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Feature

Approaches to Biology Teaching and Learning: Understanding the Wrong Answers— Teaching toward Conceptual Change

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Underpinning science education reform movements in the last 20 years—at all levels and within all disciplines—is an explicit shift in the goals of science teaching from students simply creating a knowledge base of scientific facts to students developing deeper understandings of major concepts within a scientific discipline. For example, what use is a detailed working knowledge of the chemical reactions of the Krebs cycle without a deeper understanding of the relationship between these chemical reactions of cellular respiration and an organism's need to harvest energy from food? This emphasis on conceptual understanding in science education reform has guided the development of standards and permeates all major science education reform policy documents (American Association for the Advancement of Science, 1989, 1993, 2001; National Research Council, 1996). However, this transition to teaching toward deep conceptual understanding often sounds deceptively simple, when in reality it presents a host of significant challenges both in theory and in practice. Most importantly, few if any students come to the subject of biology in college, high school, or even middle-school classrooms without significant prior knowledge of the subject. It is no surprise, then, that students can never be considered blank slates, beginning with zero knowledge, awaiting the receipt of current scientific understanding. Yet, there is often little time invested by instructors in finding out in depth what students already know and, more specifically, what they do not know, what they are confused about, and how their preconceptions about the world do or do not fit with new information they are attempting to learn. In this feature, we explore key ideas associated with teaching for understanding, including the notion of conceptual change, the pivotal role of alternative conceptions, and practical implications these ideas have for teachers of science at all levels in designing learning experiences for students.

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MOVING FROM KNOWING FACTS TOWARD DEEP UNDERSTANDING THROUGH CONCEPTUAL CHANGE

> *Knowing the facts and doing well on tests of knowledge do not mean that we understand.*
> —Grant Wiggins and Jay McTighe (1998)

> *. . . an extensive research literature now documents that an ordinary degree of understanding is routinely missed in many, perhaps most students. It is reasonable to expect a college student to be able to apply in a new context a law of physics, or a proof of geometry, or the concept in history of which she has just demonstrated acceptable mastery in her class. If, when the circumstances of testing are slightly altered, the sought-after competence can no longer be documented, then understanding—in any reasonable sense of the term—has simply not been achieved.*
> —Howard Gardner (1991)

In comparative analyses of achievement in science education internationally, a major indictment of science education in the United States has been the emphasis on what we'll refer to here as "knowing," a familiarity with a broad range of ideas in science that get covered in a course or curriculum. This U.S. approach to education, which by many measures continues at all educational levels today, has been dubbed the "mile-wide, inch-deep" approach to science education, in that students have familiarity with or knowledge of a host of concepts, but the depth of their understanding of any given science concept and its connection to broader ideas and principles is extremely limited (National Center for Education Statistics, 2004). Although instructors at all levels routinely claim that students understand the material they have taught, the traditional multiple-choice and short-answer exams commonly used to gauge learning in most university classrooms rarely assess understanding, but rather knowledge. As quoted above from their book *Understanding by Design*, Grant Wiggins and Jay McTighe (1998) associate the term *knowing* with facts, memorization, and superficial

Table 1. Six facets of understanding from *Understanding by Design* (Wiggins and McTighe, 1998)

When one understands, then one...	Understanding enables answering of questions such as...
Can **explain**	Why is that so? What explains such events? How does this work? How can we prove it?
Can **interpret**	What does it mean? Why does it matter? What of it? How does it relate to me?
Can **apply**	How and where can we use this knowledge, skill, or process?
Has **perspective**	Is there adequate evidence? Is it reasonable? What are the strengths and weaknesses of the idea?
Can **empathize**	How does it seem to you? What do they see that I don't? What do I need to experience if I am to understand?
Has **self-knowledge**	What are the limits of my understanding? What are my blind spots?

knowledge, whereas the term *understanding* signifies a more complex, multidimensional integration of information into a learner's own conceptual framework. To elaborate on their definition of *understanding*, Wiggins and McTighe define six facets of understanding and its complexity as compared with knowledge, as shown in Table 1. To demonstrate understanding in this framework, students must not only possess rudimentary knowledge, but must also be able to **explain**, **interpret,** and **apply** that knowledge, as well as have **perspective** on the information, possess **self-knowledge** of their own understanding, and **empathize** with the understandings held by others.

Striving for student understanding as a result of instruction, above and beyond memorizing or knowing, requires that instructors take into account students' prior knowledge and support students in integrating new knowledge with their existing ideas. An explicit confrontation between preknowledge and new knowledge is the critical element in teaching toward understanding put forward by Posner and colleagues' *theory of conceptual change* (Posner *et al.,* 1982). Although conceptual change theory has been defined by science education researchers in a variety of terms, we define it here as *a learning process in which an existing conception (idea or belief about how the world works) held by a student is shifted and restructured, often away from an alternative or misconception and toward the dominant conception held by experts in a field* (Chi and Roscoe, 2002; DiSessa, 2002; Posner *et al.*, 1982). Learning that accompanies conceptual change stands in contrast to learning that is associated with the accrual of new ideas put forward by others. Such accumulative learning is generally not well integrated into students' frameworks for understanding and is thus not embraced by students in explaining the natural world on a daily basis (Wandersee *et al.*, 1994). Teaching toward conceptual change, however, requires that students consider new information in the context of their prior knowledge and their own worldviews, and often a confrontation between these existing and new ideas must occur and be resolved for understanding to be achieved.

Thus, in teaching toward understanding of major concepts in biology and achieving conceptual change for students, it is first necessary to understand students' prior knowledge, examine it, identify confusions, and then provide opportunities for old and new ideas to collide. In teaching toward conceptual change, it is counterproductive to simply cover more material and present an extensive list of new ideas without engaging students in their own metacognitive analysis. As advocated by many science education reform documents, inquiry-based science teaching may be seen as one strategy for teaching toward conceptual change, in that inquiry engages students in the exact same questioning of one's preconceptions and challenging of one's own knowledge that is characteristic of both conceptual change and scientific habits of mind. In this sense, working toward conceptual change is fundamentally what scientists do in laboratories every day, yet it is not generally the norm of what students are doing in classrooms. If instructors are to be successful in changing the way students think about how living things work, in the same way biologists continue to revolutionize our ideas about the same subject, then students and instructors together must access prior knowledge and uncover misunderstandings and incomplete understandings. Perhaps paradoxically, students' "wrong answers" may be our best tool in crafting learning experiences that will move them toward the "right" answers, at least "right" in the sense that they are better aligned with current scientific evidence.

THE ROLE OF MISCONCEPTIONS RESEARCH IN TEACHING TOWARD CONCEPTUAL CHANGE

> *To successfully engineer understanding, educators have to be able to describe what it looks like, how it manifests itself, and how apparent understanding (or misunderstanding) differs from genuine understanding.*
> —Grant Wiggins and Jay McTighe (1998)

A key strategy for gaining insight into the nature of understanding and how to facilitate conceptual change in a classroom is to investigate just the opposite, the nature of misunderstanding. Research pioneered almost 30 years ago by the late educational researcher Rosalind Driver laid the groundwork for literally hundreds of studies on students' understanding and lack of understanding of major concepts in many scientific disciplines. In her methodological approach to studying misunderstanding, Driver and her colleagues' key insight was to look in detail at individual students' explanations of scientific phenomena through in-depth interviews in which the students' ideas could be probed and prodded much more extensively than any paper–pencil assessment ever could (Driver, 1985; Driver and Easley, 1978). Through this approach using detailed student interviews, Driver revealed student conceptions that were surprising to most experts in the sciences, including conceptions about the essence of living things; the movement of the earth in space; the nature of light, water, and air; the relationship between heat and temperature; and the processes of chemical change, to name but a few (Driver, 1985; Driver *et al.*, 1994). Her insights shed light on what was conceptually

Table 2. Summary of assertions about alternative conceptions from the research literature (Wandersee *et al.*, 1994)

Assertion 1	Learners come to formal science instruction with a diverse set of alternative conceptions concerning natural objects and events.
Assertion 2	The alternative conceptions that learners bring to formal science instruction cut across age, ability, gender, and cultural boundaries.
Assertion 3	Alternative conceptions are tenacious and resistant to extinction by conventional teaching strategies.
Assertion 4	Alternative conceptions often parallel explanations of natural phenomena offered by previous generations of scientists and philosophers.
Assertion 5	Alternative conceptions have their origins in a diverse set of personal experiences, including direct observation and perception, peer culture, and language, as well as in teachers' explanations and instructional materials.
Assertion 6	Teachers often subscribe to the same alternative conceptions as their students.
Assertion 7	Learners' prior knowledge interacts with knowledge presented in formal instruction, resulting in a diverse set of unintended learning outcomes.
Assertion 8	Instructional approaches that facilitate conceptual change can be effective classroom tools.

difficult for science novices, something that most science experts are blind to because of their own familiarity with and ease of understanding of the subject matter. Driver's work established a new field of educational research that has been important since its inception, influencing both traditional educational researchers and scientists-cum-discipline-based science education researchers (Fensham, 2004). Growth in the area of conceptual research in science education over the last 20 years is apparent from analysis of the Students' and Teachers' Conceptions and Science Education (STCSE) database, a comprehensive bibliography of papers on studies of conceptions and misconceptions (Duit, 2004). Since its inception in 1985, the number of references in the STCSE database has grown from barely 700 to well over 6,000 (Duit, 2004; Wandersee *et al*., 1994).

In the realm of conceptions research in science education, studies focused on understanding and lack of understanding use a variety of nomenclatures to characterize students' ideas—misconceptions, alternative conceptions, and preconceptions, to name a few. While there are rationales behind the use of each, the term alternative conception will be used here to denote student understandings of scientific concepts that are not aligned with the current understanding of scientists. What, then, is the character of an alternative conception? In their review "Research on Alternative Conceptions in Science," Wandersee and colleagues (1994) provide a summary of assertions that have emerged from the research literature on alternative conceptions (Table 2).

Of these assertions, two merit particular comment. First, with regard to Assertion 3, that alternative conceptions are tenacious and resistant to extinction, there is more evidence for such resistance to changing physical science concepts (studied in greater detail) than life science concepts (Wandersee *et al.*, 1994). That said, it is striking to consider that there may be alternative conceptions that are prevalent not only among novices, but also among practitioners within a discipline who have not explicitly confronted their understanding of particularly challenging or counterintuitive phenomena. Insights into why some alternative conceptions may be more resistant to conceptual change than others await further research and will require significant advances. Second, in relation to the idea that alternative conceptions often mirror the evolution of scientific thought over time, as captured in Assertion 4, Duit and Treagust (2003) observed that change in science content knowledge in students may be closely linked to knowledge of the nature of science and of how major concepts and principles were developed or discovered. If one accepts this contention, then student-designed experiments and exposure to scientists' activities from a historical and social science perspective become important considerations when designing a course to foster change (Qian and Alvermann, 2000).

RESEARCH ON ALTERNATIVE CONCEPTIONS IN BIOLOGY

Although the studies initiated by Driver and her colleagues have produced an impressive literature on student alternative conceptions in general, the field of research into alternative conceptions in biology is still emerging as compared with efforts in the physical sciences (Duit, 2004). Analysis of the STCSE database described above reveals that more than four times as many publications are available in the realm of physics and chemistry as in biology (Duit, 2004; see Figure 1).

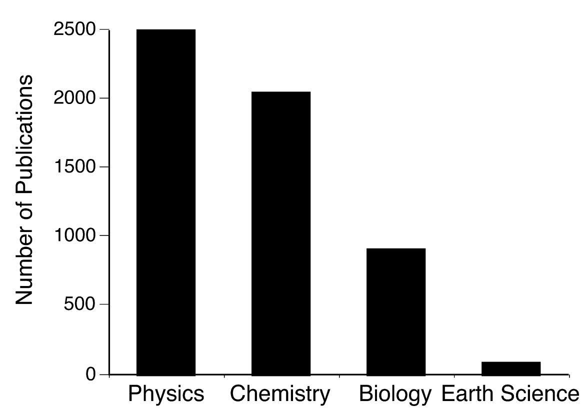

Figure 1. Analysis of citations (n = 6,314) from the STCSE database (Duit, 2004).

That said, the literature on alternative conceptions in the life sciences has expanded significantly over the last 20 years, with entries into the STCSE database increasing from approximately 100 to now over 900 (Duit, 2004; Wandersee *et al*., 1994). Wandersee and colleagues (1994) describe much of the literature as focused on four areas of life science: 1) concepts of life, 2) animals and plants, 3) the human body, and 4) continuity of living things, including reproduction, genetics, and evolution, with additional studies on a smattering of other life science topics. A detailed presentation of alternative conceptions within these areas goes beyond the scope of this feature. However, it is noteworthy that much of the literature available has investigated conceptions in very young students, addressing concepts of life, plants, and animals, including the pervasive challenge for young students to be able to consider plants to be alive and able to reproduce (Stavy and Wax, 1989). Only in the late 1980s and 1990s have researchers focused attention on alternative conceptions of students at higher cognitive levels and correspondingly investigated more biochemical concepts, such as cellular respiration, photosynthesis, cell division, and transcription and translation (e.g., Canal, 1999; Fisher, 1985; Griffard, 2001). Although topics such as cellular respiration and photosynthesis have been studied by multiple groups using multiple methodologies, student alternative conceptions for most major topics in biology remain poorly understood. And, perhaps most importantly, there has yet to be proposed a comprehensive framework for making sense of alternative conceptions identified in biology or for developing hypotheses about what makes some biological conceptions difficult for novices to understand.

APPLICATION OF CONCEPTUAL CHANGE THEORY TO THE CLASSROOM

Although conceptual change theory and research into student alternative conceptions may at first seem far removed from the practical considerations of teaching and learning in a science classroom, there are several concrete implications of these ideas that can guide instructional choices, especially given the chronic challenge of too much science to teach in too little time. In particular, teaching toward conceptual change can significantly influence 1) differentiation of instruction, namely choices about course goals and time spent on different topics; 2) the extent to which one engages students in identifying their own preconceptions as part of the learning process, using a variety of approaches; 3) using alternative conceptions to craft diagnostic "wrong answers" in assessment tools; and 4) designing assessments to detect conceptual change.

Differentiation of Instruction to Address the Common Alternative Conceptions

An understanding of the nature and basis of students' prior knowledge and alternative conceptions has immediate and compelling application to science instruction as well as science learning. This understanding could inform instructional choices, beginning with the establishment of goals for a course or curriculum. Clearly, little instructional clarification is needed in areas in which students' views overlap with those generally accepted by scientists. Instructional resources could thus be diverted from these areas toward an intentional addressing of the deep-seated, often tacit beliefs that students hold that are in varying degrees of disharmony with scientific ones. These prior beliefs warrant our focused instructional attention, because they serve as anchors for both assimilation and construction of new knowledge and thus may interfere with the learning of any new concepts introduced in the course or may result in unintended learning outcomes. As Wandersee *et al.* (1994) acknowledge, these alternate conceptions are present at all levels of formal instruction, including college, and cut across ability level, gender, and cultural boundaries, as well as age.

Engaging Students in Identifying Preconceptions as Essential to Instruction

According to the best-known model for conceptual change (Posner *et al*., 1982), if individuals are to change their ideas, they must first become dissatisfied with their existing conception or scheme and then proceed to judge a new conception to be intelligible (able to be related to some existing conceptual framework), plausible (having more explanatory power or providing solutions to problems), and fruitful (providing the potential for new insights and discoveries). In acknowledgment of this model, strategies collectively known as "conceptual change approaches" are generally (but cautiously) acknowledged as being more successful in this regard than traditional ones (Duit and Treagust, 1998, 2003; Wandersee *et al.,* 1994). In general, these approaches are constructivist in nature—that is, they explicitly connect the learner to his or her pre-existing conceptions (perhaps even intentionally invoke a misconception), then require him or her to actively explore and analyze evidence that builds on or counters the existing ideas. These approaches may also ask the learner to identify and use multiple resources, plan and carry out investigations, and apply the learned concepts (and skills) to new situations. In addition, knowledge of preconceptions naturally directs an instructor toward using learning experiences that confront students with evidence, historical experiments, or data-based problems that do not align with their prior conceptions. This instruction should be rich and varied enough to allow for multiple representations of ideas (e.g., a debate, an essay, and a poster construction centered around the same topical theme) that serve to underscore and integrate understanding (Smith *et al.,* 1993). Bleeth (1998), Martin and colleagues (2000), and others (Wandersee *et al.,* 1994) find the original conceptual change model limiting in that it has focused our attention overly much on the teacher's role in facilitating conceptual change, rather than the learner's role, as well as perhaps contributed to a pervasive notion that clings to the science education literature—that student conceptions are "problems" for the teacher to overcome by a carefully designed curriculum. They argue for inclusion of instructional approaches that engage students directly in their conceptual change process by inviting them to be metacognitive—to monitor, control, and reflect on their own learning. These approaches can be as simple as asking students to assign status constructs of plausibility and intelligibility to ideas they generate in the course of exploring and developing notions about major concepts (in Bleeth's study, about force and motion).

Table 3. Sample question from the CINS (Anderson *et al.*, 2002)

Question 4. In the finch population, what are the primary changes that occur gradually over time?

Multiple-choice answer option	Corresponding alternative conception
a. The traits of each finch within a population gradually change.	• Changes in a population occur through a gradual change in all members of a population.
b. The proportions of finches having different traits within a population change.	• *Correct Answer*: The unequal ability of individuals to survive and reproduce will lead to a gradual change in a population, with a proportion of individuals with favorable characteristics accumulating over generations.
c. Successful behaviors learned by finches are passed on to offspring.	• Learned behaviors are inherited.
d. Mutations occur to meet the needs of the finches as the environment changes.	• Mutations occur to meet the needs of the population.

USING ALTERNATIVE CONCEPTIONS TO DESIGN THE "WRONG" ANSWERS

Although the study of alternative conceptions in biology education is still an emerging discipline, common misconceptions held by students about several major biological principles have been studied enough that the findings can be employed in crafting assessment tools. This approach of using known alternative conceptions to design "wrong answers" is not a new idea, although its actual implementation in the design and validation of assessment tools in widespread use is limited and inconsistent (Tamir, 1971; Treagust, 1988). As an example of this approach, Anderson and colleagues (2002) have developed a Conceptual Inventory of Natural Selection (CINS) that employs known alternative conceptions as "wrong answers" in a multiple-choice assessment tool. Presenting actual scientific studies of natural selection, such as the work on the Galapagos finches and on Great Britain's peppered moth as scenarios, the CINS is a 20-item multiple-choice instrument. In the design of this assessment, the authors identify a scientific concept for assessment and also utilize known alternative conceptions. For example, in assessing students' understanding of the role of changes in populations over time in natural selection, Anderson and colleagues use the sample question shown in Table 3 from the CINS, which uses "wrong answers" as distracters.

The use of alternative conceptions as specifically chosen distracters in multiple-choice instruments is a promising avenue for developing cost-effective and efficiently gradable assessments that could diagnose the conceptual frameworks in use in a large cohort of students, for example in an introductory college course. With choices that are carefully crafted, these assessment tools have the added value that they could not only show which students got a correct answer, but also point instructors toward the most prevalent incorrect answer and likely reasons that students chose that "wrong answer." In addition, with the advent of classroom technologies such as "clicker systems," there is an increasing demand for such well-crafted assessment questions to provide real-time feedback to instructors during the course of interactive lectures (Wood, 2004).

Assessing for Conceptual Change

Finally, teaching toward conceptual change requires, more generally, ongoing and varied means of assessing student understanding in the course of instruction. As an example, Taber (2001) interviewed college students enrolled in a 16-week chemistry course. One of the interviewees used three different explanatory principles when probed for his understanding of chemical bonding in different contexts—he used each explanation many times in the course of the semester, or sometimes moved among all three (assigning explanatory power to each) in the course of a single interview. In other words, students may have multiple and layered explanations of a single concept, the complexity of which may not surface in response to an assessment strategy that requires only that students have memorized the "right answer." Perhaps for this reason, use of concept mapping (Novak and Gowin, 1984) at regular intervals is a popular method for documenting and understanding (as well as fostering) students' knowledge frameworks and how they may or may not grow in structural complexity as a course unfolds (Martin *et al.*, 2000; Odum and Kelly, 2001; Pearsall *et al.*, 1997; Sungur *et al.*, 2001).

In summary, teaching science for understanding is strongly informed by the ideas that have emerged from conceptual change theory in the educational research literature. In addition, explicitly uncovering and addressing students' prior and alternative conceptions in biology is essential if students are to integrate new ideas into existing conceptual frameworks about how the natural world works as a result of instruction. Importantly, the ideas of conceptual change are no longer relevant only in the theoretical realm, but also have practical implications for teachers of science at all levels in designing learning experiences for students and assessments to gauge student understanding. In fact, the usefulness of understanding the "wrong answers" in designing learning experiences and assessments adds urgency to the call for more extensive research on student conceptions of higher-order concepts in biology, as well as the development of a framework for making sense of the prevalent alternative conceptions that students harbor.

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