner, Schwartz & Schwartz, 2005). Since an understanding of evolution is vital to understanding biology and much of science, it ought to be taught as early as possible in science curricula and reinforced throughout.

Much of the research on evolution education to date has focused on teaching at high school and college levels. However, I argue that the prevalence of misconceptions about fundamental and unifying scientific concepts at high school and college levels is not a reflection of a need for improved pedagogy at these levels, but an indication of the failure of our science curriculum at the elementary stage. We shouldn't need research in evolution education to tell us that we should be teaching fundamental concepts early. Young students need these concepts in order to make sense of science and the world around them.

*Competing views are introduced early*

Children may be exposed to a wide variety of alternative views of evolution. Fundamentalist religious beliefs, which children may encounter even before they begin school, are known to interfere with acceptance of evolution. Polls in the US have for a number of decades consistently indicated about 40%-45% agreement with the statement "God created human beings pretty much in their present form within the last 10,000 years or so." (National Science Board, 2002).

Biblical literalism is problematic for evolution education and its proponents target young children with diverse, age-appropriate methods. There is an abundance of online resources that provide creationist books, learning activities, songs and coloring books designed for children. Creationist museums and theme parks are also popular, and not just in the US. A Canadian website lists five such museums in three different provinces (http://www.creationinfo.com). These attractions are marketed to families. The creationist movement capitalizes on the fact that children are particularly impressionable and presents its ideas early--ideas that often go unchallenged until high school or later.

Non-religious misconceptions about evolution are also common. Lamarckian ideas, for example, the idea that acquired traits can be inherited, are especially prevalent (Jensen & Finley, 1995, 1996, 1997; Jimenez-Aleixandre, 1992). Also common are teleological misconceptions, in which evolution is viewed as progressing toward a particular goal or serving a need or purpose. Such misconceptions may develop from biases and assumptions that have their roots in early childhood (Bloom & Skolnick Weisberg, 2007). Several researchers (Kelemen, 1999; Kelemen & DiYanni, 2005) observed that children are naturally predisposed to view the world in terms of design and purpose, a tendency he called “promiscuous teleology”. He observed that 4-year-old children tend to perceive everything as having a purpose. Lions are “to go in the zoo”, for example, and clouds are “for raining” (Kelemen, 1999). Evans (2001) similarly observed that children tend to provide and prefer creationist accounts of human and animal origins. These studies suggest that evolutionary misconceptions may grow out of innate biases, but regardless of whether the misconceptions are innate or acquired, it is clear that they are prevalent even in young children. The longer such assumptions go unchallenged, the more difficult they may become to unlearn.

*Evolutionary misconceptions are difficult to change.*

Students beginning college-level courses generally have numerous, varied misconceptions that prove to be exceptionally resistant to change (Alters & Nelson, 2002; Nehm & Schonfeld, 2007; Nelson 2007). Bishop and Anderson (1990) found that more than half of college students they studied held naive conceptions about evolution. For example, many believed that organisms develop new traits because they are needed for survival. Misconceptions about evolution are also widely held by students who have had extensive training in biology and by aspiring biology teachers (Nehm & Schonfeld, 2007). The prospective biology teachers tended to view mutations as harmful and unable to give rise to new traits, and understood the appearance of new traits to be based on need (Nehm & Schonfeld, 2007). The belief that humans and dinosaurs coexisted was also common in this study group.

Studies show that evolutionary misconceptions are difficult to change even with course materials designed explicitly for this purpose (Jensen & Finley, 1995, 1996, 1997; Demastes, Good, Sundberg, & Dini, 1992; Nehm & Schonfeld, 2007). Jensen & Finley experimented with historically rich content, paired-problem solving, and conceptual change strategies (1995, 1996, 1997). Despite some improvement, they found that students still held a wide range of misconceptions after the instruction (1995, 1996, 1997). Our best supported strategies for dealing with evolutionary misconceptions generally yield unsatisfactory results. These strategies are discussed in greater detail in the next sections on conceptual change and active learning methods.

The importance of a solid understanding of evolution, the young age at which anti-evolutionary views develop and the difficulty associated with correcting misconceptions underscore the importance of early evolution education. Since we cannot easily undo misconceptions that hinder science learning, it is critical that these misconceptions not go unchallenged for long spans during childrens' cognitive development. Key concepts, like common ancestry, must be introduced when children are forming their conceptions about the origins of life and the relationships among living things. If we wait until high school or college levels, instilling students with a satisfactory understanding of such concepts becomes exceedingly difficult. For many students, it may simply be too late.

## An Overview of the Literature on Evolution Education

This section will provide an overview of the literature on evolution education. The aim is not to be exhaustive, but to illustrate the strengths and limitations of the research and the need for better designed studies and strategies. I will also use this data to illustrate deficiencies in our current approach to evolution education. The first part will discuss the factors that influence students' learning of evolution with subsequent parts addressing a range of strategies that target these factors. To date, most research has focused on strategies that target cognitive and pedagogical factors and this is reflected here.

### Factors that Influence Learning of Evolution

Research reveals a complexity of factors that influence students' learning and acceptance of evolution. Nehm and Schonfeld (2007) grouped these influences into 5 categories: cognitive, affective, epistemological, religious, and pedagogical. There is significant overlap among factors in these categories. For example, epistemological position may be related to religiosity - a philosophical materialist will be less inclined to embrace religion. Pedagogy may also differentially influence other factors. An inquiry-based task, for example, may engage cognitive elements preferentially, while a role-play exercise may hold greater affective appeal.

There is also an important interplay between cognitive and non-cognitive factors. Attitude toward evolution (ie., acceptance or rejection of the theory) may be shaped by a host of non-cognitive factors, including a student's religious upbringing, disposition, and social pressures. Attitude may influence students' openness to learning about evolution and the amount of effort that students put into a course, thus affecting their understanding. Conversely, improved understanding may foster an appreciation for the explanatory power of evolution, thus promoting acceptance. Since both understanding and acceptance of evolution are desired, addressing both cognitive and non-cognitive factors is essential.

Because of the interrelated nature of these factors, most strategies for teaching evolution affect more than one factor; however, strategies to date have focused primarily on cognitive and pedagogical factors. Conceptual change strategies, for example, highlight reasoning and logic and aim to cause students to become dissatisfied with naive conceptions of evolution by exposing their explanatory limitations. Strategies that address pedagogical factors include active learning methods, like paired-problem solving and inquiry-based tasks.

Religious factors can certainly be an important influence on students' learning of evolution. The conflict between religious fundamentalism (ie, biblical literalism) and evolution is obvious. However, few teaching strategies directly address such factors because religious discussion in classrooms is deemed inappropriate, at least at pre-college levels. Directly addressing creationism has been tried at college levels with some success. These studies will be discussed.

Since this literature review focuses on strategies for improving students' learning of evolution, and most of these strategies focus on cognitive and pedagogical factors, I discuss strategies that target three main groups of factors: cognitive, pedagogical, and non-cognitive. Here, I consider cognitive factors to be those that relate mainly to the intellect and reason, and non-cognitive factors to be pretty much everything else. Pedagogical factors are those that relate primarily to instructional methods. Of course, pedagogy may engage both cognitive and non-cognitive factors. An inquiry-based task, for example, may promote students' learning of evolution by engaging the intellect or by creating a positive learning experience that translates to improved attitude toward the topic and greater study time. Many studies also combine a number of strategies in their intervention, which makes it more difficult still to categorize studies for comparison and to tease apart the effects of individual strategies. I have grouped strategies simply to facilitate comparison and discussion; the groups certainly are not mutually exclusive.

## Strategies that Address Cognitive Factors

Many of the best researched strategies for teaching evolution have focused on cognitive factors. These have largely been based on the Conceptual Change Model (CCM) developed by Posner and his colleagues (Posner, Strike, Hewson, & Gertzog, 1982). This section will provide an overview of the CCM and discuss the findings of studies that have investigated conceptual change strategies. Limitations of the CCM and the need for other approaches will also be discussed.

### The Conceptual Change Model

The CCM is based on an earlier "constructivist" view of learning, which was shaped by contributions from a number of prominent educational theorists, including John Dewey (1910) and Piaget (1964). Constructivism recognizes the role of subjectivity in learning, with new learning building on, or reconstructing, knowledge derived from previous experience. As Dewey described, "every experience both takes up something from those which have gone before and modifies in some way the quality of those which come after" (1963, p. 35).

Building on the constructivist view, Posner and colleagues (1982) described learning as a rational activity - a kind of inquiry. Learning, they suggested, is concerned with ideas, their structure and the evidence for them - "not simply the acquisition of a set of correct responses, a verbal repertoire or a set of behaviors" (Posner et al, 1982).

Srike and Posner (1985) later emphasized the distinction between this philosophy and traditional empirical thinking, which views learning as additive. They posited that learning is instead a process of conceptual transformation, in which new ideas interact with older ones, sometimes altering both in the process. While acknowledging that empirical evidence is relevant to learning, Strike and Posner contend that a theory (or set of beliefs) is judged primarily on its ability to solve intellectual problems (1985). Conceptual frameworks are retained or replaced on the basis of their explanatory utility, not on the basis of supportive or contradictory empirical evidence.

Based on this philosophy, Posner and colleagues (1982) outlined 4 key requirements for conceptual change:

**1** ) *Dissatisfaction with existing conceptions.* Students must be aware of intellectual problems that their current conceptions are unable to solve.
2) *The new conception must be intelligible.* The student must be able to understand the new concept well enough to see its explanatory potential.
*3) A new conception must appear initially plausible.* The new concept should appear to be able to solve the intellectual problems associated with the existing conception.
4) *A new concept should be fruitful.* It should be testable and useful in new scenarios or problems.

Translating the principles of conceptual change theory into pedagogy is not an easy task. Nevertheless, a number of researchers have contributed modest experimental evidence of its effectiveness. Bishop and Anderson (1990) endorsed the conceptual change model and applied it to the teaching of evolution. Students' understanding of evolution was measured before and after instruction using tests that required them to explain situations related to natural selection and changes in populations. For example, one question was as follows:
"Cave salamanders are blind (they have eyes which are non-functional). How would a biologist explain how <u>blind</u> cave salamanders evolved from sighted ancestors?"

Acceptance of evolution was also assessed on the pre- and posttests by asking students if they believed the theory of evolution to be truthful. The tests showed that students generally viewed evolution as a need-driven process whereby species respond to environmental conditions through gradual changes. The Lamarckian view that acquired traits are inherited was also prevalent in the group.

The instruction used a variety of laboratory activities, problem sets and handouts that were closely aligned with the criteria of the CCM. The aim was that students would become dissatisfied with their current views, reach a basic understanding of the scientific view, and come to appreciate the utility of the scientific explanation in a variety of applications.

The instruction was successful in improving students' understanding of evolution. The authors noted an increase in the percentage of students who used scientific explanations of evolutionary change from less than 25% to over 50%. The study also revealed a lack of relationship between belief in the truthfulness of evolution and understanding. In fact, they noted that a higher percentage of the non-believers demonstrated understanding of the scientific explanations, but this difference was not statistically significant. Gains in understanding as a result of the instruction were not associated with changes in acceptance.

The authors make a number of important points in relation to these findings. They state: "If the students that we studied are taken as representative of college-educated non-scientists, then it appears that a majority of people on both sides of the evolution-creation debate do not understand the process of natural selection or its role in evolution" (p. 426). An important implication of this finding is that strategies aimed at resolving the creation-evolution debate (ie, improving acceptance of evolution) should not focus exclusively on improving comprehension of natural selection and evolution. The heavy focus on strategies that target cognitive factors may be misguided.

The authors also note that, despite a 25% increase in the number of students able to explain evolutionary events correctly, the instruction failed to help a significant number of students. Ideally, much more than half of students should be using correct scientific explanations by the end of instruction. The conceptual change approach used in this study was helpful, but not sufficient in bringing about satisfactory levels of understanding.

Jensen and Finley (1995, 1996, 1997) used conceptual change strategies in three different studies of students learning about evolution. In the earliest of these, instruction was administered in five steps that were closely aligned with the CCM: students were first introduced to the general nature of evolution, Lamarckian principles were taught, evidence against Lamarckian principles was examined, Darwinian principles were taught, and finally, students were required to solve evolutionary problems from both Lamarckian and Darwinian perspectives (1995). In the subsequent studies (1996,1997) the instructional strategy included additional alternative models but remained consistent with the principles of the CCM. These additional models included natural theology, in which an intelligent creator is in control, and Cuvier's teleology, which holds that evolution occurs in response to the needs of the organism.

An additional feature of these studies was the inclusion of "historically rich" content. For example, Darwin's ideas were presented along with information about other people, like Malthus and Lyell, whose works influenced his thinking. Darwin's life history was also discussed with details about his academic career and his voyage aboard the H.M.S Beagle. The authors reasoned that students would more readily replace their initial conceptions with modern scientific thinking if instruction were to recapitulate important events in the development of modern evolutionary theory. The implication here is not that students' progress in their thinking recapitulates historical development, but that in covering the historical development of evolutionary thinking, students will likely encounter their own misconceptions along the way. The authors also reasoned that the historical content might help to humanize Darwin and make the development of evolutionary thinking more relatable.

Jensen and Finley's findings were similar to those of Bishop and Anderson, with significant improvement between pre- and posttests, but poor posttest performance nonetheless. For example, in the 1995 study, the percentage of correct test answers rose from less than 25% to 45%. Despite the marked improvement, students were still answering fewer than half of the questions correctly. This study did not include a comparison group, but the later studies demonstrated little improvement with a traditional approach. The authors noted that students typically begin their courses with "a mixed bag" of ideas and finish with a "mixed bag" that has a slightly greater proportion of Darwinian ideas (1997).

Because the historical content was embedded in a conceptual change strategy and the comparison was to traditional instruction, it is unclear as to what extent the historical content improved learning beyond a typical conceptual change approach. It appears, however, that even in combination with a conceptual change strategy, benefits are modest at best.

More recent studies have produced similar findings. Kampourakis and Zogza (2009) applied a conceptual change strategy to teach evolution in a study of 98 14-15 year-old students. The course incorporated both lectures and student discussion and used slides designed to confront students with weakness in their conceptions and elicit conceptual conflict. Students' understanding of evolution was assessed before and after the instruction using a five-task, open-ended, written questionnaire designed by the researchers. Students explanations were coded as "evolutionary, proximate, or teleological". The results showed a net gain of 32% in correct explanations provided for the tasks. Across the tasks, the average proportion of students providing correct explanations following the instruction was 59%, with only 29% of students responding correctly on all five tasks.

Banet and Ayuso (2003) provided what might seem to be the most promising results using a conceptual change approach. 70% of students in their study held views consistent with evolutionary theory after the intervention - an improvement of 44%. However, this study was quite small, with only 50 subjects, only 42 of whom wrote the posttest. Students' understanding of evolution was measured by instructor-designed instruments and students were categorized as either "Lamarckian" or "Darwinian". As in the study of Kampourakis and Zogza (2009), the coding or categorizing of students may be problematic. As Jensen and Finley's studies show, students tend to draw from a mixed bag of ideas and their conceptions are unlikely to fit neatly into distinct, mutually exclusive categories (1995, 1996, 1997). Grouping students in this manner thus requires a degree of approximation. Though the findings of Kampourakis and Zogza, and Banet and Ayuso seem promising, the greater gains may be largely attributable to differences in methodology and study design.

*Limitations of the CCM*

The complexity and variety of evolutionary misconceptions may partly account for the limited success of conceptual change strategies. Compared to misconceptions in other subjects, evolutionary misconceptions may be more deeply rooted in students' fundamental assumptions about the nature of knowledge. Posner and Strike (1985) acknowedged that such assumptions may prevent students from seeing flaws in their initial conceptions. For example, students who do not adhere to the principle that their views must be consistent with empirical facts will not see empirical facts that contradict their views as problematic. Consequently, improving their understanding of evolution may not help them see why the scientific model is superior to their chosen alternative.

The sheer number and variety of evolutionary misconceptions may make it more difficult for students to distinguish clearly between different models. Jimenez-Aleixandre (1992) noted that the students she studied tended to attribute Lamarckian ideas to Darwin. Jensen and Finley's findings were similar: students' conceptions before or after instruction didn't fit neatly with a specific model of evolution, but were "mixed bags". Perhaps these "bags" need to be well sorted before students will exchange whole bags instead of just some of their contents.

Jimenez-Aleixandre (1992) applied a conceptual change strategy which emphasized the distinction between the alternatives and their incompatibility. She reasoned that students would more readily abandon their incorrect conceptions if they were are able to better distinguish them from modern evolutionary theory. She also emphasized the importance of distinguishing between modern evolutionary ideas and students' *own* initial ideas. Applications of the CCM typically make general comparisons between different models or between modern evolutionary ideas and common misconceptions. In order to achieve greater specificity, she had groups of students discuss their own responses on pre-test questions and how these differed from scientific thinking.

Both experimental and control groups involved a typical conceptual change approach. In the control group, comparison was made between a modern scientific conception and commonly-held Lamarckian ideas. In the experimental group, discussion of students' own pre-test responses replaced discussion of commonly-held Lamarckian misconceptions. The experimental group additionally included an initial small group discussion of pretest responses and a final comparison of students' new and original views at the end.

The experimental group outperformed the control group at the completion of the instruction and a year later. For some questions, dramatic improvement was observed and statistical significance beyond $p = 0.01$ was reported. It should be noted, however, that the study was quite small and statistical comparisons between pre- and post-test scores could only be made for three questions. The findings do, however, suggest ways in which typical conceptual change strategies might be improved. Perhaps greater emphasis on the distinction and incompatibility between students' *own* conceptions and the scientific conception would be helpful. This might be a good focal point for future studies.

*Criticisms of the CCM*

The CCM has been criticized for portraying conceptual change as a primarily rational process that occurs through wholesale exchange of complete conceptual frameworks (Demastes, Good, & Peebles, 1996). Demastes and colleagues used a series of structured and open-ended interviews to study conceptual change in 4 students learning about evolution. The study revealed a number of patterns that are inconsistent with the CCM. For example, students may modify their views gradually and in small steps and may simultaneously apply incompatible conceptions.

The researchers noted that if the participants had been followed for only days or weeks it would have appeared that no conceptual change had occurred. In this study, participants were observed over an entire school year. Complete conceptual change from an incorrect model to a fully scientific conception may be an unrealistic goal for a single 10-day module or even a year-long couse. Because students develop and modify their conceptions gradually over long periods of time, evolution instruction should extend over as long a time frame as possible, with early introduction of basic concepts and regular revisitation.

Another drawback of the CCM is that it assumes that the learner chooses a conception on the basis of explanatory power or empirical support. This is certainly not always the case. As Posner and Strike (1985) acknowledged, not everyone requires that their views be consistent with empirical facts. The popularity of superstition, astrology, and alternative medicine attests to the fact that people's choices are often based on factors other than reason and evidence.

The literature on conceptual change strategies demonstrates some of the common problems with the evolution education literature in general. Studies tend to be small, of short duration, and highly variable in design and methodology. The measurement of students' understanding of evolution, for example, varies widely and prevents easy comparison of results of different studies. Control groups are rarely used and strategies are sometimes combined, which makes it difficult to determine individual effectiveness. More specific determination of the effectiveness or relative effectiveness of these strategies would require better designed, larger and longer studies. This said, I think we can draw a few general conclusions from the conceptual change data. Students have great difficulty understanding evolution and conceptual change strategies are helpful, but insufficient. Gains in learning with these strategies may be statistically significant, but given relatively low levels of understanding following the intervention, their practical significance is unclear.

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## Teaching about the Nature of Science

An understanding of the Nature of Science (NOS) is considered by many organizations to be an important objective of science education (AAAS, 1993; NRC, 1996; NSTA, 1982). This view has been held for over a century (Central Association of Science and Mathematics Teachers, 1907; Lederman, 2007, p. 832). Despite widespread and longheld agreement on the importance of NOS, however, there seems to be little agreement on what the term actually means (Alters, 1997; Lederman, 2007). According to Lederman, NOS refers to "the epistemological underpinnings of the activities of science and the characteristics of the resulting knowledge" (2007, p. 835). NOS is thus distinct from scientific processes and inquiry, though the two are often conflated.

Regardless of the definition used, studies have consistently shown over a number of decades that students have low levels of NOS understanding. Several researchers found that almost a third of high school students studied viewed the products of scientific research as incontrovertible and absolute truth (Rubba, 1977; Rubba & Anderson, 1978). Poor NOS understanding was also found in studies of high school students (Lederman,1986; Lederman & O'Malley, 1990) and college students (Gilbert, 1991). A later study demonstrated a similarly inadequate grasp of NOS in 7th graders of both Cree and Euro-Canadian backgrounds (Sutherland & Dennick, 2002). NOS seems to be a problem at most, if not all, grade levels.

Misconceptions about NOS are prevalent among teachers of both elementary and high school levels as well. Aguirre and colleagues (Aguirre, Haggerty, & Linder, 1990) studied 74 pre-service high school science teachers, all of whom had undergraduate science degrees. Teachers' conceptions of NOS, and the teaching and learning of science were assessed with 11 open-ended questions. The authors concluded that teachers' conceptions of the nature of science were inadequate. Nehm and Schonfeld (2007) also found prevalent misconceptions in a similar group of pre-service teachers with biology degrees. Findings of studies of elementary school teachers are consistent with those of higher levels. Bloom studied a group of 80 pre-service elementary teachers and found that they tended to view science as people-centered and serving to benefit mankind (1989).

Addressing misconceptions about the nature of science may be important in the teaching of evolution. Pre-service biology teachers studied by Nehm and Schonfeld (2007) expressed a number of NOS misconceptions directly related to evolution. These included the views that theories become facts when they are well-supported and that evolution must be observed in order to be true.

Cooper (2001) emphasized the importance of expanding students' conceptions of the nature of science beyond "The Scientific Method", in which hypotheses are formulated and tested in laboratory experiments. Branches of evolutionary biology, he notes, may involve reconstruction from the past, using similar methods and reasoning that a forensic scientist might use to reconstruct a crime scene. Those who view science as relying on direct observation may question the validity of evolution since no one observed humans evolving from their ancestors (Cooper, 2001). An understanding of the processes by which scientists construct knowledge may therefore be helpful in promoting acceptance of evolution.

A number of researchers have observed that students who view knowledge as flexible and changing are more likely to change their conceptions (Andre & Windschitl, 2003; Qian & Alvermann, 2000). Such students may also be more likely to accept scientific explanations of phenomena (Sinatra, Southerland, McConaughy, & Demastes, 2003) and use reasons and evidence to evaluate claims (Weinstock & Cronin, 2003). Students' understanding of the nature of science may thus be related to acceptance of evolution.

A number of approaches to improving understanding of NOS have been tested. The most successful seems to be a reflective, activity-based approach that explicitly addresses NOS. Studies have demonstrated improvement with such approaches in groups of pre-service elementary teachers (Akerson, Abd-El-Khalick, & Lederman, 2000; Abd-El-Khalick, 2001; Abd-El-Khalick & Akerson, 2004) and also in a secondary teaching methods course (Scharmann et al, 2005).

Lin and Chen (2002) reported similar findings in a study of 63 pre-service chemistry teachers. Using historical materials that explicitly addressed NOS, they demonstrated significant improvement in NOS understanding relative to a control group. The improvement may be attributable to the explicit attention to NOS, as opposed to the historical materials, however. A larger study of 166 college students and 15 pre-service secondary science teachers found little improvement in NOS conceptions as a result of a history of science course (Abd-El-Khalick & Lederman, 2000).

Explicit attention to NOS concepts seems to be key. A study of 62 6th-graders compared students who received inquiry-oriented instruction that addressed NOS either explicitly or implicitly (Khishfe & Abd-El-Khalick, 2002). The group in which NOS was explicitly addressed showed improved NOS understanding, while those in the implicit group showed no improvement. Bell and colleagues (Bell, Blair, Crawford, & Lederman, 2003) also found that simply doing inquiry was insufficient to improve students' NOS knowledge. Looking at the effects of an apprenticeship program for high ability high school students, they found that students' ability to do inquiry improved, but not their understanding of NOS, as assessed by pre- and posttests.

Verhey (2005) tested a more controversial approach to teaching NOS, involving overt comparison of scientific and creationist models of evolution. Students read and discussed a text on Intelligent Design in conjunction with a critique of the book and a defense of evolution. Instruction also included content about the history, philosophy, and nature of science, the role of uncertainty, and the value of inductive reasoning. Those receiving the experimental instruction were compared to those receiving similar instruction on evolution, but without discussion of creationism and the nature of science. Students' attitudes toward evolution were classified into groups ranging from Christian literalist to atheistic evolutionist. Verhey found that students in the experimental groups demonstrated greater change in attitude toward the rationalist end of the spectrum. These findings suggest that addressing NOS may promote acceptance of evolution.

Ingram and Nelson (2005) lent further support to the importance of NOS in evolution education. Their study similarly involved overt comparison of standard science and creationist views. An interactive instructional approach was used and the nature of science and its limits were emphasized. They reported both improved acceptance and understanding of evolution.

Authors who advocate direct discussion of creationist conceptions stress that the models should be compared and evaluated using appropriate scientific criteria (Alberts, 2005; Verhey 2005; Nelson 2008). This differs importantly from a "teach the controversy" approach advocated by proponents of creationism, in which non-scientific conceptions of evolution are treated as if they are on equal footing.

Discussion of creationism in the classroom may generally be inappropriate at pre-college levels, since creationism is based on religious ideology. It may also be risky in the hands of a college professor who is unskilled in the art of diplomacy and should be employed with caution. It’s worth noting, however, that the criteria for evaluating alternative models and theories can be taught using non-religious alternatives. In teaching the nature of science, it may be more appropriate to emphasize *how* scientists evaluate different positions rather than the positions themselves. In other words, the aim should be to improve students’ decision making, not to make their decisions for them.

Based on the NOS literature, we can conclude that misconceptions are prevalent in students at both pre-college and undergraduate levels and in pre-college level teachers. We can also conclude that explicit reflective approaches with active student engagement are helpful in improving NOS understanding. Improving understanding of the nature of science may also promote acceptance of evolution.

It is difficult to draw further conclusions from this literature. Many of the same criticisms made of conceptual change strategies also apply to the NOS literature. Differences in terminology and measurement may be particularly problematic. At least 25 different measures of NOS are available for research use and many researchers design their own tests or interviews (Lederman, 2007). Lederman discussed a number of criticisms that have been made of these instruments, such as lack of validity, poor content, lack of subscales, or length (2007). The Wisconsin Inventory of Science Processes (WISP), for example, is considered to have excellent validity and reliability, but takes over an hour to administer. The wide variety in measurement instruments and lack of consensus on the definition of NOS make it difficult to compare findings from different studies.

Many misconceptions about evolution, such as the idea that evolution is “just a theory”, have their roots in misconceptions about the nature of scientific knowledge. An understanding of the nature of science may thus promote acceptance of evolution. Just as an understanding of evolution is important for making sense of science, understanding the nature of science may help students understand the nature of evolutionary theory.

The nature of science is similar to evolution in its fundamental nature. Students should ideally learn what science is and how it works when they start learning science. The prevalence of misconceptions about such fundamental concepts at the high school and college level makes an embarrassing statement about our current K-12 science curriculum. What are we teaching at lower levels if not fundamentals, and how do we expect students to make sense of what they do learn? The nature of science, like evolution, should be taught early so that students can build upon this framework throughout their schooling.

## Strategies that Emphasize Pedagogical Factors

This section will discuss pedagogical strategies that aim to improve students' learning of evolution. These strategies also address cognitive factors, however, the emphasis is on learning in general as opposed to conceptual exchange. These strategies may also address some non-cognitive factors. Similar to strategies based on the CCM, studies indicate that these methods are helpful, but not generally sufficient to achieve desired learning objectives when used alone. Each section will provide a brief description of the strategy and discuss the findings of studies in which they have been applied in the teaching of evolution.

### Active learning / Interactive Engagement

Interactive engagement methods aim to achieve a high level of student involvement in learning activities. These methods lie in contrast to tradtitional lecture-style methods, which treat learning as a simple transfer of knowledge from instructor to student. Often such "passive learning" is superficial and based on rote acquisition of information, instead of deeper conceptual understanding, which is more durable and useful to the student.

Interactive engagement methods were more precisely defined by Hake (1998), who conducted the largest study on their effectiveness. He defined such methods as "those designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors". Interactive engagement methods may include inquiry labs (Laws 1997), paired problem-solving activities (Jensen & Finley 1996, 1997), and small group discussions (Springer, Stanne, & Donne, 1997), among other activities.

Nelson (2008) outlined four key features of effective interactive engagement. These are 1) extensive structuring of learning tasks by the instructor, 2) strong interaction between students in exectuting the tasks, 3) assessments that provide prompt feedback to the instuctor as to whether the intended learning occurred, and 4) modifications of the instruction based on the feedback.

Hake (1998) provided the strongest evidence of the superiority of interactive engagement over traditional methods, at least for teaching physics. In a study of over 6000 introductory physics students, gains in knowledge were compared for students in traditional courses and courses that made substantial use of interactive engagement methods. Traditional courses were considered those which relied on passive-student lectures, recipe labs, and algorithmic-problem exams. The difference in normalized gains between the groups was nearly two standard deviations, with the students instructed using interactive engagement methods dramatically outperforming their peers.

Other researchers have similarly reported benefits with the use of active learning methods. McKeachie (1994) reported improvement in students' problem-solving ability, retention, and transfer of knowledge to other situations with student-centered discussion. Springer and colleagues (1997) performed a meta-analysis of research on the effects of small-group learning and found large effects for learning of content, retention, and attitude. Gardiner (1998) also reported improvement in critical thinking skills as a result of in-class student involvement with high-level cognitive responses to questions.

Benefits of interactive engagement have also been demonstrated with the teaching of evolution. Sundberg (2003) found very little gain in understanding of natural selection with traditional pedagogy, but a gain of over 25% when interactive engagement was used. Given the low level of understanding with which students typically begin, however, a 25% gain does not yield a desirable level of achievement.

Udovic et al (2002) designed a biology workshop to promote conceptual change, teach science in context, and teach science as a process of inquiry. Active learning activities emphasized decision-making and assigned students greater responsibility for their learning. One activity required students to research a science topic of social importance with the goal of making a personal decision on the issue. Other activities required students to pose problems and come up with methods to solve them. The authors found greater gains in conceptual learning with the workshop compared to a traditional lecture and laboratory format. Improvement in pre- and postest performance was between 15% and 25% for questions related to natural selection. For these questions, the comparison group performed the same or even worse than they had on the pretest. The difference between the workshop and comparison groups was most striking for questions related to natural selection and ecology.

It is clear that interactive engagement methods are superior to traditional lecture-style teaching. A potential drawback is that designing active learning activities requires a degree of pedagogical skill and knowledge on the part of the instructor. This could be problematic for university instructors, who typically have little or no training in pedagogy, or for inexperienced pre-college level teachers. Perhaps this is part of the reason why passive learning methods remain in widespread use. Providing teachers with resources, such as prepared lesson plans that incorporate active methods, may help them to make this transition.

A recently-developed online magazine, called Beyond Penguins and Polar Bears, provides a nice example of the benefits that such resources may offer. The magazine relates elementary science concepts to the real-life context of the polar regions, discussing topics like rocks and minerals, the water cycle, and climate change. It provides professional development and instructional resources, including inquiry-based lesson plans that integrate science and literacy.

The magazine's effects were investigated in a study of 19 teachers and 173 K-5 students over a 2-year period, in which the resources were used either to supplement or to replace the existing curriculum (Woodruff, Morio, & Li, 2009). Teachers reported that they were more likely to provide opportunities for reading about science and to have their students communicate scientific results through writing. They also expressed increased confidence in teaching science as a result of increased knowledge about the polar regions.

Third graders who received the instruction were more likely to agree that writing is important in science, and less likely to agree with that "science was mostly memorizing facts" (Woodruff, Morio, & Li, 2010). Exposure to the materials did not produce significant changes in fourth and fifth graders' agreement with these statements, however. The authors suggested that third grade might be a critical point in the development of students' understanding and attitudes toward science.

This study adds further support to the benefits of inquiry-based learning and provides a nice example of how science concepts can be integrated with other subjects. The primary focus was to combine the development of reading and writing skills with science learning, but the resources also provide ideas for integrating concepts in mathematics, social studies, and art into science lessons. This approach allows for greater reinforcement of important ideas in a variety of subjects throughout the curriculum.

It's worth noting that the youngest students in the study benefitted most from the instruction. Inquiry-based activities may seem too complicated for children, but a growing body of research suggests that this is not the case. A group of 8- to 10- year-olds at a UK primary school recently conducted a sophisticated investigation of bee foraging methods. They reported their findings in Biology Letters: “We discovered that bumble-bees can use a combination of colour and spatial relationships in deciding which colour of flower to forage from. We also discovered that science is cool and fun because you get to do stuff that no one has ever done before.” (Blackawton et al, 2010). Maloney and Hempel de Ibarra (2010) eloquently described the significance of the study: “The insatiable curiosity that characterizes childhood, combined with the skeptical discipline of scientific method, provides a powerful tool that allows us to prosper and grow.” Indeed, the students of Blackawton demonstrated that with a bit of guidance curious children can do impressive scientific research.

## Quality Over Quantity

This section focuses on the sheer volume of material to be learned as opposed to its delivery. It's worth noting, however, that reduction in content is generally necessary when lecture-style teaching methods are to be replaced with more effective interactive engagement methods. Heavy content can lead to confusion and reduced learning and it is a common feature of introductory college-level science courses. Given the conceptual difficulty of evolution and the degree of confusion surrounding the topic content reduction may be especially important in the context of evolution.

With the growth of scientific knowledge, there has been a trend toward covering more material in an increasingly superficial manner (Hoskins & Stevens 2009). Students at various institutions have expressed the view that their introductory courses in science are too content-crammed and of limited utility (Seymour & Hewitt, 1997). The expectation among educators may be that students will nevertheless achieve a solid understanding of the material. Evidence suggests, however, that there is a limit to the amount of new material that students can process and that exceeding this limit is counterproductive (Russell, Hedricson, & Herbert, 1984). Evidence also suggests that this limit is frequently surpassed.

Interference is a well-established mechanism by which excessive content is believed to hinder learning. Dempster (1993) describes interference as "one of the most thoroughly investigated phenomena in the study of learning." It occurs when the acquisition or retention of knowledge is impaired by the presentation of other material. Interference may be proactive, in which knowledge acquired previously inteferes with learning of new material (Underwood, 1957) or retroactive, in which newly learned material displaces knowledge acquired earlier (Slamecka, 1960). Giles and his colleagues suggested a third form, called coactive interference, in which learning is impaired by additional material that is presented at the same time (Giles, Johnson, Knight, Zammett, & Weinman, 1982). All three types of interference may be relevent to the teaching of evolution.

Excessive content can take a number of forms. A course may generally include too many topics, individual lectures may be too detailed or introduce too many concepts, and individual learning activities can overwhelm students information-processing capabilities. Additionally, content of textbooks and multimedia aids may be excessive and presented in a manner that creates interference and hinders learning.

*Excess content in courses and lectures*

A number of studies have demonstrated that high information density impairs learning and retention of material. Sundberg and colleagues compared learning outcomes for undergraduate biology non-majors and majors (Sundberg & Dini, 1993; Sundberg, Dini, & Li, 1994). The majors' and non-majors' courses were nearly identical in their topical coverage, but the majors' course included substantially more detail. Despite the more rigorous treatment of topics in the majors' course, nonmajors showed greater improvement and ultimately achieved the same level of understanding. Notably, the gains of nonmajors were particularly pronounced with respect to ecological and evolutionary concepts, with some sections of nonmajors outperforming the majors (1993).

Russell and colleagues (Russell, Hedricson, & Herbert, 1984) observed a similar trend in a study of medical students. The study compared retention of information acquired during lectures of high, medium, or low information density. Students who attended low density lectures learned and retained substantially more material.

Excessive content in lectures is believed to impair learning mainly through retroactive interference. Students are more likely to remember information presented in the last 15 minutes of high density lectures (Russell et al 1984; Giles et al 1982). It is believed that information learned later in the lecture replaces what was learned earlier. In contrast, students who attended low information density lectures retained information evenly from beginning, middle, and end portions (Russell et al 1984). Reduction in lecture content appears to eliminate interference, resulting in greater learning and improved retention.

Reducing lecture content alone may substantially reduce interference. Thus, a reduction in overall course content may not be necessary. Alters and Nelson (2002) suggested that material removed from lectures could be addressed through homework or other assignments. Reduction of overall course content may nevertheless be prudent. Sundberg and colleagues (1994) showed that heavy course content can also have a negative impact on students' attitude toward the subject. It is unclear as to whether this effect stemmed solely from the content-laden lectures or also from the overwhelming nature of the volume of material to be learned during the course. Given the importance of a solid understanding of evolutionary basics and the difficulty students have in achieving this, a narrow focus may be best.

*Learning activities*

Forms of interference have been demonstrated in a wide variety of subjects. Mayer and colleagues studied students learning hydraulic braking systems (Mayer, DeLeeuw, & Ayres, 2007). Students were presented either with material on hydraulic braking systems alone or with the same material, followed by information on other braking systems. Those presented with only one system demonstrated better learning of the material. Mayer (2005) referred to this phenomenon as the coherence principle: students learn better when the information to be learned is presented without extraneous material.

The coherence principle also applies to students learning new words. Dempster (1987) presented students with a list of vocabulary words to learn. One group was given just the words and definitions, and another group was given the words, their definitions, and an additional few sentences using the words in correct context. The group given just the definitions outperformed the group given additional context, even on measures of ability to use the words correctly in sentences.

These findings are somewhat counterintuitive. It may be that context is helpful once key concepts are solidly learned, while concurrent presentation is detrimental to new learning. Once students have a basic idea of the words' meanings, perhaps additional sentences using the words in context would reinforce what was learned and deepen students' understanding to more subtle nuances and varied uses. These findings may be directly relevant to science teaching. Eylon and Linn (1988) noted that the vocabulary in a week-long science unit is often greater than that of a foreign language unit of the same length.

Effective management of interference requires attention not only to the density of content, but also to its nature. Dempster (1988) showed that the similarity of the items to be learned is important. The study compared two groups of students learning about electricity. One group read a passage about direct current, followed by a passage about alternating current. The other group read the same passage on direct current, followed by an additional unrelated passage. Students who read the unrelated passages performed better on tests of knowledge of electricity. Dempster concluded that when people read about related topics in succession, without an opportunity to fully understand the material, the result is confusion and reduced learning (1988).

Giles and colleagues, studying the effects of lecture density (1982) also noted that the risk of interference is highest when a lot of similar information is presented and the material is not well-learned. This may be very relevant to the teaching of evolution, since alternative models of evolution are often poorly differentiated in students' minds.

*Textbooks and multimedia tools*

Efforts to reduce content should also target text books, which contain abundant sources of interference (Dempster, 1988). Experimental evidence indicates that embellishments and elaborations in texts may do more harm than good (Dempster, 1988; Reder, 1985; Catley et al, 2008, Catley et al, 2010). Reder (1985) compared the learning of students reading text summaries containing only main ideas to those reading unabridged texts containing greater detail and embellishments. The elaborations hindered students' learning and retention of the material and also their ability to learn new information related to the material presented in the summaries. The effect was observed even though students reading unabridged texts were given extra time to study the elaborations.

Evolutionary diagrams in particular may cause confusion. Catley and Novick (2008) found that cladograms comprise a large majority of evolutionary diagrams in biology textbooks. They observed that these are almost always accompanied by little or no attempt to explain their structure or theoretical basis. The authors concluded that many of these diagrams are confusing and may reinforce students' misconceptions.

Non-cladogenic diagrams can also cause confusion. Diagrams based on Haeckel's well-known tree of life are common in biology texts (Catley & Novick, 2008). Such diagrams depict evolution as a progression from simpler or lower organisms to more complex or higher organisms. These diagrams can reinforce teleological misunderstandings (Catley, Novick & Shade, 2010).

Evolutionary diagrams are not only confusing in their depiction of evolution or their lack of accompanying explanation, they distract students from more basic, and sometimes more accurate, information. Even accompanied by an explanation, cladograms are unlikely to be helpful to students who lack a basic understanding of speciation. Given that students often have a poor grasp of basic concepts even at the end of their courses, time spent studying elaborations might be better spent studying more basic concepts.

The same principles apply to textbooks also apply to multimedia presentations. Mayer (2001) demonstrated the superiority of multimedia aids with fewer visual stimuli. College students viewing an animation retained the presented material better than those who viewed the animation with narration that duplicated or summarized the material. The authors suggest that the additional information may exceed students' visual information-processing capacities, requiring them to split their visual attention between two sources. This finding may be particularly relevant to the design of powerpoint presentations, since lecturers often narrate slides as they are presented. Regardless of the source of excess information, the conclusion is the same: exceeding the limit of information-processing capacity is counterproductive.

The affective response of students to overwhelming amounts of information can also impair learning. McLaughlin and Mandin (2001) coined the term "lecturalgia" to describe the pain of tedious and overwhelming lectures. According to the authors, lecturalgia is "characterized either by a state of heightened emotions (eg. agitation, frustration, anger), or suppressed emotions (eg. apathy and somnolence)". The authors indicate high content density as an important cause of the condition. Consistent with this idea, Sundberg, Dini, and Li (1994) observed that content-laden majors' biology courses had a generally negative effect on the attitudes of students toward science.

The impact of content density on student attitude may be especially relevant in the context of evolution. Some authors have suggested that rejection of evolution can impede learning (Cobern, 1994; Meadows, Doster & Jackson, 2000; Smith, 1994). Though, as discussed in an earlier section, the relationship between acceptance of evolution and learning is not well-defined, it stands to reason that a student with a negative attitude toward the topic may be less open to learning about it or accepting it as truthful. A positive, or at least neutral, attitude toward evolution might therefore facilitate learning and acceptance. If overwhelming students with excessive content has a lasting and negative impact on their attitude toward evolution or science in general, it may might influence acceptance and learning of evolution.

The success of a "less is more" approach to science curricula has already been demonstrated in some countries. Singapore, China, Hong Kong, Japan and Korea, applied a "less is more" philosophy in reforming their high school science curricula (Ng, 2008; Zhao, 2005). Notably, these countries have consistently been top performers on international assessments of science knowledge for elementary and secondary school students (TIMSS, 2007).

The need to reduce content in North American science curricula has been recognized. As the NSF acknowledged, an analysis of TIMSS performance revealed "that mathematics and science curricula in U.S. high schools lack coherence, depth, and continuity; they cover too many topics in a superficial way." (1999). Project 2061 of the AAAS called for the trimming of "overstuffed and under-nourishing curricula" (2001).

Despite recognition of the need for both content reduction and a shift toward teaching for deeper understanding, these changes are difficult to implement. Nelson (2008) acknowledged that he personally found limiting content to be so difficult that he later argued that it is the most difficult step in becoming a good teacher (Nelson, 2001).

An additional challenge for teachers is knowing what content to eliminate. Ideally, science teaching should build on concepts that were learned in previous grades, thus reinforcing basics and integrating new concepts with students' existing knowledge. If individual teachers are left to choose which concepts they will teach and which they will eliminate, it becomes more difficult to coordinate learning across grade levels. In this respect, the provision of pre-trimmed science curricula may be helpful to both teachers and students. This might ensure coverage and reinforcement of key concepts and relate concepts learned at different grade levels in a way that is conceptually helpful.

Reducing content may be the single most important step toward teaching evolution effectively. Reduction of content alone may improve learning substantially and also allows for the implementation of superior pedagogies, since active learning methods and conceptual change strategies generally take more time per concept than lecture-style coverage. Reducing content across grade levels in a coordinated manner may also help to streamline the science curriculum in a way promotes correct conceptual development.

## Distributed Practice and Concept Mapping

The following two sections describe teaching practices that may promote learning of evolution and also work well with a reduction in content. Distributed practice takes extra time and generally requires that content be reduced. It also helps to mitigate the effects of interference that arises from dense or confusing content. Concept mapping similarly takes extra time. It may help the instructor to identify points on which students are confused. Problem areas identified through concept mapping can be revisited through distributed practice.

### Distributed Practice

Distributed practice refers to the episodic revisiting of concepts through review or testing. The "distribution" of the reviews or tests is key. "Massed" practice that occurs over a relatively brief period (eg. three reviews in one week) may result in rapid acqusition of material, but retention is comparitively poor (Dempster, 1991). Dempster suggests that three reviews in three months would constitute better spacing of practice sessions (1991).

Distributed practice serves a number of functions. Mayer suggested that it may facilitate meaningful learning by shifting the learner's attention from the verbatim details of the material to its deeper conceptual structure (1983). The practice may also minimize the effects of cognitive interference (Dempster, 1991). Szpunar and colleagues (2008) found that testing reduced the build up of proactive interference during extended study sessions.

It's worth noting that misconceptions about evolution that are present at the beginning of a course may act as a source of proactive interference. For example, previously acquired Lamarckian concepts may interfere with the learning of Darwinian principles. Since instructors cannot prevent prior exposure to such models, presenting only the Darwinian model would not solve the problem of interference. Students will come to class already possessing knowledge that may impede their learning of evolution.

Distributed practice may partly account for the success of the experimental group in Jimenez-Aleixandre's 1992 study (discussed in greater detail in the section on conceptual change strategies). Not only was a distinction made between Darwinian evolution and students' *own* conceptions in the treatment group, but this distintion was revisited an additional time at the end of the sequence. Whether the extra discussion was a factor in the improved performance, however, is unclear.

Repetition may be especially useful when students are required to evaluate the truth of particular conceptions or theories. A well-known phenomenon in psychology called "the illusory-truth effect" suggests that subjects are more likely to view repeated statements as true, compared to new statements (Hasher, Goldstein, & Toppino, 1977; Begg, Anas, & Farinacci, 1992). This effect is generally attributed to the tendency for people to prefer things that are familiar. The phenomenon may partly account for the difficulty in changing students' conceptions about evolution at the high school or college level. By this stage, anti-evolutionary ideas may be preferrable because they are familiar.

Recent research suggests that testing, a form of distributed practice, may be a powerful learning tool. Karpicke & Blunt (2011) demonstrated greater learning gains in science with "retrieval practice" compared to elaborative studying in conjunction with concept mapping. Earlier research similarly revealed large positive effects on recall of learned material as a result of repeated testing (Karpicke & Roediger, 2008). Despite the common view that testing simply measures prior learning, the results of these studies suggest that the process of retrieving knowledge can powerfully promote conceptual learning of science.

Though little research has directly investigated the impact of distributed practice on evolution learning, there is good reason to think that it would be helpful. Cognitive interference is a well-known phenomenon and distributed practice is one of the most effective ways to manage it. Evolution is known to be a conceptually difficult topic for many students and prevalent misconceptions may serve as a source of interference. It is important that key evolutionary concepts are revisited regularly. Both content reduction and an earlier introduction of evolutionary concepts would provide greater opportunity for distributed review.

**Concept Mapping**

A concept map is a hierarchical diagram that describes relationships between concepts using linking words. The most general and inclusive concepts are typically placed at the top of the diagram, with more specific concepts below. Figure 1 provides an example of a concept map depicting a modern scientific conception of evolution.

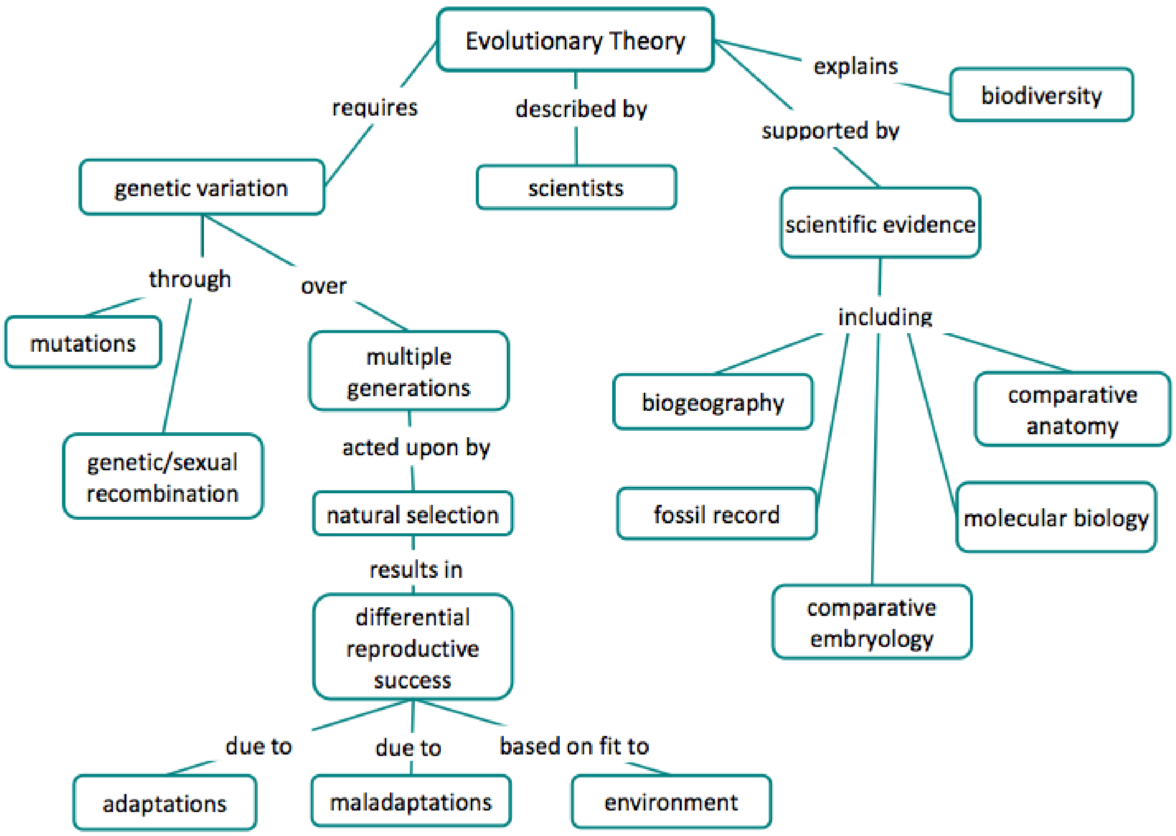


Figure 1. A concept map illustrating linkages between evolutionary concepts. (http://outreach.mcb.harvard.edu/teachers/Summer06/ElliottGimble/ModernEvolution.html)

Concept mapping was developed in 1972 by Joseph Novak and his colleagues at Cornell University as a tool to describe changes in children's understanding of scientific concepts (Novak and Canas 2006). Grounded in constructivism, the technique provides a means of assessing a student's conceptual understanding and guiding further learning. The process is intended to promote meaningful learning beyond rote acquisition of the material, and thus improve long-term retention of what is learned.

A number of researchers have used concept maps to teach biology and evolution. Trowbridge and Wandersee (1994) reported that mapping increased the amount and distribution of students' studying of the course material. Students in the study spent an average of 48 minutes constructing each map, typically soon after a lecture. They reported spending more total study time on the course as a result of the concept mapping, and studied more evenly throughout the course, rather than concentrating their studying close to exams. Concept mapping can be considered a form of distributed practice, since it requires students to revisit concepts from lectures and helps to improve the distribution of study time.

In addition to facilitating learning, concept maps can be helpful in monitoring students' understanding of course material and their progress throughout the course (Wallace & Mintzes, 1990; Demastes et al, 1996). Problem areas that are identified can be revisited in review sessions.

The process of creating concept maps requires contemplation of the conceptual meaning of lecture material and its relation to students' current knowedge and thus promotes meaningul, rather than rote learning. The process helps to clarify and reinforce ideas presented in class and equips students with skills that they can use to integrate new information in other courses and in the future. As Trowbridge and Wandersee note, the rapid growth of scientific knowledge means that the most important thing students can learn in a course is how to learn more about the topics on their own (1994). Concept mapping may help them do this.

It's worth noting that concept mapping requires that the instructor have an accurate understanding of the material to be learned. As discussed in previous sections, this is often not the case with evolution and the nature of science at pre-college levels. When used by an instructor who holds an incorrect conception of evolution, concept mapping may do more harm than good.

## Strategies That Emphasize Non-Cognitive Factors

This section will address strategies that emphasize non-cognitive aspects of learning. The first part will describe an aesthetic framework for approaching evolution education, while the second part describes more general persuasion tactics. Both approaches consider sensory and affective elements in addition to cognitive aspects of learning.

### An Aesthetic Framework

Aesthetic properties like order, simplicity and complexity, pattern and rhythm, and symmetry, are often found in science and in nature (Flannery, 1991). Charles Darwin made reference to such qualities in his own theory when he wrote: “There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved” (2001). Indeed, a scientific theory can be beautiful in its explanatory power, and in its ability to describe complex processes in simple terms. Aesthetic properties can also influence our judgment of scientific ideas and theories. According to James Watson, the double helix model of DNA was once described as “too pretty not to be true” (1968, p.134).

Aesthetic experience is comprised of cognitive, sensory and affective elements, but emphasis is often placed on the sensory. Berleant (2004) suggested that it is really the sensory component that makes experience aesthetic: “When intellectual, moral, or emotional elements begin to obtrude, experience becomes less aesthetic and more cognitive, homiletic, or affective.” The sensory component of experience makes it highly subjective and phenomenal.

Affective and cognitive elements also contribute to the subjectivity of aesthetic experience. An individual observing a painting may have quite a different response compared to someone else looking at the same piece. The image and its sensory stimuli may trigger memories and associated feelings and ideas that are unique to the observer. The sensory, affective, and cognitive elements of the observer's experience of the work will be influenced by the observer's past experience and unique interpretation.

Aesthetic experience may be intense and multidimensional with a strong sensory component, but it need not be pleasant. Francisco de Goya's famous depiction of Saturn devouring his son, for example, is richly evocative but not exactly pleasant. As Berleant suggests, the opposite of aesthetic is really *anaesthetic* (2004). "Aesthetic" may describe the depth or dimensionality of the experience, rather than its positive or negative character.

Aesthetic experience is typically associated with works of art, like paintings or music, but art is not exceptional in its ability to create such experience. It can be also be created by immaterial entities, like concepts. Evolution is one such concept. Just as with a piece of art, we can present evolution to a group of people and each person may respond differently. Students' perception of evolution isn't shaped just by empirical facts or evidence, but by their present conceptions and the meaning and feelings they attach to these.

Intentionality is an important concept in aesthetics research, and refers to the distinction between an object and the object *as it is experienced*. Scruton (2009), offers the example of a person who is frightened by a white sheet flapping in a hallway. The person is actually frightened of ghosts, so a distinction is made between the material object (the sheet) and the intentional object (a ghost). Here "intentional" refers to the "object-as-experienced".

Just as we can talk about objects-as-experienced, we can talk about scientific concepts-as-experienced. Students bring to their science classes a set of preconceptions and past experiences that influence their attitudes toward the course material. For controversial topics at the interface of science and religion, the response may be intensely emotional and personal. In this case, the scientific concept is analogous to the material object, while the student's understanding of the concept and its implications are similar to the intentional object. The idea of human evolution may be upsetting to a student who believes in biblical creationism, but it may not be the idea *per se* that is upsetting, but its implications for the student's cherished beliefs. Evolution-as-experienced may be a more important determinant of learning than evolution as it is understood on a purely cognitive level.

The aesthetic nature of student experience of evolution has important implications for pedagogy. To be optimally effective, instruction must appeal to more than just the intellect, and create a positive learning experience on multiple levels. This requires some creativity.

*Aesthetics in the Classroom*

A number of classroom exercises have been described which aim to appeal to students' senses as well as their minds. Staub proposed a model for teaching about genetic drift using M&Ms and reported that the activity captured students interest and was helpful in clarifying challenging concepts (2002). A similar model uses jelly beans to teach a variety of evolutionary concepts, including natural selection (directional, stabilizing, disruptive), competitive exclusion, sexual selection, optimum foraging theory, and Hardy Weinberg Theory (Lauer, 2000). Improvement in students' understanding and retention of concepts was noted with this exercise. The children's game "Yahtzee" to illustrate how seemingly improbable outcomes can occur readily through selection and there is even an exercise that illustrates the concept of deep time using a roll of toilet paper (Dickinson, 1998; O'Brien, 2000). Improvement in students' understanding and attitude toward evolution as a result of these exercises was not formally evaluated, but it is easy to see that such exercises can be fun and engaging, particularly when compared to traditional lecture-style teaching.

Videos, animations, and computer games may also be helpful. Speth and colleagues reported significant gains in students' understanding of natural selection using the digital evolution software "Avida-ED" (Speth, Long, Pennock, & Ebert-May, 2009). The program was designed to allow students to observe evolution in action and uses "actual instances of the evolutionary mechanism" instead of simulations. In addition to promoting conceptual understanding of principles of natural selection, the program provides students with an opportunity to learn through inquiry and to learn about the nature of science. Students are able to ask open-ended questions about evolution and test hypotheses.

Role-play can make scientific concepts more personal and meaningful for students. Duveen & Solomon (1994) described their use of role-play to teach evolution to high school students. While the authors did not use a formal method of evaluation, they perceived the activity to be a success. They reported that in interviews several months after role-play exercises, students were able to remember the exercise vividly and quote details of the story to illustrate how scientistific knowledge is constructed (Duveen & Solomon, 1994).

An excellent example of an aesthetic approach to promoting evolution is Baba Brinkman's Rap Guide to Evolution. The album's accuracy is ensured by Mark Pallen, Professor of Microbial Genomics at the University of Birmingham, making it the first rap album to be peer reviewed (Craze, 2010). Students' testimonials offer evidence that the rap can have a profound effect on some students' attitudes toward evolution. One High School student offered this comment:

> Wow, what can I say? Watching Baba perform at Binghamton High School was amazing! Before Baba came to my school I hated science with a passion; it would just annoy me, mainly because I didn't get the subjects that were being taught. But when Baba came he made it fun and interesting. We all enjoyed it! Music changes everything. To hear the learning in the music makes things 10 times easier! Just wanna say thank you Baba for helping me realize how easy science could be! (http://www.crowdfunder.co.uk/investment/the-rap-guide-to-evolution-educational-dvd-58)

While such testimonials constitute only anecdotal evidence, they demonstrate the extent to which such an approach can affect some students. The effects of Brinkman's music on students' comprehension of evolutionary principles remain to be seen, but it is evident that his work can be a potent influence on students' attitude toward evolution and science in general.

The important role of non-cognitive factors in shaping attitude toward conceptions of human origins is also reflected in the popularity of creationism. Creationist accounts of human origins leave a lot of questions unanswered and conflict with a large body of scientific evidence. Almost nothing makes sense in the light of creationism. Whatever factors are responsible for the persistent popularity of creationism, they are not of a rational or intellectual nature but nonetheless very important to many people.

While cognitive factors are undeniably important and conceptual change strategies somewhat helpful, strategies which focus exclusively on cognitive aspects of learning fail to address the full scope of student experience of the material, particularly when the topic is controversial.

To the empirically-oriented science educator, it might seem that solid evidence and factual information should be sufficient to persuade any rational person. It is clear, however, that simply presenting the evidence for evolution is insufficient to foster acceptance and understanding of evolution. Verhey (2005) reported the least improvement in understanding and attitude toward evolution in groups of students instructed using methods that most emphasized evidence.

Affective and sensory aspects of learning may often be overlooked by science educators. As Demastes and others have noted, many educators have embraced Posner and colleagues' (1982) conceptual change model, which portrays conceptual change as primarily rational (Demastes, Good, & Peebles, 1996). Students often are not rational in their decision-making.

Like the conceptual change model, concept mapping also largely ignores non-cognitive factors in learning. However, this tool could be expanded to incorporate a larger range of experiential factors. White (2009) devised a similar tool for examining aesthetic experience of art. These "aesthetigrams" are simply defined as "maps of one's experiential encounters with artworks" (White, 2009, p. 88). A hybrid of a concept map and an aesthetigram - an "evogram", perhaps - might be created by encouraging students to include non-cognitive factors that relate to or influence their understanding or acceptance of evolution or specific concepts. An example of such a diagram is depicted in Figure 2. This might be useful for researchers who wish to examine a broad range of influences on conceptual change and may be useful to instructors as a guide for shaping learning activities. The tool might also be helpful to students, by raising their awareness of factors that influence their own thinking.

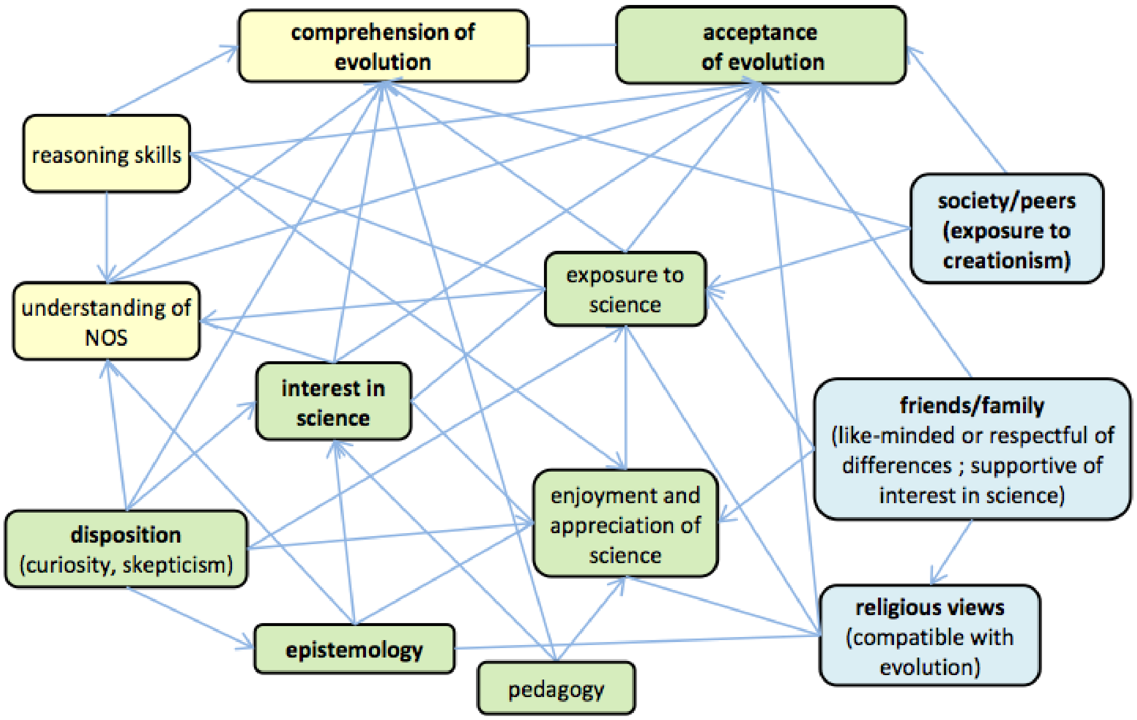


Figure 2. A concept map depicting a range of factors that may influence acceptance and understanding of evolution and the web of relationships among them. Cognitive factors are shown in yellow, non-cognitive factors in blue, and those which could belong to either category are shown in green. Connectors which lack arrowheads depict bidirectional relationships.

Aesthetic strategies for teaching evolution may be similar to active learning methods in that they aim to engage the student and may create hands-on learning experiences. Aesthetic strategies are broader in scope, however, aiming to engage more than students' interest and attention. By creating a positive and enjoyable learning experience, the student may not only be more "engaged" but may associate positive feelings generated by the activity with the topic.

By the time students encounter evolution in science classrooms, many have already formed an attitude toward it. More so than other scientific concept, it needs to be *presented*, as opposed to just explained. Similar to a work of art, it needs to be properly framed and cast in a favorable light. The goal should not simply be that students understand evolution, or even that they accept it, but that they appreciate its grandeur.

## Persuasion Tactics

Persuasion is a form of influence that aims to cause a person to adopt a particular idea, attitude or behavior. Persuasive strategies may act on both cognitive and non-cognitive levels. These tactics are often used in marketing and advertising and their success in these applications is well-established. Some of these strategies can be applied in educational settings and may be helpful in changing student attitudes about evolution.

Robert Cialdini described a number of key principles of persuasion that might be useful to evolution educators (2001). These include reciprocity, consistency, social proof, authority and liking. I will describe each of these, the evidence for strategies based on them, and how they might be applied in the context of evolution.

### *Reciprocity*

Reciprocity refers to the tendency for people to feel compelled to return favors. The use of free samples in marketing is based in part on this principle. Proponents of Creationism employed this strategy in 2009 when they dispensed adulterated copies of Darwin's Origin of Species. People tend to feel a sense of appreciation for the free gift, which may improve their opinion of the gift-giver or of the gift itself.

### *Consistency*

Once people commit to a position, orally or in writing, they are more likely to act in a manner that is consistent with the stated position. In sales, this is often applied by raising the price of a product - a car, for example - after the buyer has already made the decision to purchase. Once the commitment to purchase is made it is unlikely to be reversed, despite the price change.

The principle of consistency underscores the importance of early evolution education. If instuction in evolution is given after students have committed to alternative views, they may be less likely to change their minds. The improved explanatory power of evolutionary ideas may be insufficient to evoke change if students have already "bought" creationism or other alternative views.

Strategies based on this principle might draw links between evolution and students' existing values and views. Though evolution may not be consistent with the religious views of creationist students, most people, creationists included, value modern medicine and its power to save lives. Illustrating the importance of evolutionary principles in medicine may foster openness to learning about the topic, as students who value and use modern medicine attempt to maintain consistency in their views and practices. Students may be more willing to reject a scientific theory than they are willing to stifle progress in areas that may save their lives and the lives of their loved ones.

*Social Proof*

People tend to imitate or conform to behaviors they observe. A series of studies published by Asch in the 1950's nicely illustrated the power of social influence. Students were asked to participate in a vision test. When other group members agreed on an obviously incorrect answer, subjects tended to respond incorrectly as well.

This finding is somewhat consistent with constructivist views of learning as a social process and may underlie the success of some active learning methods. Students are influenced by their peers' views. This principle would seem to be of greater benefit when the ideas to be replaced are in the minority. When a large proportion of group members holds undesirable views, the undesirable views might be more likely to be adopted by those holding more correct views, if only to fit in. Alters and Nelson (2002) stressed the importance of instructors taking responsibility for guiding group discussions. Student preparation for group discussions, guiding questions, and supplemental materials may help to focus the discussion around key principles and points in favor of the conceptions to be learned.

*Authority*

People tend to obey authority figures. The famous Milgram experiments attest to the power of this tendency. Milgram demonstrated that people are willing to perform acts that conflict with their own conscience if they are instructed to do so by an authority figure (1963). In the experiments, subjects complied with requests to administer electric shocks to other study participants. Subjects were unaware that the receivers of the shocks were actors.

More subtle applications of this principle can be applied in the classroom. Cialdini (2001) reported that patient compliance with physical therapists' instructions rose 34% as a result of the therapists' displaying their awards, diplomas and certifications on the walls of the therapy rooms. Evolution instructors might similarly consider making their credentials known - perhaps by providing a copy of their CV or academic background on their faculty websites. They may also want to refer to some of their own research experience to illustrate examples. Students may be more likely to be persuaded to the views of the professor if they are aware that he or she has studied the subject extensively and is an authority on the issue.

Perry's modes of cognitive growth are worth keeping in mind here (1970). Dualists and multiplists tend to rely heavily on the word of authorities to determine their own views. Students who fall into these categories may be particularly influenced by this tactic.

*Liking*

People are more readily persuaded by others whom they like. Similarly, attractive people, who tend to be viewed as likable, also tend to be more persuasive. This phenomenon has been described as “the halo effect”. People’s perception of one trait influences their perception of other traits. For example, people who are viewed as attractive may therefore tend to be viewed positively with regard to other traits. They may also be seen as more intelligent, knowledgable, friendly, etc. Positive feelings about a person may also be extended to ideas and products with which they are associated.

This principle has also been employed by creationists in the form of celebrity endorsement. Their 2009 efforts to dispense altered copies of Origin of Species involved former actor Kirk Cameron. People who were familiar with the actor, deemed by many to be physically attractive, might have extended any associated positive feelings to the ideas he was promoting. The phenomenon may also work the other way. Strong opponents of evolution may have been more inclined to negatively adjust their views of the actor.

The principle of liking may have implications for the way in which evolution is best presented in the classroom. If the likability of the instructor affects his or her persuasiveness, avoiding overtly offensive comments about creationism would be prudent. Cobern (1995) compared the teaching of science to “foreign affairs”. When it comes to controversial topics like evolution, a degree of diplomacy may go a long way.

Research on persuasion also suggests that there may be benefit to presenting two-sided arguments. O’Keefe (1999) conducted a meta-analysis comparing the persuasiveness of one- and two-sided arguments in various contexts. Data were collected from 107 studies and more than 20, 000 participants. The results indicated that two-sided arguments are more persuasive.

Importantly, this does not qualify as support for the "teach the controversy" approach but perhaps for addressing multiple perspectives. O'Keefe stresses that counter-arguments must be raised when the opposing view is presented. Two-sided arguments that do not refute the opposing view may be less effective than one-sided presentations. These findings are consistent with those of Verhey (2005) and Ingram and Nelson (2005), which demonstrated improvement in understanding of evolution with explicit comparison of standard scientific and creationist views using scientific criteria for evaluation.

As with aesthetic strategies, persuasion tactics have not been investigated to any great extent in evolution education. However, the limited success of conceptual change strategies and other strategies with a primarily cognitive focus would suggest that non-cognitive factors are very important in the learning of evolution. It's worth keeping in mind that improving students' understanding of evolution does not ensure acceptance. When it comes to improving attitude and acceptance, educational theory may not be the best source of strategies. Strategies for influencing attitude are the specialty of marketing and advertising fields. Evolution educators and researchers would be wise to consider research in these areas. Persuasion strategies have proven their utility not just in selling products, but in political and public health campaigns. Application in evolution education warrants further investigation.

## Challenges to Effective Teaching

The American National Association of Science Teachers states that it “strongly supports the position that evolution is a major unifying concept in science and should be included in the K-12 science education frameworks and curricula” (2007). Despite agreement among science educators that evolution is a cornerstone of science education, it is often taught late and taught poorly. Recent research revealed that 13% of high school science teachers in the US explicitly advocate creationism, while an additional 60% are advocates of neither creationism nor evolution (Berkman & Plutzer, 2011).

The situation in Canada may not be much better. The Quebec Education Program dictates that evolution is to be taught at both elementary and high school levels. However, Jason Wiles of the Evolution Education Research Centre in Montreal, reported that many elementary and high school teachers have confessed that evolution is never actually taught in their schools (2006). Even where evolution is prescribed for both elementary and senior curricula, whether and how it is taught is largely a matter of teacher preference.

A report by Lerner (2000) revealed that the quality of evolution instruction varies widely from state to state. A similar study of Canadian provinces would be very helpful. The Ministry of Education in PEI not long ago assured residents that evolution is not part of the curriculum because it is “too controversial” (Wiles, 2006). In other provinces where evolution is supposed to be taught coverage seems to depend on the teacher.

Improved teacher training and pedagogical support may help. In a study of Quebec pre-service elementary school teachers, many expressed concerns about their own understanding of evolution and about opposition from students’ parents (Asghar, Wiles, & Alters, 2007). While the majority of teachers in the study nevertheless indicated their intention to teach evolution, interviews revealed low levels of understanding. It is possible that teachers who are themselves confused about the topic may do more harm than good.

Berkman and Plutzer (2011) advocated imposing a required course on evolution for pre-service science teachers. The authors reported a greater tendency for teachers who had taken evolution courses to be strong advocates for evolution and recommended the course requirement on this basis. However, the direction of the effect isn't clear. Strong advocates for evolution may also be more likely to take a course on the topic.

While additional training for science teachers is clearly indicated, we should temper our expectations. Some researchers have reported a significant association between teachers' acceptance of evolution and prior exposure to biology and evolution (Rutledge & Mitchell, 2002). Others have found no association between previous training in biology and understanding (Bishop & Anderson, 1990; Nehm & Schonfeld, 2007). Additional pre-service training in evolution will not reliably solve the problem. Even if some improvement is achieved, we will still have a considerable number of teachers who do not understand the topic.

For this reason, it is imperative that teachers of evolution receive greater pedagogical guidance and support. The provision of prepared lesson plans and learning activities, videos and teaching materials may enable even teachers who lack a solid understanding of evolution to teach it effectively. Such resources may have an additional benefit of improving teachers' understanding of essential concepts.

Additional support and guidance in dealing with opposition from parents is also needed. Even teachers who accept evolution may adjust their handling of the topic in order to avoid conflict. According to the American National Survey of Biology Teachers, more than 20% of teachers of evolution are nervous about interactions with parents (Berkman & Plutzer, 2011). Dealing with opposition is part of teaching evolution and teachers need to be up for the task.

At the college level, there are unique obstacles to the effective teaching of evolution. University biology professors presumably have a solid understanding of evolution, but may have little or no knowlege of effective pedagogy. As Nelson (2008) states, “Although science faculties are experts at using data, they have often continued to teach ineffectively, even as the evidence that those ways are inferior has become stronger and stronger.”

Part of the problem may be that teaching is not the top priority at universities. Hoskins and Stevens note that “[t]enure and promotion are largely tied to “productivity”–a measure of grant dollars and published research–while teaching expertise rarely factors into the equation” (2008). University professors have other priorities and may have little time to devote to experimentation with new pedagogies.

The impediments to teaching evolution well at the college level differ from those at lower levels, but the solution may be much the same. Pedagogical resources and support would help professors to improve their teaching without detracting from their research endeavors. As a generator of scientific knowledge, research should play an important role in science education. As discussed earlier, an understanding of the nature of scientific knowledge and how it is generated is important to students’ learning and acceptance of evolution. Greater pedagogical support may help instructors to more effectively infuse their teaching with their research.

Additional guidance related to curriculum may also facilitate content reduction. Instructors at both college and pre-college levels may find it hard to know which topics to choose. Covering too much can overwhelm students and impair learning, but eliminating the wrong topics can also be problematic, especially at lower levels.

Content should not only be streamlined, but reduced in such a way as to coordinate teaching across grade levels. Providing greater curriculum guidance at pre-college levels would better ensure that instruction builds on what students have learned and reinforces basic concepts.

In short, evolution teachers need better training and more help. Teachers at all levels need to understand evolution, how to teach it effectively, and how to deal with opposition to evolution. Since comprehension is problematic for pre-college teachers and pedagogy problematic at the college level, strong resource support and curriculum guidance are essential.

## Conclusion

The vital role of evolution in understanding science is well established within the scientific community. What remains to be established is how to elevate acceptance and understanding in the public sphere. This literature review discussed a number of promising teaching strategies for improving both acceptance and understanding of evolution.

There appears to be no single teaching strategy or approach that will bring all students to full acceptance and understanding of evolution. Evolution is conceptually difficult and learners are complex. A good grasp of evolution doesn't ensure acceptance and acceptance doesn't require understanding. Students' attitudes and learning are influenced by a range of factors such as epistemology, sociocultural environment, reasoning skills, disposition and past experience. The complexity of these factors demands a synthesis of diverse strategies.

Conceptual change strategies and active learning methods are useful in promoting conceptual change. But, as Demastes and colleagues acknowledged, learners aren't entirely rational (Demastes, Good, & Peebles, 1996). Addressing non-rational influences on learning requires strategies with a different focus. Some of these can be borrowed from marketing and cognitive psychology. The power of affective and sensory appeals is evidenced by the success of marketing. Methods for harnessing this power to improve acceptance of evolution are a worthy focal point for future research efforts. Given the robust wealth of supporting evidence, evolution shouldn't need a fancy package, but it does - in this case for the benefit of the science consumer.

Conceptual change strategies, active learning methods, and efforts to engage both the senses and affect take more time per concept than lecture-style coverage, but make for more efficient learning. Reducing the content of biology courses may be one of the most important steps toward optimizing evolution education. Reducing content alone reduces cognitive interference and confusion, which may translate to improved student learning, retention, and attitude. It also opens the door to a wide range of pedagogies that better engage students and create more positive learning experiences.

Providing effective evolution instruction to students of diverse views and backgrounds is a challenge. It demands combinations of our best evidence-based strategies with both aesthetic and intellectual appeal and a streamlined, coordinated science curriculum that teaches fundamentals early. Given the right training and resource support, teachers can present evolution so that students not only learn it well and build on a solid foundation throughout their schooling, but enjoy the process.

**Synopsis**

*The Importance of an Early Start*

- Evolution is a fundamental and unifying concept that students need in order to make sense of much of science.
- Children's conceptions of human and animal origins develop early.
- The high prevalence of evolutionary misconceptions ensures early and regular exposure to alternative and incorrect views of evolution.
- Evolutionary misconceptions are exceptionally difficult to unlearn.
- And introduction to evolution at the high school level may be too late to help many students.

*An Overview of the Literature*

A number of general criticisms can be made of the evolution education literature. Studies tend to be small, short in duration, and highly variable in design and methodology. They infrequently include control groups, use a wide array of measurement instruments, and differ in their definition of terms. This makes comparison of the findings of different studies difficult. Statistical significance is often not determined or not reported. When it is reported, it is typically unclear as to the practical significance of the findings. If a 25% improvement in students' understanding brings the average posttest score to 60%, can we conclude that the intervention was successful?

*Strategies that emphasize cognitive factors*

These are strategies that appeal primarily to the intellect and reason. Examples include conceptual change strategies and teaching about the nature of science. Research shows that such strategies are an improvement over traditional methods, but may not be sufficient to achieve satisfactory levels of understanding.

*Strategies that emphasize pedagogical factors*

These are strategies that address instructional influences on learning. They may also directly or indirectly address a range of cognitive and non-cognitive factors. For example, a role-play exercise related to evolution may appeal to students' sense of fun, while improving comprehension of evolutionary ideas. Examples of these strategies include hands-on learning activities, paired problem-solving tasks, and inquiry-based lessons. As with the previous category, these strategies generally result in greater learning but may not achieve desired levels of comprehension.

*Quality over Quantity*

Research shows that students generally learn and retain more when less material is presented. There is a limit to how much students can learn in a given time frame and exceeding this limit is counterproductive. In content-heavy courses, as biology has been traditionally, a tendency to exceed students' limits may apply to the course, individual lectures and exercises, and textbooks.

Coordinated reduction of content has three main benefits:

- The reduction itself promotes deeper and more durable learning.
- The reduction allows for the replacement of relatively ineffective lecture-style methods with more engaging but time-consuming methods.
- Streamlining of the curriculum across grade levels and science courses will help to ensure that the most important concepts are taught and reinforced at appropriate intervals throughout the curriculum.

*Distributed practice and concept mapping.*

These generally require a reduction in content, but may promote deeper, conceptual learning and assist the instructor in identifying and addressing areas of confusion.

*Strategies with of non-cognitive focus*

These strategies primarily aim to improve attitude toward evolution through appeals to the senses and affect. Little empirical research has been done on these strategies in the context of evolution, but they hold promise. Research indicates that non-cognitive factors are important influences on students' learning and acceptance of evolution. Persuasive and aesthetic appeals have proven their utility in improving public opinion of everything from household products to political candidates. When it comes to improving attitude toward evolution, research in marketing and persuasion may have as much to offer as research in education.

*An aesthetic framework*

Students' classroom experience of evolution can be compared to the experience of objects of beauty and art in the sense that it may be multi-dimensional, with significant sensory, affective, and cognitive elements. With this in mind, instructors might aim to create a learning experience that is positive and meaningful on multiple levels, and artistic and creative approaches may be especially appropriate. Strategies that create positive aesthetic experience of evolution might involve music, like Baba Brinkman's "Rap Guide to Evolution" or theatrical activities like role-playing.

*Persuasion Tactics*

Principles of persuasion, such as likability, consistency, reciprocity, and authority may be applied in the context of evolution. For example, since people tend to be more readily persuaded by authorities, college professors might increase their impact by making their academic credentials and experience known. This could be done simply and unobtrusively by posting their curriculum vitae on their faculty website or discussing their background when they introduce themselves at the beginning of the course.

### *Challenges to Effective Teaching*

At pre-college levels, teachers' comprehension of evolution may be problematic, while at the college level instructors may lack knowledge of pedagogy. Though the circumstances of each educational setting are different, the solution may be much the same. Providing greater resources, pedagogical support and curriculum guidance may help teachers to teach evolution effectively even when knowledge of evolution or pedagogy is poor.

### *Key Points*

- There is a need for larger, longer, and better designed studies of strategies for teaching evolution.
- No single strategy is sufficient to achieve satisfactory levels of understanding and acceptance of evolution. Our best bet is an approach that combines a diverse array of strategies and addresses both cognitive and non-cognitive factors.
- The curriculum should be streamlined and coordinated across science courses and across grade levels.
- Instruction is likely to be most effective and beneficial to students if it is implemented early in the K-12 curriculum.

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