Implications of Learning Research for Teaching Science to Non-Science Majors

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Abstract

In this paper we discuss ways in which learning research has affected conceptualization of how people learn science, and then discuss the implications of these research findings for teaching science to non-science majors. Prior to the cognitive revolution, learning a complex process was conceived as demonstrating mastery through observable behaviors of all the sub-components of the complex process. Within the cognitive perspective learning a complex process is perceived as constructing knowledge, meaning, and sense-making by the learner. Hence, the shift has been from a view that learning is the acquisition of desired behaviors, to a view that learning is the construction of knowledge by the individual—construction that is mediated by the context of the learning, the social environment, and the prior knowledge of the learner. We begin with an overview from a cognitive perspective of several areas relevant to science teaching and learning, including the role of prior knowledge in learning, the nature of expertise, transfer of learning, metacognition, and assessment. We then consider instructional implications suggested by the science of learning and formulate nine instructional principles for successful science instruction. We conclude with suggestions for ways of structuring science courses for college non-science majors that reflect the instructional principles that we present.

I. Introduction

What we know about learning science should influence how we teach science, but we don't always find that science instruction is influenced greatly by the science of learning. Whether we are trying to teach science to elementary school children, or to science majors in college, or to music or language majors, many learning principles that have emerged from four decades of learning research can be used to make informed choices about instructional strategies. We begin by contrasting how teaching and learning based on the "cognitive revolution" contrasts with those based on "behaviorism." We then present insights about the learner based on cognitive research findings (Bransford, Brown, & Cocking, 1999; Mestre & Cocking, 2000, 2002) and offer several instructional principles based on the science or learning. We conclude by discussing the implications of the science of learning for teaching non-science majors in college, who may only take one or two science courses in their entire college careers.

The "cognitive revolution" started about forty years ago and signaled a major shift in the study of, and view of, learning. Prior to this (as well as concurrent with the emergence of the cognitive revolution) the behaviorist view of learning prevailed. In the behaviorist view learning consists of making connections between stimuli and responses. Evidence of learning is restricted to observable behaviors that are interpretable as "competence." The behaviorist approach to teaching a student a complex process (e.g., knowledge and procedures for solving a certain class of problems) consists of breaking up the process into component parts, teaching the student each component, then teaching the student how to string together the various components until, ultimately, the desired behavior is obtained. Learning is achieved once the student exhibits behavior consistent with behaviorally defined performance goals.

Absent from the behaviorist view is an interest in the cognitive mechanisms used by the individual to learn the complex process. This would seem to be an important consideration since knowledge about the cognitive mechanisms underlying learning might provide insights into how to shape instruction to make learning more efficient. Recent cognitive research, in fact, suggests that a complex process cannot be completely learned by decomposing and teaching individuals sub-processes without regard to the context within which the complex process will be performed. Knowing how the sub-processes interact within the context of performing the entire process is as important as knowing how to perform the individual sub-processes. In short, knowing the individual sub-processes does not "add up to" knowing the entire complex process (Resnick & Resnick, 1992). Also absent from the behaviorist approach is an interest in whether or not the process learned made sense to the individual. If the process learned conflicts with knowledge already possessed by the individual, then the individual either may not be able to accommodate in memory the process learned in any meaningful sense or will construct parallel, conflicting knowledge structures.

Hence, the focus of the behaviorist approach is the final manifestation of competent behavior by the learner, not whether the knowledge learned makes any sense to the learner, or whether the learner is able to use the acquired knowledge flexibly in novel contexts. This latter issue remains a problem for most approaches to learning. A behavioristic approach is quite successful at teaching many skills, for example, multiplication of two multi-digit numbers. Sequential mastery of progressively more complex procedures in the presence of feedback can be accomplished in limited domains. However, learning of procedures is quite different from developing conceptual understanding of a domain (Anderson, 1990).

In stark contrast, the term *learning* within cognitive science is synonymous with understanding, and the study of learning with understanding in cognitive science is often approached from a multidisciplinary perspective. Current views of learning include the idea that individuals construct knowledge (CPSE, 2003). Learners not only construct knowledge but the knowledge they already possess affects their ability to learn new knowledge. If new knowledge that we are trying to construct conflicts with previously constructed knowledge, the new knowledge will not make sense to us and may be constructed in a way that is not useful for flexible application (Anderson, 1987; Resnick, 1983, 1987; Schauble, 1990; von Glasersfeld, 1989, 1992). In contrast to behaviorism, prior knowledge and sense-making are very conspicuous in the constructivist view of learning.

Although the views of learning expressed by the cognitive revolution had their antecedents in earlier decades (Henry, 1947; Hunter, 1934; Twiss, 1929), it was not until the mid-50's that learning was widely viewed as an active and constructive process. The cognitive revolution that occurred in the 60's may have been the inevitable outgrowth of ideas and trends that were in place in the earlier part of the century, but the emergence of that revolution depended on the development of more adequate tools for measuring cognitive performance and on the invention of the computer that was then used as an analog for the human mind. In the early part of the 20th century, there were few instruments available for measuring intellectual performance. The measurement of learning was often confined to counting incidences of observable behavior that could be reliably measured. The onset of the cognitive revolution depended on the availability of more sophisticated measures of complex thinking and performance. In concert with the increased availability of better measurement tools, the development of the computer and its use as a model for human thinking provided a methodology for testing theories about complex mental performance.

The cognitive revolution made it possible to go beyond observable behavior to make inferences about the mental activities of learners, to distinguish among kinds of learners, and to provide a methodology for testing hypotheses about the mental processes implicated in complex thinking. The work begun by the cognitive revolution in the 1960's has developed into a rich science of learning in the early part of the 21st century.

II. Insights About the Learner from the Science of Learning

A. Constructivism and the Role of Prior Knowledge in Learning

Constructivism has important implications for learning and instruction. Constructing knowledge is a life-long, effortful process requiring significant mental engagement from the learner. The learner's mind is not a blank slate upon which new knowledge can be inscribed. S/he comes into a classroom with a brain already wired by previous experiences. Depending on the existing connections, even the same concrete experiences are perceived differently by different learners.

Moshman (1982) describes three types of constructivism that suggest that knowledge construction is directed from outside, from within, and from a combination of internal and external directions. Externally directed knowledge construction occurs as students construct a representation of the outside world. Information processing approaches to cognition allow for such construction, as learners must always construct their own representation from "given" knowledge or experiences. Knowledge construction that is internally driven requires the learner to utilize existing knowledge to transform, organize, and reorganize existing knowledge. Social constructivism describes knowledge construction that occurs as a result of both internal and external directions and is the result of the reciprocal interaction between individual knowledge construction and the external direction of the outside world. Vygotsky's theory of cognitive development is a good example of this latter type of constructivism (Bruning, Schraw, & Ronning, 1999). In all three approaches to constructivism, knowledge previously constructed by the learner will affect how s/he interprets what the teacher is attempting to teach.

A constructivist teacher probes the knowledge that learners have previously constructed in order to make appropriate instructional choices with respect to the content to be learned. The teacher needs to evaluate if sufficient prior knowledge is available and to evaluate whether this knowledge conflicts with the knowledge being taught. If it does, the teacher should guide learners in reconstructing knowledge. The teacher encourages knowledge construction or reconstruction on the part of the learner that is compatible with current scientific thought so that learners will store the knowledge in memory in a form that is optimal for long-term recall or for application in problem-solving contexts (Anderson, 1987; von Glasersfeld, 1989, 1992; Mestre, 1994; Resnick, 1983; Schauble, 1990). To ignore learners' pre-knowledge makes it highly probable that the message intended by the teacher will not be the message understood by the student. For example, when children who believe the Earth is flat are told that it is round, they may understand this to mean that it is round like a pancake, with people standing on top of the pancake (Vosniadou & Brewer, 1992). When subsequently told that the Earth is not round like a pancake, but rather round like a ball, children envision a ball with a pancake on top, upon which people could stand (after all, children reason, people would fall off if standing on the side of a ball!).

Another instructional implication of constructivism is that instructional strategies that facilitate the construction of knowledge should be favored over those that do not. This should not be interpreted to mean that we should abandon all lecturing and adopt only instructional strategies where students are actively engaged in their learning. Although the latter goal is certainly desirable, the former is an overreaction; research suggests that students can reap significant benefits from lectures, but only after they are primed to learn from them by previous activity-based preparation (Schwartz, Bransford and Sears, in press). Moshman's (1982) analysis also suggests that active learning is still possible when explanations are provided, although clearly a more social constructivist approach will result in greater learner activity. Instructional approaches where students are discussing science, doing science, teaching each other science, and offering problem solution strategies for evaluation by peers will facilitate the construction of science knowledge.

B. The Nature of Expertise: Organization and Application of Knowledge

Much of what is known about the acquisition of knowledge, its storage in memory, and its application to solving problems has come from studies of expertise and how it develops. Experts have extensive knowledge that they can apply flexibly to solve problems, and so cognitive scientists have focused on characterizing the development of expertise, as well as the organization, acquisition, retrieval, and application of experts' knowledge (see Ch. 2, Bransford, et al., 1999). One salient finding is that experts' knowledge is highly organized (Chi & Glaser, 1981; Glaser, 1992; Larkin, 1979; Mestre, 1991). The organization is hierarchical, with the top of the hierarchy containing the major principles/concepts of the domain. Ancillary concepts, related facts, equations, and other details occupy the middle to lower levels of the knowledge pyramid. Because of the highly organized nature of their knowledge, experts are able to access their knowledge quickly and efficiently. Ericcson and Kintsch (1994) described experts as being able to retrieve large amounts of information during problem solving because of the retrieval cues that were stored in long-term working memory that allowed for swift access to long term memory stores. Further, procedures for applying the major principles and concepts are closely linked to the principles, and retrieved with relatively little cognitive effort when a major principle is accessed in memory. Automation of these processes allows experts to focus their cognitive efforts on analyzing and solving problems, rather than on searching for the appropriate "tools" in memory needed to solve the problems (Anderson, 1990). Experts not only know more and can access their knowledge easier, but it is easier for them to learn more about their area of expertise, since new knowledge is integrated into the knowledge structure with the appropriate links to make recall and retrieval relatively easy.

Experts also approach problem solving differently from novices (Chi, Feltovich & Glaser, 1981). For example, when asked to categorize physics problems (without solving them) according to similarity of solution, experts categorize according to the major principles that can be applied to solve the problems (e.g., conservation of momentum), whereas novices categorize according to the superficial attributes of the problems (e.g., according the objects that appear on the problem statement, such as "pulleys" and "inclined planes"). This difference between attention to deep structural characteristics of problems rather than surface level characteristics distinguishes experts from novices. In approaching problems, experts focus on the major principle they would apply, the justification for why the principle can be applied to the problem, and a procedure for applying the principle. In contrast, novices jump immediately to the quantitative aspects of the solution and to discussing the equations they would apply to generate an answer. Experts spend more time in planning for problem solving, monitoring their problem-solving efforts, and regulating their use of strategies more than novices do.

Research on the nature of expertise indicates that expert performance involves the use of automated knowledge and procedures. One implication for instruction resulting from this is that the tacit knowledge that experts use to solve problems should be made explicit during instruction: students should actually practice applying this (no longer tacit but now explicit) knowledge while solving problems. In addition, students will need to practice the kind of metacognitive activity in which experts engage. Simply telling students how major ideas apply to problems will not lead to the construction of knowledge. Students need to engage actively in applying and thinking about how the big ideas are relevant for solving problems so that they become internalized as used purposely as problem solving tools. Possessing automated knowledge and procedures translates to being able to perform lower level activities without much thought, thereby freeing up more working memory for focusing on more complex activities.

C. Transfer of Learning

Transfer of learning (hereafter, “transfer”) in educational psychology is defined as the ability to apply knowledge or procedures learned in one context to new contexts. A distinction is commonly made between near and far transfer. The former consists of transfer from initial learning that is situated in a given setting to ones that are closely related. Far transfer refers both to the ability to use what was learned in one setting to a different one, as well as the ability to solve novel problems that share a common structure with the knowledge initially acquired. We note that there is an emerging third way to talk about transfer, one that meets a criterion of generativity (Carey & Spelke, 1994; Gelman & Williams, 1998). The idea here is that learners can, on their own, come up with novel instances or solutions. A number of overviews of issues in transfer can be found in Chapter 3 of the National Research Council report, *How people learn* (Bransford, et al., 1999), Brown and Campione (1998), and Brown, Bransford, Ferrara & Campione, (1983); for topics related to generativity see Carey and Spelke (1994) and Gelman and Williams (1998). Barnett and Ceci (2002) provide a literature review of the salient research on transfer, a taxonomy that can help organize the field, and directions for future study. The proceedings of a recent conference on transfer provide an overview of the field and a research agenda (Mestre, 2003). Finally, a forthcoming volume on transfer (Mestre, in press) offers new perspectives of transfer as a dynamic process, rather than viewing transfer simply as measuring whether or not some previously learned body of knowledge was successfully applied in a new setting.

A major, but often tacit, assumption in education is that the knowledge that students learn in school will transfer to situations and problems encountered outside of school. Yet, some classic studies of analogical transfer illustrate that transfer of relevant knowledge is not common from one situation to a second situation, where both situations are isomorphic (i.e., share the same structure) but differ in context (Gick & Holyoak, 1980; Hayes & Simon, 1977; Reed, Dempster, & Ettinger, 1985; Reed, Ernst, & Banerji, 1974). Only after receiving hints pointing out that two situations are isomorphic are students able to transfer relevant knowledge. More recently, Blanchette and Dunbar (2001) found that although students can spontaneously draw analogical inferences from one domain to another, they do not make enough inferences to support a fully-fledged transfer from one domain to another. If, as these studies suggest, the ability to apply knowledge flexibly is context-bound, then an important question for education is how to structure instruction to encourage transfer, short of the impossible task of covering in detail all the relevant contexts in which the knowledge being taught could be applied. What, then, is known about successful transfer and upon what does it depend?

Research suggests that several factors affect transfer. First, initial learning is necessary for transfer (Brown et al., 1983; Carey & Smith, 1993; Chi, 2000). Although this seems obvious, it is noteworthy that many failures to produce transfer have resulted from inadequate opportunities for students to learn effectively in the first place (e.g., see discussions by Brown, 1990; Klahr & Carver, 1988; Littlefield, Delclos, Lever, Clayton, Bransford, & Franks, 1988). Attention to initial learning is very important for transfer, especially when measures of transfer are used to evaluate the degree to which educational interventions are, or are not, "effective." Whereas rote learning does not tend to facilitate transfer, learning with understanding does (Bransford, Stein, Vye, Franks, Auble, Mezynski, & Perfetto, 1983; Mandler & Orlich, 1993; see also literature review in Barnett & Ceci, 2002). Thus, attempts to learn too many topics too quickly may hamper transfer since the learner may simply be memorizing isolated facts with little opportunity to organize the learned material in any meaningful fashion or to link it to related knowledge. Although previous learning can enhance transfer, it can also obstruct it (Bransford, et al., 1999; Gelman & Lucariello, 2002). For example, new learning may not proceed rapidly if knowledge that the learner possesses that is relevant to the new learning remains inactivated; on the other hand, when tasks share cognitive elements, transfer is facilitated (Glaser & Baxter, 1994; Singley & Anderson, 1989). This is true even for young children (Brown & Kane, 1988).

Context also plays a pivotal role in transfer. If the knowledge learned is too tightly bound to the context in which it was learned, transfer to superficially different contexts will be reduced significantly (Bjork & Richardson-Klavhen, 1989; Carraher, 1986; Eich, 1985; Lave, 1988; Mestre, 2002; Saxe, 1989). For example, students who learn to solve arithmetic progression problems can transfer the method they learned to solve similar physics problems involving velocity and distance, but students who learn to solve the physics problems first are unable to transfer the method to solve isomorphic arithmetic progression problems (Bassok & Holyoak, 1989). The transfer from physics to arithmetic was apparently blocked by embedding the physics equations within that specific context that then precluded students from seeing their applicability to another context. These findings also suggest that because students had more general knowledge about arithmetic/algebra, those who learned to solve the problems within a mathematical context first were able to screen out the content-specific details of the problem-solving procedures, whereas those who learned to solve the physics problems first appear to attribute the underlying physics context as crucial to the application of the problem-solving procedures, and hence were unable to apply those procedures to a math context. Further, the context within which quantities/variables in a problem are presented affects transfer, as a study by Bassok (1990) demonstrated; students exhibited spontaneous transfer from problems involving speed (meters per second) to problems involving price rate measured in dollars per minute, but not to problems involving salary rate measured in dollars per year. It appears that dollars per minute was interpreted by students as a continuous rate similar to meters per second, but dollars per year was interpreted more like a discrete quantity rather than a rate, and hence the lack of transfer.

In summary, research suggests that transfer is enhanced when the learner abstracts the deep principles underlying the knowledge being learned, and that abstraction is facilitated by opportunities to experience concepts and principles in multiple contexts. People's prior knowledge and experience in a domain affects their subsequent transfer, although sometimes the effect is initially negative because previously learned concepts and routines must be changed to deal with new settings (e.g. Barnett & Ceci, 2002; Bransford, et al., 1999; Bransford & Schwartz, 1999; Hartnett & Gelman, 1998; Singley & Anderson, 1989). In educational settings, this is frequently referred to as "the implementation dip" or the "J curve effect" (e.g., Fullan, 2001).

D. Metacognition: Self-Reflecting about Learning

Acquisition and transfer of knowledge can be improved, research suggests, by the use of metacognitive strategies and metacognitive awareness (Brown, 1975, 1980; Flavell, 1973). Metacognition includes the awareness of self as a learner (e.g., “I am good at mathematics”), knowledge of strategies for successful learning (e.g., “Drawing diagrams can aid understanding), and knowledge of when to apply strategies. Metacognitive strategies refer to strategies learners use to become more aware of themselves as learners, and include the ability to monitor one's understanding through self-regulation, to plan, monitor success, and correct errors when appropriate, and the ability to assess one's readiness for high level performance in the field one is studying (Bransford, et al., 1999). Reflecting about one's own learning is a major component of metacognition. This does not occur naturally in the science classroom, possibly due to lack of opportunity, because instructors do not emphasize its importance, and because it develops slowly. It is common to hear during a one-on-one tutorial session with a student the comment, "I am stuck on this problem," but when asked for more specificity about this condition of "stuckness," students are at a loss to describe what it is about the problem that has them stuck. Often they just repeat that they are just stuck and can't proceed. In this instance, the student has a metacognitive awareness of his/her level of understanding but is unable to bring conditional knowledge of learning strategies to bear on the task. Without knowledge of learning strategies and an ability to fit their use to the needs of the current situation, a student will be unable to make progress.

A second kind of metacognition is learning to reflect on the types of problem-solving strategies one has learned in the past. While the first type of meta-cognition discussed above is focused upon *oneself as a self-monitoring learner,* there is also a meta-level to understanding how to select problem-solving strategies. That is, thinking about strategies and how strategies are selected for problem-solving relates to students’ deeper understanding of the possibilities—it is thoughtful behavior geared toward selection and application. Kuhn (2000) has shown that understanding *why* a particular strategy is preferable over others plays a critical role in determining whether an available strategy will be used. Kuhn believes that such meta-level understanding plays a critical role in students’ sustaining their own learning management and problem-solving once the teacher and other supports (peers in groups) are no longer present. *What makes learning last* is the ability to monitor one’s thinking, including selecting from the knowledge base of strategies one has learned in the past. Failure to transfer is the major limitation of many educational approaches because they do not focus on deep understanding and applying strategies or on how to develop such knowledge in students (Kuhn, 2000).

Promoting the habit that students should reflect on their learning is also pivotal in science courses that deviate from the norms of pedagogical practice in these courses. Despite research evidence demonstrating that students learn best when actively engaged, the norm in most science courses, especially at the college level, is the lecture, in which most students are passively taking notes. Courses that attempt to get students to work collaboratively, or that try other techniques to engage them, are often viewed by students as being deviant from the norm, and they simply tolerate the course rather than becoming engaged in more active learning. In addition, students’ epistemological beliefs about the nature of science knowledge and how it might be acquired may be in conflict with their experiences in more activity-based courses (Hofer, 2000). In cases such as these, instructors should communicate with students why the course is being taught the way it is, and explain how research on learning suggests that the approach being used is superior to the teach-by-telling approach. Only by getting students to reflect on their learning, and by accruing evidence that in fact the "active learning" approach is making them learn more than a lecture approach, will students begin to buy into the approach and become active participants rather than simply tolerant participants. One possible way to engage students in reflecting on knowledge construction is journal writing (Etkina & Harper, 2002).

E. Assessment in the Service of Learning

Numerous studies involving a variety of disciplines and age groups (Gunstone & Mitchell, 1998, Hake, 1998) demonstrate that for many students a constructivist approach to teaching works better than a traditional one. However, a truly constructivist teaching philosophy requires assessment that is consistent with constructivist epistemology. If we want our students to construct and reflect on their knowledge, ask questions, and plan their own learning, we need to devise assessment strategies that evaluate and encourage these aspects of learning (Black and Wiliam, 1998, Glaser and Baxter, 1994; Zoller, Tsaparlis, Fatsow, & Lubezky, 1997). Formative assessments (assessment that helps guide instruction and learning) and summative assessments (assessment that evaluates student performance) that are used in science courses send messages to the students about what the instructor considers important, as well as provide feedback on whether these efforts are successful. Black and Wiliam showed that the learning gains from systematic attention to formative assessment followed by feedback are larger than most of those found for any other educational intervention (effect sizes of 0.4 to 0.7). Although such findings provide impressive evidence of classroom practices that improve learning, Black and Wiliam also report that such practices are currently underdeveloped in most classrooms.

What is needed is a way to help students understand the target concept or ability that they are expected to acquire and the criteria for good work relative to that concept or ability. Students also need to evaluate (metacognitively) their own efforts in light of the criteria. Finally, they need to share responsibility in taking action in light of the feedback. The quality of the feedback rather than its existence or absence is a central point. Research suggests that the feedback should be descriptive and criterion-based as opposed to numerical scoring or letter grades (Black & William, 1998). A “scoring rubric” containing criteria for the grading helps an instructor evaluate a student’s response and provide feedback. Students working individually or in groups can use the rubric to assess their own work. Self-assessment was found to be the most productive form of formative assessment. Formative assessment also provides timely feedback to the instructor and allows him/her to modify her/his instruction to better achieve the course goals.

Several instructional strategies have emerged for incorporating formative assessment strategies in both large and small college lectures. For example, classroom communication systems now allow instructors to conduct large lecture classes in a “workshop” format where students are given questions to work on in groups, then students submit their answers electronically. Following a histogram display of the class’ responses, a class-wide discussion can ensue where students present and evaluate the reasoning that led to different answers (Dufresne, Gerace, Leonard, Mestre & Wenk, 1996; Mazur, 1997; Mestre, Dufresne, Gerace & Leonard, 1997). Other “workshop style” approaches to instruction (Laws, 1991; McDermott,

1996) where students actively participate in their own learning with instructors continuously probing for understanding and serving as learning coaches have also proven effective in college science teaching.

One formative assessment approach that has shown promise for providing useful feedback to instructors is journal writing. Writing a journal encourages students to reflect on their learning (a metacognitive strategy), to put their thoughts into coherent sentences, and to communicate them to a reader (Eisen, 1996; Liss and Hanson, 1993; Moore, 1997; Moscovici & Gilmer, 1996). Yet, journal writing is not used in high school science courses and especially in college courses (Lester et al., 1997). Perhaps the major obstacle is that writing is time consuming for both students (to write) and instructors (to evaluate) (Moscovici & Gilmer, 1996).

An alternative to journal writing is the Weekly Report concept (Etkina, 2000, Etkina & Harper, 2002). A Weekly Report is a structured journal written by students each week, in which they answer three questions:

- What did I learn this week and how did I learn it?
- What remained unclear?
- If I were the professor, what questions would I ask my students to find out if they understood the material?

Weekly Reports provide benefits for both students and instructors. For the students, these benefits include developing metacognitive skills, such as reflecting upon their own learning process and upon their own particular knowledge state at a given moment. This tends to foster in a student a sense of responsibility for his/her own learning and move him/her away from being the traditional passive learner. The instructor gets the benefit of frequent feedback from students, finding out for all students (not just the vocal ones) which topics were learned thoroughly and which need some extra attention. Similar to portfolio assessment, Weekly Reports determine “what the student does know” as opposed to the tests that reveal what “the student does not know” (Slater, 1997, p.315).

Summative assessment in the sciences at the post-secondary level has tended to focus on problem solving. Although problem solving is crucial for doing science, there are many other skills that scientists possess and value that are not evaluated in students. Recent research within the domain of physics education suggests that it is possible to construct summative assessment strategies to probe skills that we value in experts. For example, research reviewed earlier (Chi et al., 1981) indicates that experts categorize problems on the basis of the underlying principle needed to solve the problem, whereas novices cue on problems’ surface features. Assessment tasks have been devised that probe whether students are cueing on surface features or underlying principles when categorizing problems (Hardiman, Dufresne & Mestre, 1989; Leonard, Dufresne & Mestre, 1996; Royer, Carlo, Dufresne & Mestre, 1996; Van Heuvelen, 1995). Further, Chi, Feltovich, and Glaser (1981) also demonstrated that when asked to state an approach they would use to solve specific problems, experts discuss the major principle they would apply, the justification for why the principle can be applied to the problem, and a procedure for applying the principle, whereas novices provide the equations they would manipulate. An assessment technique termed “strategy writing” (Leonard, Dufresne, & Mestre, 1996), where physics novices were asked to write strategies for solving problems that contained the three attributes contained in experts’ discussions of solutions (principle, justification, procedure), has shown promise both as an instructional tool and as a summative assessment tool. Finally, it is clear that most of the research in the sciences entails the posing of interesting problems. Recently "problem posing" has been used as a means of probing students' conceptual understanding, and ability to link and apply conceptual knowledge flexibly across problem contexts (Mestre, 2002).

III. Instructional Principles Implied by the Science of Learning

In this section we discuss instructional principles that are suggested by the review of research on learning from the previous section. We make nine recommendations for consideration:

1. Construction and Sense-Making of Science Knowledge Should Be Encouraged

Although teachers can facilitate learning, research evidence indicates that students must construct the understanding themselves. Science ideas are not parcels that can be sent by a teacher to a student (Reddy, 1979) in ready-to-use form. They are complex constructions that the teachers (or book authors) code into words or symbols and students then have to decode, process, and accommodate into useful understanding. The effort made by a student into decoding of the information and making sense of it cannot be substituted by even the most excellent presentation given by the teacher. Further, construction of knowledge is also a social enterprise. Just as scientists work collaboratively in research groups and discuss their findings at professional meetings and in refereed journal articles, students should have an opportunity to work collaboratively on science problems, to discuss the solutions with peers, to argue their point of view, and to ask questions and to challenge the views presented by others.

The process of construction of new knowledge by an individual student depends heavily on his/her prior experiences as well as knowledge derived from these experiences. A teacher should be aware of the knowledge state of her/his students (through questioning, pre-tests and other activities) and design the instruction to incorporate students' ideas, keeping in mind that these ideas are context dependent and often hard to change. Authoritatively telling students the correct scientific view does not produce good results since students first have to engage in the difficult process of reconstructing knowledge, a process that is effortful and time consuming. However, if incorporated into instruction through experimentations, discussions of every-day phenomena, or practical applications, students' ideas can serve as a productive foundation for new learning (Minstrell, 1999).

2. Hypothetico-Deductive Reasoning Should Be Encouraged

How do scientists come to believe in the different explanations of natural phenomena that students are asked to learn during their science classes? A scientific explanation serves not only to explain findings from experiments that scientists have already performed, but also to predict new phenomena that scientists have not observed before. It is its predictive power that distinguishes a scientific from a nonscientific explanation, even if the prediction does not match the experimental outcome. To make a prediction, scientists follow hypothetico-deductive reasoning: If "such and such" is correct, and we do "this and that," the following will happen.

Then they perform the experiment, compare the results with the prediction, and decide whether the explanation should be revised (Lawson, 2000).

Similar reasoning can be used by students to test their ideas. For example, many students believe that an object thrown upwards continues to carry the force of the throw, a force which they believe diminishes as the object ascends until eventually dying out when the object reaches its apex, at which point gravity “takes over” forcing the object to fall back to Earth. A constructivist approach would not simply inform students that this is a misconception, but rather encourage them to use hypothetico-deductive reasoning to test their hypothesis. Students might come up with the following reasoning: If an object continues to move in the direction of the force of the throw until the force dies out, then, if an object is thrown at an angle, it should move in a straight line in the direction of the throw, then stop when the force dies out, and then fall straight to the ground due to the pull of the Earth. With that predictive reasoning in mind, they then perform the experiment and observe that the object neither moves in a straight line if thrown at an angle, nor falls straight down after it reaches the highest point. This “failure” creates the need for a new idea to explain the actual observed motion of the object. Lawson and colleagues found that students who are able to perform hypothetico-deductive reasoning are better in acquiring new concepts (Lawson, Baker, DiDonato, Verdi, & Johnson, 1993).

3. Ample Opportunities Should Be Available for Learning “the Processes of Doing Science”

Students should construct meaning of science concepts in ways that make sense to them. However, it is possible for them, under a teacher’s guidance, to use processes similar to those used by scientists to construct knowledge (Etkina & Van Heuvelen, 2001, Etkina et. al, 2002b). These processes include: observing natural phenomena or laboratory events, classifying, recording, identifying patterns, devising models to explain patterns, testing the explanations in new experiments, and applying explanations to design simple devices or solve problems. Experimental testing of the students’ devised explanations means that students use the model that they constructed to explain the outcomes of one experiment to predict the outcomes of an undone experiment through hypothetico-deductive reasoning. An unsuccessful prediction means that the model should be revised. For example, students observe how a wet water spot dries out. Their explanation of the phenomenon is that the air “absorbs” water. It work well for many phenomena—blowing air makes hair or paint dry faster. How can the students find out whether this is a good explanation? Using hypothetico-deductive reasoning they can reason: “if the air is responsible for drying, then, if we remove the air, the wet spots should not dry.” They can then test this prediction using two equally wet pieces of paper that are placed inside and outside a vacuum jar. According to students’ hypothesis, the paper inside a vacuum jar should dry slower. However, the experiment shows that it dries faster. Thus students conclude: “when we did the experiment, the paper in the absence of air dried faster than in the presence of air, therefore the air does not absorb water.” Now the teacher can ask students whether they had similar experiences before. Many students will remember that in the mountains their lips become dry – supporting the testing experiment.

If similar processes are used throughout instruction, they will help students develop the explanations of phenomena consistent with scientists' current models for how the physical and biological worlds work. Classroom environments in which students are actively engaged and the instructor plays the role of learning coach (cooperative group learning, problem-based learning, Socratic dialogue, inquiry laboratory investigations, instead of cook-book labs, minilabs) are helpful in achieving this goal.

4. Ample Opportunities Should Be Provided for Students to Apply Their Knowledge Flexibly Across Multiple Contexts

In the physical sciences, it is usually the case that a handful of concepts can be applied to solve problems across a wide range of contexts. The transfer research literature suggests that when people acquire knowledge in one context they can seldom apply this knowledge to situations in related contexts that look superficially different from the original context, but which are related by the major idea that could be applied to solve or analyze them. The implication is that students should learn to apply major concepts in multiple contexts in order to make the knowledge “fluid.” Other sciences that have larger sets of concepts also require practice for students to relate the concepts to new and varied situations. Providing practice exercises across a variety of contexts and situations is what makes learning last—it is the way to promote *transfer of learning.* An example from physics is using vectors to solve problems. Students learn vectors at the very beginning of the typical introductory physics course and apply them immediately in kinematics while dealing with two-dimensional motion. Later they can use vectors to draw force diagrams when solving problems in dynamics, or to determine complex electric and magnetic fields in electromagnetism, or to explain interference patterns in optics. Frequent opportunities to apply vectors in different contexts is a necessary condition for mastering vectors. If teachers emphasize vectors at the beginning of a course but later do not provide ample opportunities for using them for problem solving, students will not be able to transfer the ability to apply vectors to problems in new contexts such as electricity, magnetism, or optics.

5. Qualitative Reasoning Based on Concepts Should Be Encouraged

Much of the knowledge that scientists possess is referred to as “tacit knowledge”; it is frequently used knowledge that is seldom made explicit or verbalized (e.g., when applying conservation of mechanical energy, one must make sure that there are no non-conservative forces doing work on the system). Working with principles tacitly is fine for experts, but tacit knowledge should be made explicit to novice learners so that they recognize it, learn it, and apply it. One way of making tacit knowledge explicit is by constructing qualitative arguments using the science that is being learned. By both constructing qualitative arguments and evaluating others' arguments, students can begin to appreciate the role of conceptual knowledge in “doing science.”

Qualitative reasoning is strongly enhanced by using multiple representations of the same process. For example while solving a problem of a final speed of a skier going downhill, students can draw a picture, a motion diagram, a force diagram, and an energy bar-chart (Van Heuvelen & Zou, 2001). All these representations should agree with each other. If the motion diagram shows that the skier is speeding up, the force diagram should have the resultant force pointed downhill and the energy bar chart should indicate that the kinetic energy of the skier at the bottom is higher than on top. If all representations do not agree with each other, then qualitative reasoning can be used to find the source of the disagreement. In chemistry, students can solve ideal gas problems by drawing a picture of the container with the gas in the initial and final states; or a graph of the process plotted against coordinates P(ressure) and V(olume), V(olume) and T(emperature), and P and T; or a picture of the molecules inside the container in different states accompanied by a verbal description of the microscopic explanation of the situation. These representations should also agree with each other. For example, suppose students are discussing what happens to the pressure of air in a syringe after its volume decreased by 2/3 by moving a plunger. They could start by drawing molecules inside the syringe before and after the plunger was moved and consider whether the molecules get closer together or farther apart as the volume allowed for them decreases, whether they push the walls of the syringe more or less often, and whether the overall effect is to increase or decrease the pressure. In short, we should keep in mind that mathematics is just one of the languages that science uses, and that other more qualitative forms of reasoning from representations such as verbal, pictorial, and graphical, are equally useful.

6. Helping Students Organize Content Knowledge According to Some Hierarchy Should Be a Priority

To learn lots of things about a topic, to recall that knowledge efficiently, and to apply it flexibly across different contexts requires a highly organized *mental* framework. A hierarchical organization—in which the major principles and concepts are near the top of the hierarchy, and ancillary ideas, facts and formulas occupy the lower levels of the hierarchy but are linked to related knowledge within the hierarchy—is needed if a learner is to achieve a high level of proficiency in a field. There are several ways to incorporate this idea into instruction. One is to ask students to list major concepts that they need to solve a particular problem without actually solving the problem. Another one is use hierarchical charts during instruction to show students the place of newly learned knowledge in the knowledge system. Later, the same chart can be used to decide what concept is needed for a particular problem (Van Heuvelen, 1995).

7. Metacognitive Strategies Should Be Taught so that Students Learn How to Learn

Students should learn to predict not only their ability to perform tasks but also to assess their current levels of mastery and understanding. Helping students to be self-reflective about their own learning will assist them in *learning how to learn* more efficiently. For example, when stuck trying to solve a problem, asking oneself questions such as the following can be helpful in deciding on a course of action:

> "What am I missing or what do I need to know to make progress here?"
> "In what ways is this problem similar to others I've seen before?"
> "Am I stuck because of a lack of knowledge or because of an inability to identify or implement some procedure for applying a principle or concept?"

After solving a problem, reflecting on the solution by asking questions such as the following will help a student monitor her/his mastery and understanding of the topics being learned:

> "What did I learn that was new by solving this problem?"
> "What were the major ideas that were applied and what is their order of importance?";
> "Why did the instructor give this particular problem to us?"
> "Am I able to pose a problem in an entirely different context that can be solved with the same approach?"

Teachers should implement these self-reflective strategies in problem-solving exercises by having students engage in post-problem solving summaries that address these kinds of questions. In this way, students' own learning progress becomes more evident to them.

Students should also reflect on the process of construction of knowledge. They will be greatly aided in this reflection if they become accustomed to answering such questions as:

> "What did you learn today?"
> "How did you learn it?"
> "Why do you believe in this particular idea, law?"
> "How is what we learned today connected to what we learned yesterday?"

With reflection and the answers to these kinds of questions, students can engage in independent learning and develop scientifically appropriate epistemologies.

Encouraging students' questions also promotes metacognition. For a scientist, asking a good question is often more important than getting an answer. In the practice of schooling these values are reversed. Students seldom are rewarded for asking a good question, especially since most questions come from the teacher. A classroom atmosphere where profound questions are rewarded the same way as profound answers would resemble the practice of science more closely.

8. Formative Assessment Should Be Used Frequently to Monitor Students' Understanding and to Help Tailor Instruction to Meet Students' Needs

Assessment provides feedback to both students and instructors, but the kind of assessment that would be useful in guiding teaching may be quite different from the kind of assessment used to determine students' competence at the end of instruction. Formative assessment helps students realize what they don't understand (an online monitoring of the learner's progress, so to speak). Formative assessment also helps teachers craft tailored instructional strategies to help students achieve necessary and appropriate understanding in a particular learning exercise. It is important that students get assessed on a regular basis, not only on mastering problem solving but also on an ability to collect and analyze data, devise hypotheses explaining patterns in the data, test hypotheses experimentally, reason qualitatively, and represent a concept in multiple ways. Other examples of formative assessment tasks can be problem design, evaluation of other students' work, and review of the section in their textbook.

As we noted earlier, self-assessment is the most productive variation of formative assessment (Black and Wiliam, 1998). To be successful at these tasks students need to be provided with guidelines and examples of work at different levels of competence, or so-called “scoring rubrics,” which greatly facilitate self-assessment for students.

9. Motivation is an Important Factor

Young children are curious about the world surrounding them. They constantly ask “why” questions. Bugs, rainbows, magnets fascinate them. What happens to all this interest when it is time for them to learn physics or chemistry? Many factors contribute to the decline in enthusiasm and motivation (e.g., social comparison, experiences of failure, etc). One important contributing factor to low levels of motivation is the lack of connection between what they are learning in a classroom and their everyday experiences. For example, problems encountered in physics class deal with the frictionless situations, which are unrealizable in the “real” world; in chemistry class chemical reactions occur with materials that students never see or use in day-to-day experience. Thus, to students, there often seems to be no practical benefit of learning “school science” except to get a good grade. The focus on performance and grades can be deleterious. Performance-oriented learners use strategies that are less productive than strategies of interest-oriented learners (Thorkildsen & Nicholls, 1998).

The question is: How can we maintain students’ curiosity and motivation? A study by S. Nolen (2003) showed that “students in science classrooms where teachers were perceived to endorse independent thinking and to desire deep understanding of science concepts had higher achievement and greater satisfaction with their science learning” (p. 363). Thus, motivation can be increased by: encouraging students’ questions, focusing on the explanations of phenomena, promoting collaboration of students, and making students’ grades independent of each other (no curving). A natural way to achieve these goals is to turn the students into young scientists at every step of their learning (see using the processes of science above) and help them develop the ownership of ideas and the application of the ideas to real world problems. The experience of autonomy that is necessitated by the student as investigative scientist is strongly associated with motivational gains (Stipek, 2002). For school students, for example, teachers can use homework assignments to encourage students to identify phenomena at their homes similar to those learned in class. For example, when students are learning about acids and bases they can use red cabbage juice as an indicator to find out which substances used in cooking at home are basic and which are acidic. Then they can test their saliva and decide of there is a relationship between the food taste and the properties of the saliva.

IV. Application of the Instructional Principles to Teaching Science to Non-Majors in Post-Secondary Education

Cognitive research findings led to our list of instructional principles discussed in the previous section. The question now becomes: How can these principles be applied to teaching college students who are not majoring in science and who may have only one exposure to a science course? This section addresses this question in broad strokes.

First, it is important to keep in mind that non-science majors take science courses in college largely because they need to satisfy their liberal arts requirements, and not necessarily because they have a passionate interest in learning science. Obviously, we cannot count on them learning scientific principles deeply, being able to solve complex problems or remember the content of the course years later. However, it is possible, even with only one science course, to help them appreciate the process of science and the similarities and differences between scientific reasoning and every-day reasoning. We can help them develop critical thinking skills that they can use later in many aspects of civic life.

Perhaps most important with this audience is the issue of motivation. Developing science courses for non-science majors around timely topics that may already have had a direct impact on students' lives (e.g., by having friends and/or family members touched by the topic, or by having an interest in the topic due to its national and international importance) is a good place to start. Topics that meet these criteria include HIV/AIDS, genetics, or cancer. These are topics about which students already possess prior knowledge and opinions, and so could serve as "motivation pumps."

Equally important to remember from the learning principles discussed earlier is that teaching a science course to non-science majors via traditional information-transmission methods, no matter how interested students are in the topic, is likely to cause students to become disengaged and to lose interest. One activity to consider very early on in the course, which falls under the category of encouraging knowledge construction and sense-making, is to have students consider the preconceptions about the topic that they and their fellow students bring to the class. What do they think they know about HIV and about how AIDS is transmitted?; Why do they think is the reason behind the fact that some cancers are curable and others are not?; What do they think about genetic engineering, about cloning, about stem-cell research—is it a good thing or a bad thing, and under what circumstances? This will serve not only to demonstrate to students that there are others in the class who have similar views/concerns, but that there is a diversity of views in the class, and that they cannot all be scientifically correct—which leads naturally to discussions about the process of doing science (experimentation, evidence-based model building, hypothetico-deductive reasoning). How might scientists go about addressing the questions and issues brought up by students? This could by itself prove to be another very fruitful discussion very early on in the course.

As the course progresses and science knowledge and methods are presented, the instructor should consider how students are prioritizing and organizing the knowledge—are students distinguishing between the "big ideas" and the ancillary concepts and facts? And, equally important, are they able to use the knowledge they are learning to construct coherent qualitative arguments? To do so, the instructor could employ formative assessment techniques, such as using a classroom communication system (Dufresne, et al., 1996) to probe students' understanding by having them work in small groups on qualitative questions during class and then polling them anonymously to gauge progress; this allows the instructor to tailor instruction to meet students' needs (Wenk, Dufresne, Gerace, Leonard, & Mestre, 1997). Concept maps (Novak, 1998) can also prove valuable tools for both formative and summative assessments, and reveal how students' organize their knowledge.

Activities that allow students to develop, and appreciate the value of, metacognitive strategies are also desirable for helping them become life-long learners. For example, during their argumentation and problem solving, getting students in the habit of considering questions such as the following can be very productive:

> "Did I bring all relevant knowledge I possess to bear on the issue/question?"
> "Did I overreach in what/how I applied knowledge to arrive at a conclusion?",
> "What do I need to know to make progress in constructing an argument or in trying to frame an answer to this question?"

Developing metacognitive strategies can be also accomplished in cooperative learning groups with different members of the group taking on different roles. One student could construct an argument, with another student elaborating on the argument, and the third student acting as skeptic, raising the types of questions outlined above.

Learning knowledge in ways that afford flexible application across multiple contexts is difficult, and even more daunting to teach well. Activities/assignments whereby students are given novel contexts and asked to consider which of the major ideas they learned in the course could be brought to bear to reason about the context not only help diversify the application of knowledge for students but also cue the instructor on whether students' knowledge is too tightly coupled to specific contexts. These types of activities would work best in the latter stages of the course once most of the course content has been presented and students have a wide range of ideas to apply. Instructors may even want to consider a capstone activity/assignment where students are asked to apply what they learned about the process of science to a topic totally outside the course. For example, can the scientific method be applied to decide which among several political candidates running for public office might be best on some specific issue (e.g., helping the environment)? Another example that stays closer to science is to have students consider whale evolution and discuss some paleontologists' theory that whales (cetaceans) evolved 50 million years ago from hoofed hyena-like land mammals (mesonychids) in a process that lasted between 8-15 million years.

The range of possible activities is enormous, but the need to stimulate the flexible application of learning across multiple contexts is a challenge for all who would seek to strengthen the learning of science majors and non-science majors alike.

VI. Conclusions

Ideas supportive of constructivist theory have been around a long time. But it is only in recent years that there is a consensus on the view of learning described in this paper. The principles of learning that we presented—and parallel ones clearly articulated by APA's *Learner Centered Principles* (CPSE, 2003) and by scholars in the emerging science of learning (Bransford et al., 1999)—portray the learner as active, engaged, motivated and self-regulated, deploying metacognitive skill in solving problems, and utilizing prior knowledge and experience to make sense of new experiences. This portrayal of the general learner is consistent with the vision of students learning science that has been advanced by the National Research Council (1996) and AAAS (1989). In this paper, we have discussed examples of instruction in science that support such learning. We have also provided specific suggestions for how to apply these principles to science instruction for non-science majors in college. Much remains to be done in helping science teachers implement these principles.

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