Application of Research on Learning to College Teaching: Ecological Examples

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Encouraged by improvements in the quality of science education since the 1960s, cognitive researchers are testing and applying theory-based research on learning in science classrooms. To introduce faculty to research on cognition and learning, I focus on metacognition: the awareness of one's own thinking, or "knowing what we know." I analyze two ecology texts and describe several active-learning strategies in the context of metacognitive theory. Information about pedagogy and its theoretical underpinnings may well help faculty improve their teaching practices.

Keywords: science education, ecology teaching, biology teaching, metacognition, learning

Forty years ago, Novak (1963) described science education as a "poor cousin" of the sciences, because it lacked theoretical models that could be tested in educational settings, and because it was intellectually isolated from disciplines such as psychology and behavior. The period since then has been marked by substantial improvements in education as a science. Ideas based in theory have been tested in classrooms, and the outcomes of this research have been applied to teaching practice (e.g., Chi et al. 1981, Clement 1982, Schoenfeld and Herrmann 1982, Lawson and Thompson 1988, Holliday 2003). In addition, what some call a "cognitive revolution" is taking place as neuroscientists, linguists, psychologists, and educators study the mind and integrate their ideas into new conceptions of how people learn (Bransford et al. 1999). Examples of how this learning research has influenced science teaching include the recognition that

- Experts' knowledge is integrated and organized around several essential scientific concepts, and, as a result, experts can apply their knowledge to new contexts instead of relying on memorization, as naive learners typically do (Chi et al. 1981, Dufresne et al. 1992, Wenk et al. 1997).

- Students come to a course with deeply held, often predictable misconceptions based on their understanding of the world; these ideas are so ingrained that they are often intractable to traditional teaching (Posner et al. 1982).

Research on learning has been applied to college biology instruction to some extent; examples include the use of computer models on topics such as Mendelian genetics (Jungck and Calley 1985, Jungck 1988) and of approaches that help students overcome misconceptions in introductory biology (Lawson and Thompson 1988, Ebert-May et al. 1997, Udovic et al. 2002) and physiology courses (Michael et al. 2002). These approaches to biological modeling and to common student misconceptions can certainly be used by biologists in different fields, but as an ecologist, I have observed that the application of cognitive research to college teaching appears to be less common in ecology teaching than in other scientific fields. To assess this hypothesis, I counted the number of articles on teaching physics, biology, chemistry, geology, and ecology that were published from 1997 to 2002 in *The Journal of Research in Science Teaching,* a good source for articles about cognition and learning. Over this period, most articles focused on teaching physics (33), followed by chemistry (21) and biology (19) (figure 1). In these three disciplines, about half the studies dealt with college teaching. In contrast, during the same period, 7 articles featured ecology teaching; most of these articles concerned environmental science, and all focused on grades K–12. These results are not surprising, given the number of basic physics, biology, and chemistry

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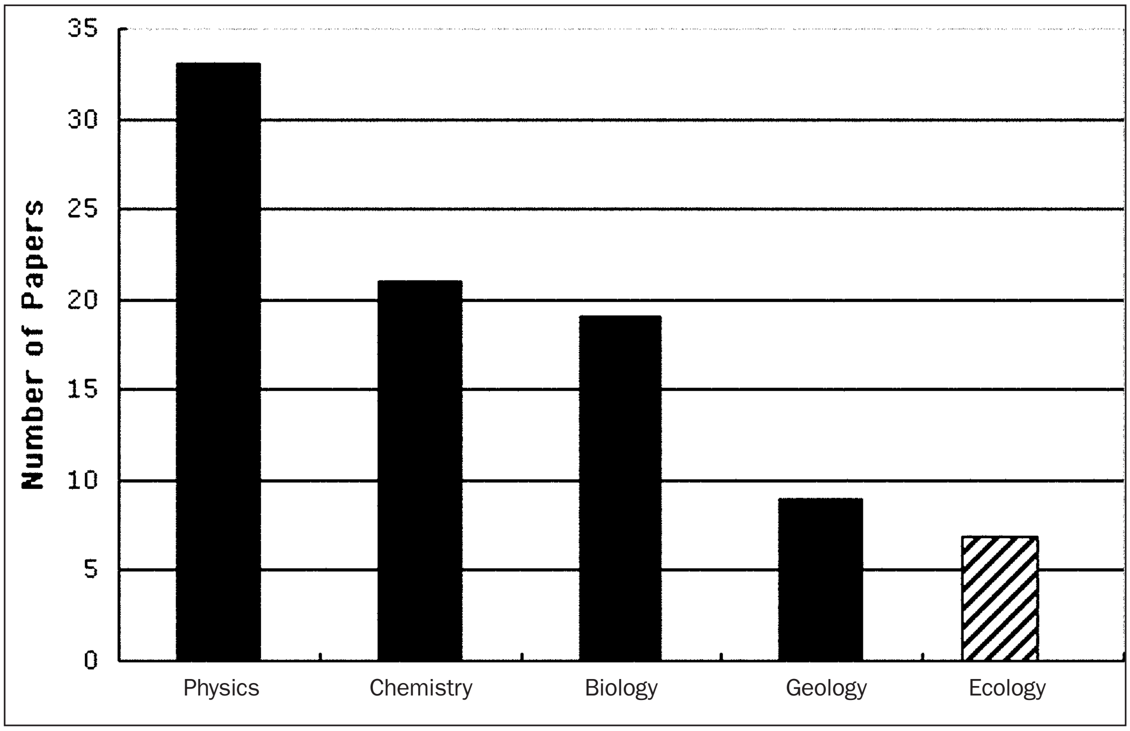

Figure 1. Articles published in **Journal of Research in Science Teaching** *from 1997 to 2002 in five scientific disciplines.*

courses taught nationwide, and given that ecology is taught as a subdiscipline of biology in introductory biology courses. However, to emphasize the point that the "cognitive revolution" (Bransford et al. 1999) can influence all disciplines at all levels, my focus here is on college ecology teaching.

This article is intended to introduce college faculty to theories about how people learn, with the ultimate purpose of improving college and university science teaching. Although the examples are ecological, they apply to science teaching in general. I first illustrate the concept of a learning theory with a learning strategy called *metacognition.* Next, I analyze two ecology texts as models of teaching in the context of metacognitive theory. Finally, I describe numerous student-active teaching approaches as they relate to metacognition.

Metacognition and implications for college science teaching

Metacognition is a problem-solving skill in which students use strategies to monitor their learning and control their attention (e.g., Flavell 1979, Kurfiss 1988). While reading, for example, students use this skill to summarize main points, analyze the meaning and implications of a text, and recognize when they fail to comprehend an idea, as opposed to simply trying to memorize the information. Metacognition has been described as knowing what is known and not known, using self-teaching skills, and employing student-centered as opposed to teacher-centered learning (box 1; Bransford et al. 1999).

Knowledge about metacognitive theory is useful because it can help teachers understand and better evaluate the effectiveness of various student-active approaches. For instance, cooperative group work, in which students work in small groups and talk about a problem or question, is at the center of many workshops and books on student-active learning. One likely reason why group work is an effective way to learn is that it can help students hone metacognitive skills (e.g., Hogan 1999). Students become more conscious of their own thinking when they talk to a partner to summarize a text or to address assigned questions, such as "How is this concept different from...?" (Kurfiss 1988; see examples later in this article). Although research on this subject is limited, several studies demonstrate that students who use metacognitive approaches in groups improve their scientific thinking (Schoenfeld and Herrmann 1982, Kramarski et al. 2002). This work is related to the ideas of social constructivists, who propose that knowledge is internally constructed and greatly influenced by social discourse (Steffe and Gale 1995).

Application of metacognitive learning theories to teaching has been especially fruitful in comparisons of how experts and novices learn physics (Larkin et al. 1980, Dufresne et al. 1992). These studies suggest that skill at solving new problems depends on organization of information within mental structures that facilitate information recall and application. Thus, metacognition may help students apply old knowledge in new situations because effective learners organize knowledge into "chunks" of stored patterns that they can readily call on

Box 1. Metacognition: Characteristics with special reference to reading

Definitions and processes

- Metacognition is awareness of one's own cognitive processes (ways of thinking and learning) or "knowing what we know."
- Metacognition involves three types of knowledge that help students learn better: knowledge about oneself, knowledge of the learning task, and knowledge about available strategies (Flavell 1979).
- "I am engaging in metacognition...if I notice that I am having more trouble learning A than learning B; if it strikes me that I should double-check C before accepting it as a fact..." (Flavell 1979).

Assumptions and implications

- The concept of metacognition focuses on the learner as being active and in control.
- Metacognitive skills are higher-order thinking skills that are transferable and generalizable from one discipline to another (Kurfiss 1988).

Related theories

- Constructivist learning: Information is organized around conceptual groupings of problems and questions; students connect insights with prior learning (Steffe and Gale 1995).
- Relative judgment stages: People move through predictable stages of thinking that define the degree to which they can trust their own judgment as opposed to relying on authorities for answers (Kitchener and King 1981).

Implications for reading

- Active-reading strategies that aid in comprehension include (a) clearly understanding why one is reading, (b) recognizing major content rather than trivia, (c) monitoring comprehension, and (d) taking action when comprehension is poor (Baker and Brown 1980).
- According to cognitive theories, people develop cognitive "chunks"—patterns of understanding—about the content and the structure of a text (Bransford et al. 1999). Therefore, comprehension is improved if the reader is aware of the organization of the text.

Source: Griffiths and Grant 1985, Lawson and Thompson 1988, Anderson et al. 1990, Bishop and Anderson 1990, Nazario et al. 2002.

(Bartlett 1932, Eylon and Linn 1988). These ideas offer new insight about what knowledge is and how effective learners use knowledge.

Application of metacognitive theory to two ecology texts

I have selected two ecology textbooks, Manuel Molles's *Ecology: Concepts and Applications* (1999) and Ivan Valiela's *Marine Ecological Processes* (1995), to illustrate the application of metacognition to student learning. This is not to imply that when writing their texts these authors intentionally used cognitive theories, including metacognitive ones (although they may have). My goal is to show the relationship between these books' effective teaching and this particular learning theory, so that readers will better understand how theoretical research on cognition can be used to improve teaching practice. Although most of the research linking metacognition to textbook use deals with reading instruction (e.g., Flower and Hayes 1980), I will point out related studies about learning science from textbooks.

For these two texts, I focus on considerations of scale in the study of patches. I selected this topic because the examination of systems at different scales is a relatively recent shift in perspective (Schneider 2001), with a host of ramifications for ecologists (the study of flux between systems, equilibrium distribution of patches across the landscape, and similarity of disturbances; Pickett et al. 1994). It is therefore a rich subject, and its recent development gives students the opportunity to appreciate how ecological perspectives change over time, which is a metacogntive skill.

Thinking about theories, not just with them. An important implication of metacognition for teaching is that students need to learn how to stand back from their subject matter and think *about* it, not simply what it is. This kind of reflective thinking, which is second nature to veteran researchers, means asking such questions as "Does that make sense? How is this idea different from that one? What evidence supports it?"

In the section of his book called "The Problem of Upscaling," Valiela helps students reflect on the challenges of extrapolating results from one scale to another (for example, from a mesocosm of several thousand liters to a lake). Despite its significance in ecology, most students have not thought about the problem of extrapolation. Valiela helps his readers appreciate its importance by asking them to "stand back"—to pause for a moment and think about what upscaling means. First he encourages them to consider the problem of extrapolating from a necessarily limited number of samples to larger units—for example, from 1-liter water samples to the subarctic Pacific. Next, after commenting that there are too few evaluations of upscaling, he gives three examples. (I quote from the third). Here Valiela asks his readers to pause and consider whether it is possible to extrapolate from a system that is about 5 kilometers (km) long to one that is more than 200 km: "We can measure processes such as nitrogen transport (from land through the estuary to the sea) in one system, say Waquoit Bay [a small embayment on Cape Cod] and wonder whether the measurements are applicable to the Chesapeake Bay. Note that the spatial dimensions in these two systems differ by three orders of magnitude" (Valiela 1995, p. 351).

Considering different points of view. Another way that scientists stand back is by looking at questions from different points of view. Because this way of thinking is second nature to them, faculty are often surprised to learn that many undergraduates, and even beginning graduate students, do not realize that scientists reflect on questions in this way. Students need models to help them develop the skill of comparative reflection (Kurfiss 1988), and Valiela models such thinking: *"There are two ways we could think about* comparing data from two such bays. First, we could think of coastal environments such as Waquoit Bay as representative of the myriad of estuaries...[I]n this case, we could multiply results from Waquoit Bay.... Second, we may ask...*can we simply apply results from one bay to another?* In this case, we need to find a way to make the comparisons in spite of the differences in scale" (Valiela 1995, p. 351; emphasis added). In this example, residence time (turnover) can be used as a scaling factor. Valiela illustrates how this is possible with a figure showing export of nitrogen as a function of residence time in a variety of estuaries.

Like Valiela, Molles asks his readers to reflect on questions throughout his text. He models this practice in the section titled "The Fractal Geometry of Landscapes" by posing a series of questions about measuring the length of coastlines. He also counters the misconception that there is only one answer to complex questions: "During the development of fractal geometry, Madelbrot asked a deceptively simple question: 'How long is the coast of Great Britain?'.... Think about this question. At first you might expect there to be only one, exact answer.... However, an estimate of the perimeter of a complex shape often depends on the size of the ruler you use" (Molles 1999, p. 412).

Molles demonstrates this "different points of view" type of thinking, in regard to scaling, by describing Bruce Milne's research on the ecological significance of ruler length (Molles 1999). Milne argues that because eagles are big and barnacles are small, their ecological "rulers" are different, and as a result, barnacles perceive the Alaskan coastline perimeter as nearly 20 times longer than eagles do. This is an accessible example of a difficult concept; one can imagine students visualizing the eagle–barnacle difference and saying, "Wow, I never thought of it that way," which is exactly what Molles is trying to get his readers to do.

The importance of modeling comparative, reflective thinking is supported by a large literature on epistemology (the nature of knowledge). Introductory-level college students have predictable beliefs about scientific knowledge that interfere with their ability to "think like a scientist" (Perry 1970, Wenk 2000). Such beliefs result from black–white and known-answer thinking (i.e., there is one right answer that some expert knows; Kitchener and King 1981). As a result, these students are not reflective and are often satisfied with limited analyses of viewpoints that fit their existing convictions; this is called "make-sense epistemology" (Kurfiss 1988). These ideas, based on theories about intellectual growth, help us understand why students need considerable help developing a mature epistemology about science.

Textbooks and their potential as metacognitive teaching tools

The forms of scientific reflection described above, such as using data to address questions from several viewpoints, are sophisticated cognitive skills. For this reason, teaching these ways of thinking requires considerable effort and planning. One aspect of that planning is simply the time needed to do it. Research on cognition indicates that learning how to juxtapose theory and evidence is difficult and takes place not all at once but instead many times over (Kuhn 1989). Dawson (2000) says it well: "[The evidence indicates] that becoming aware of the thinking processes, generating the ability to coordinate theory and evidence, and developing the capacity to recognize false theories is dependent on sufficient repetition of thinking tasks.... The task of teaching thinking skills is going to be slow, fitful, and with numerous reversals" (p. 84).

Given this need for repetition, textbooks have real potential to help students develop the ability to reflect on theories—the supporting evidence, implications, and so on—because authors can return to this instruction repeatedly with new examples. Authors can also remind students about earlier commentary. Perhaps more importantly, students can read and reread text, and this allows the slow "sinking in" process to happen more effectively compared with the rapid transfer of ideas that is typical of the classroom.

In addition, faculty who are familiar with metacognitive and other learning theories can help students use texts more effectively. For example, they can teach students the value of rereading and underlining, or of questioning their own understanding of concepts. Other examples include showing students how to interpret graphs (Bowen et al. 1999, D'Avanzo and Grant 2003) and helping them learn to write higher-order questions as a means of reviewing a chapter (Marbach-Ad and Sokolove 2000).

Metacognition and your teaching

Numerous commonly used student-active approaches are well supported by theory and research on metacognition. For faculty interested in exploring one or two of these ideas for the first time, and for those more experienced with these teaching tools, the cognitive-education theory outlined below should clarify why, how, and when to use them.

Skill: Learning how to ask questions. For each skill you might emphasize in a class session or a course, I give examples of several approaches you could use and their bases in education theory.

Approach: Students ask their own questions. Design your courses so that over the semester students often ask and answer their own questions. There are many ways to do this—for example, the teacher can require students to come to class with questions about a reading and can rely entirely on these questions during discussion or use them in exams.

At the highest level of metacognition, students ask and answer their own questions to increase comprehension. For this reason, transfer of control from the teacher to the learner is central to metacognitive development (Kurfiss 1988). Tactics such as using student questions on exams are powerful signals that students can take more control of their own learning.

There is some empirical evidence that teaching students how to question improves learning. For example, King (1992) concluded that college students who were taught self-questioning strategies had better long-term retention of information on exams compared with the control group not trained in asking questions. Self-questioning skills can also be used to measure students' intellectual development. By examining the quality of students' questions—their relevance, depth, and creativity—faculty can assess the cognitive growth of students in a course.

Approach: The teacher models the skill of asking questions. Good question asking is a sophisticated skill that teachers can model in class. For instance, a teacher might show students the types of questions to ask by reading several paragraphs aloud from the introduction of an article, posing questions he or she considers interesting, and explaining why.

Students who depend on teacher-generated inquiry are using less advanced metacognitive skills than those who generate questions themselves. However, during their intellectual development, students need help shaping high-quality questions. When teachers model good questioning skills, they act as surrogates for learners who are still practicing this skill (Kurfiss 1988).

Skill: Learning from other students.

Approach: Students explain solution strategies. Pose a question in class, and then ask a student with good study skills to verbally categorize the type of question and the sources of information the student would use to address it.

When given a problem, novice learners often do not know how to begin working on it. In contrast, more skilled learners are aware of the various sources of information available to them and are practiced at assessing which sources are most useful and relevant. These more advanced students can be very helpful to less-experienced students as they explain, in their own words, how they find and evaluate relevant information.

Approach: Students describe how they study. Ask students to describe to other students how they read a text and prepare for exams.

Less sophisticated learners know little about the variety of learning strategies they can use and often do not realize how much time others devote to learning tasks. Categories of strategies that aid in learning include rehearsal (e.g., highlighting text, using flash cards), elaboration (e.g., making connections by comparing two texts), organization (e.g., making diagrams of related course concepts), comprehension monitoring (e.g., pausing to focus one's attention or checking for comprehension), and resource management (e.g., scheduling homework time or working in a quiet setting) (Cross and Steadman 1996). It is important to add that students need also to understand the *purpose* of a particular strategy (e.g., underlining helps focus attention); several studies show that simply being taught such techniques without an explanation of why they are important does not necessarily aid learning (Segal et al. 1985).

Approach: Students use paired problem solving. Teachers can ask students to work in pairs on a set of problems. For this technique, one partner reads the problem and explains how he or she would work on it, while the other listens. The two then switch roles on the next problem. The listener is expected to check for accuracy and encourage thinking aloud. As with all group work approaches, faculty must help students understand their roles as teachers and learners—what they should do and why.

As Whimbery and Lochhead (1980) point out, "In contrast to playing golf, analyzing complex material is an activity which is generally done inside your head. This makes it somewhat difficult for a teacher to teach and a learner to learn.... There is one way to reduce this difficulty—to have people think aloud while they solve problems.... [In this way] the steps they take are open to view and their activities can be observed and communicated" (p. 78). The objective of paired problem solving is for students to learn to be both listeners and problem solvers, able to watch their own line of reasoning and to catch errors when working a problem with another student. Ultimately, students should be able to do the same while listening to a lecture.

Skill: Recognizing what is not known. A circular problem for novice learners is that they don't know what they don't know. In contrast, more experienced learners better appreciate what they already understand and what they don't yet know. In Plato's *Meno,* Socrates explained the conundrum of knowing what is not known: "You argue that man cannot inquire either about that which he knows, or about that which he does not know; for if he knows, he has no need to inquire; and if not, he cannot; for he does not know the very subject about which he is to inquire" (see *http://classics.mit.edu/Plato/meno.html).*

Approach: Problem-based learning. Problem-based learning (PBL) is a distinct approach to teaching that is characterized by the use of "real-world" problems as a means for students to learn content and problem-solving skills (McKeachie 2002). Students work cooperatively on problems that are "mysteries" designed to capture the students' interest and motivate them (Allen 1997, D'Avanzo 2000). A PBL problem can take weeks of course time or, in contrast, 20 minutes during a lecture. Although PBL has its roots in medical school, it can be used in all settings—in small and large enrollment classes and for K–12, undergraduate, graduate, and medical school students. It is especially designed to strengthen students' ability to recognize the relevant information they already have, and will need, to solve a problem.

As an example, Allen (1997) uses the "Geritol solution" problem in an introductory biology course at the University of Delaware. For this problem, students are given a brief description of John Martin's idea that seeding waters off Antarctica with iron might be one solution to global warming (Martin 1994). The dilemma for students is to explain how and why this proposal might work. Content goals for this problem are use of carbon dioxide in photosynthesis, the global carbon cycle in relation to atmospheric carbon dioxide and photosynthesis, the greenhouse effect and its causes, the role of pigments in photosynthesis, and marine food chains. In working though the Geritol solution, students synthesize concepts usually presented in different parts of a course, such as photosynthesis, marine food chains, and biogeochemistry.

To identify what is known and not known, after reading through the problem, students write down "what we know" (e.g., Martin suggests adding iron to Antarctic waters) and "what we need to know" (e.g., what are phytoplankton, and why would adding iron stimulate their growth?). In the next step, students divide up the work and then report back what they found. Students often work on PBL problems in class, with faculty providing reference texts with background information.

There are empirical studies on particular aspects of PBL instruction. For example, group work changes students' beliefs that good students solve problems in a few minutes and, therefore, their beliefs about how experienced learners work on problems (Schoenfeld and Herrmann 1982). Particularly relevant is Kramarski and colleagues' (2002) work on the interactive effects of metacognitive instruction (e.g., discussing such questions as "What's the question?" or "Does that make sense?") and cooperative learning on students' ability to solve mathematics problems. In this study, students were given either cooperative plus metacognitive instruction or only cooperative instruction. The students who were taught both learning skills outperformed the single-skill comparison group on both authentic (real-world) and traditional math tasks. Therefore, intentionally verbalizing specific metacognitive questions worked better than simply talking about the math problems.

Approach: "Teaching to" common misconceptions. Students come to class with background knowledge that may or may not be correct; when incorrect, this information is called a misconception (or a prior, alternative, or intuitive conception; Eylon and Linn 1988). Misconceptions are a special category of knowing–not knowing, in which students think they understand a concept, but their understanding is fundamentally incorrect (Eylon and Linn 1988). To address this obstacle to learning, teachers should carefully select questions for discussion and lecture that are specifically designed to elicit common misconceptions in the discipline (table 1). For instance, a classic misconception for many ecology students is the belief that the source of plant biomass is solid material in soil and not air, which they perceive as weightless (Ebert-May et al. 1997). To confront this misconception, the teacher can ask in class (especially in a medium-large one), "Where do the elements come from that make up most of the mass of trees?" Students should select one or more of three answers—(1) soil, (2) air, and (3) water—by holding up colored cards specific to each number (e.g., red for 1, green for 2, etc.; see D'Avanzo 2000, forthcoming Uno 2002). With this method, the teacher and students will quickly see what most students believe is the correct answer. Next, the teacher can instruct the students to convince their neighbor of their answer, and then ask for a revote. The degree of improvement in understanding will help

Table 1. Common misconceptions of college biology and ecology students.

Naive concept	Example or implication
Rooted plants immediately die when pulled from the earth.	Carrots out of the ground are "dead"; their cells do not metabolize.
Respiration equals breathing.	Plants and bacteria do not respire.
Air is "nothing."	Plants absorb all elements through roots.
Energy is not lost in trophic transfers.	Energy accumulates in food webs.
Adaptation equals evolution.	Adaptations are inherited.
Only animals have sex.	Plants do not reproduce sexually.
Biodiversity is "good."	Low-diversity systems must be polluted.
Competition drives ecology.	Mutualism and cooperation are not very important.
Only top-down regulation exists in communities.	Bottom-up regulation is not important.
Predators eat everything.	Predators cannot increase species diversity.
Plants are "weak."	Plants cannot defend themselves against herbivory.
Native peoples live in harmony with the land.	Human-caused environmental problems are recent.
Historically, extinction has been rare.	Over Earth's time, extinctions are mainly human-caused.
Nature is in balance.	Disturbance is bad.
Systems are stable.	Communities change little over time.

the teacher decide how much more time to spend on this topic. This iterative approach is called the learning cycle (Ebert-May et al. 1997).

Students' misconceptions are notoriously difficult to change, and numerous studies show that students come to class—and leave—with the same content misinformation even when the content is directly dealt with in class (Nazario et al. 2002). Clement (1982) found that even after a year of college physics, many students believe that a ball thrown into the air is affected by gravity on the way down but not on the way up. Anderson and colleagues (1990) found similar results in a study of college students' understanding of photosynthesis and respiration. Therefore, what students know (or think they know) is arguably the most important thing a teacher needs to be aware of when designing a course.

The special importance of metacognitive theory in university biology instruction

Today, perhaps more than ever before, colleges and universities are challenged to help students become critical, independent thinkers. For instance, the technical revolution is forcing graduate programs to reexamine the ever-narrowing training of their students, as industry demands researchers who can solve new problems and quickly realize the practical implications of their work (Smith and Tsang 1995). At the same time, even the best undergraduate programs are claiming that students are deficient in their ability to reason, use information, and distinguish between evidence and opinion (Moffat 1994).

Although no teaching philosophy or method is a panacea for educators, metacognitive approaches are especially useful now, because they cut to the heart of helping students think critically and flexibly. A particular goal of metacognitive teaching is for students to be aware of, active in, and in control of their own learning. In my own courses, knowledge about metacognition as applied to teaching has helped me understand how to put students in charge of their learning and why various approaches accomplish this goal.

One difficulty in informing college science faculty about teaching and learning lies in exposing them to pedagogical literature; this is especially true for articles and books on cognition and learning. From my experience giving workshops across the United States, I have found that science faculty know surprisingly little about pedagogy and especially about its theoretical underpinnings. In my judgment, this ignorance will limit the extensive science education reform efforts now under way in the United States. Therefore, I urge science professors to become familiar with modern ideas about teaching and learning.

For faculty looking for a simple way to start reading about research on learning, I suggest using the Internet. For instance, to learn more about metacognition and teaching, the search term "metacognition" can be used to find many useful sites. As I have shown with the metacognitive examples in this article, classroom research shows the effectiveness of teaching approaches that are based on learning theories. This research should help faculty to better understand the theoretical bases for methods that they are already using and to think about teaching in new and creative ways.

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