Improving Engineering and Technology Education by Applying What is Known About How People Learn

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Abstract

The scientific knowledge base on learning has only recently become well-enough established that educators can use this knowledge to design educational experiences that will result in learning. This paper summarizes the current scientific knowledge on learning from the book *How People Learn* and applies these learning principles to engineering and technology education. Methods to improve teaching and help professors learn these new teaching methods are delineated.

Ideally, engineering and technology education would be built on a foundation of principles based on how people learn. Although information of how people learn has been available (e.g., US Dept. of Education, 1986; McKeachie, 1999; Wankat and Oreovicz, 1993), the information has been fragmentary and some of the "knowledge" has not been reproducible. In addition, most professors are not aware of the scientific knowledge base and design their courses on a "seat of the pants" feeling for what improves learning. The purpose of this paper is to provide interested engineering and technology professors with a succinct review of the current state of knowledge on how people learn and suggestions on how to apply this information to improve technical courses.

Researchers have been slowly unraveling the mystery of how people learn. The best source for non-experts on the current state of these scientific developments is the National Academy Press book, *How People Learn: Brain, Mind, Experience, and School: Expanded Edition*, published in 2000. [This book will be cited as HPL]. Although the main focus of this book is on the learning of students in K-12, the principles can be applied to higher education. The application of this knowledge to improve technical higher education is based on my teaching experience and study of engineering education. HPL is also fascinating reading for anyone with small children or grandchildren.

Constructivism

The key learning principle is "*People construct new knowledge and understanding based on what they already know and believe*." (HPL, p. 10). This principle is the basis for the educational theory known as constructivism. It has a number of ramifications that we will explore throughout this paper.

First, since learning is done by the students not by the professor, learning is always based on what the students know and believe. Thus, the students' *preconceptions* are very important for learning (HPL, pp.14-15). Preconceptions are always present and they will affect the knowledge structure. If the preconceptions are correct or close to correct, they can be very helpful in learning. For example, when I teach sophomore chemical engineering students the principles of mass balances in CHE 205, I first discuss balancing their checkbook. This balance includes the inlet, outlet and accumulation terms in the general mass balance. Then I discuss the government balancing its budget since this allows inclusion of generation terms (printing and burning money). Finally, the general mass balance expression,

$$\text{In} - \text{Out} + \text{Generation} = \text{Accumulation} \qquad (1)$$

is presented and discussed. Although half a semester is needed to consider all of the ramifications of mass balances, this approach results in an excellent start since most of the students construct an initial knowledge structure within their brains that is essentially correct.

Incorrect preconceptions can obstruct learning (HPL, pp. 14-15, 70). Unless the incorrect preconceptions are engaged and forcefully corrected, they can remain embedded at the base of the new knowledge structures built by the students. Students can then often do surface calculations correctly, but incorrectly understand the basics of the material and cannot apply what they are supposed to know to unusual situations. As an illustration, consider teaching students the fundamentals of Newtonian physics and the expression $F=ma$. American students all drive automobiles and they "know" that if you want to go a constant speed you must keep pushing on the accelerator. Thus, their inherent picture (which is rarely described explicitly) is that $v = (\text{constant})\, F$. Unless this misconception is explicitly discussed, they still believe that a constant force will provide a constant speed even though they will use $F=ma$ in calculations.

There are a number of ways that professors can determine what the students' preconceptions are. Professors who have taught a course several times will often have a good idea of what these are. Reflect on the mistakes the students made in the past to determine likely preconceptions. Give the students a pretest with questions that can be answered without resorting to calculations. For example, will a car going down a hill speed up, slow down or stay at constant speed? Or, ask the students to explain phenomena (e.g., explain how you can have frost on your car windshield when you know the ambient temperature never got to the freezing temperature.) Then ask students who get the answer wrong to explain their answers. Repeat this procedure throughout the course.

Building a knowledge structure is an *active process* requiring a number of steps (HPL, p. 16). First, students need to be motivated to spend the time and energy necessary to build or rebuild a knowledge structure. We will return to student motivation later. Second, students need to learn correct facts. If the facts don't fit into the students' current knowledge structures, the easiest things to do are discard the facts, memorize the facts as unconnected items, or change the facts so that they will fit the knowledge structure. For many students facts must be very compelling to induce them to change their knowledge structures. The most compelling facts are those that are obtained from direct experience by the students. This is why beginning physics classes often use frictionless air tables to provide data and experience. Once the students analyze the data, the professor can discuss the role of friction. After the facts have been learned, students need to organize these facts using a conceptual framework. An organizing lecture can be very helpful to the students at this point, but note that the lecture is after the students have grappled with facts that require them to rethink their knowledge structure. Finally, the framework of the knowledge structure needs to be organized in a way that helps the students retrieve and apply the knowledge. Students will initially organize facts based on the way things look (e.g., are there wheels or pulleys involved). Since the most effective knowledge structures are based on fundamental principles, it will take the students some time to organize their knowledge into an effective knowledge structure.

As an example of active, hands-on learning let's again consider sophomores learning mass balances. Probably the most difficult concept is the principle of recycle. Recycle is difficult because few students have experienced it in their lives and few have an accurate conception of what will happen. I have found that it is very effective to have about ten students role-play molecules being processed by a reactor and separator with recycle. Every third student who enters the reactor is given a card that signifies he or she has reacted. The separator lets these students exit the process. The separator recycles students who have not reacted to the entrance of the reactor. The students quickly realize that the recycle causes the flow inside the reactor to be much greater than the entering and leaving flows. If the presentation is done entirely with equations and arm waving, many students never have this insight.

To learn efficiently, people must use *metacognition* to control their own processes of learning (HPL, pp. 15-19, 97-98). Metacognition involves monitoring one's own learning. This is a skill that people do naturally, but like most natural skills it can be strengthened and improved with practice. Metacognition starts with sense making. It is very difficult to incorporate anything that does not make sense into our knowledge structure. We can memorize this material but we can't understand it if it doesn't make sense. Next, students need to learn to self-assess their learning. Is the material understood correctly? Different strategies can be used to learn material. People usually develop their strategies on successes, not failures. Finally, metacognition requires reflection. Students need to ask themselves which learning approaches worked and which did not work.

As an example of metacognition consider Phil the fisherman trying to catch fish. He arrives at the stream or lake and selects a lure. Usually he tries whatever lure worked last time he fished under similar conditions. If this lure doesn't work he tries different lures and different approaches. Incorporating everything he knows about fishing, he tries to make sense of the data (lack of fish). Different strategies can be tried based on past experience, but it is difficult to develop a strategy for today until the first fish is caught. It is important to remain motivated despite the lack of success. With the first glimmer of success he can start developing a theory of what will catch fish today. He reflects on what worked and what didn't work both while fishing and afterwards. A short break for a snack or lunch is often very useful because it provides an opportunity to reflect and perhaps develop a more effective strategy. Students trying unsuccessfully to learn technical content are often in the position of a fisherman who is not catching fish. They start to lose their motivation and can't see any successful strategy for learning. Thus, it is important to start by building on what students already know so that they will have some successes that can be used for building learning strategies.

Teacher's Role in Helping Students Learn.

Although professors cannot learn for the students, they can structure their courses to make learning easier. First, teachers need to understand the students' preconceptions. If students have incorrect preconceptions that will undermine their construction of correct knowledge structures, teachers need to make the students aware of their misconceptions. This is more difficult than it sounds. Just telling them the correct approach (e.g., F=ma) will probably result in a superficial overlay of this information on top of their misconceptions instead of a restructuring of their previous knowledge structure. Before lectures or readings on the correct conceptions, have the students grapple with real data. This is most effective if the students generate the data themselves (e.g., with a frictionless table for F=ma or in a role play for recycle). If direct hands-on generation of data is not possible, give them raw data. Have the students individually or in small groups try to organize the data and make sense of it.

After the students have grappled with the specific data, provide organizing material or an organizing mini-lecture. The organizing mini-lecture can go from the specific data to a general organizing principle and then apply this general principle to specific situations. That is, inductive reasoning followed by deductive reasoning. Plan to have coverage in depth plus at least one example (HPL, p. 20). Note that there is a place for lectures in active learning, but it is after the students have tried to organize specific information on their own.

Then the students need *deliberate practice* that includes feedback on performance and a chance to revise (HPL, pp. 58-59, 177-178). Deliberate practice involves doing one skill at a time followed by immediate feedback and revision of that one skill before moving on to the next skill. For example, if the students were learning problem solving skills, they would first be exposed to one of the models for problem solving (e.g., Wankat and Oreovicz, 1993, chapter 5). Then they would be given a problem to solve either in groups or individually and would be told to work their way through the problems one step at a time. After each step, they would receive feedback and be told to revise their response before going to the next step. The steps might look like this:

1. Define problem and sketch – feedback – revise.
2. Explore possible approaches – feedback – revise.
3. Plan, write down or derive equations to use and do solution symbolically – feedback – revise.
4. Do calculations – feedback – revise.
5. Check results – feedback – revise.
6. Generalize what was learned about the content and about problem solving – feedback – revise.

Deliberate practice is obviously time consuming, but it is a very effective way to learn complex skills such as problem solving. Students could reach a professional level of performance in 25 days for a task that normally took two years without deliberate practice (HPL, pp. 58-59).

In addition to deliberate practice in class, students need assignments to work on outside of class. They need feedback for this practice, and they need to be strongly encouraged to revise their assignment based on the feedback. "Strongly encouraged" means that the revised assignment needs to be handed in and graded. Revisions should require students to think about and apply the corrections, not just copy the professor's red ink. Suppose that one of your learning objectives is to have students learn how to improve their writing. If a student makes the same error throughout his or her paper, correct the first couple of errors and require him or her to find and correct similar mistakes in the remainder of the document.

Metacognitive skills should be integrated with the teaching of the subject. Ask the students to explain orally or in writing why they are doing a procedure, have them self-assess their progress and their answers, and require them to reflect on their learning procedures. Since many students are not in the habit of automatically reflecting, ask them, "What was the most important thing you learned?" and, "How did you learn it?"

The ideal classroom environment should be (HPL, pp. 133-149):

> **Learner centered.** Pay attention to the students' preconceptions, skills and attitudes.
> **Knowledge centered.** Pay attention to the subject, student understanding and mastery.
> **Assessment centered.** Use frequent formative assessment by both the teacher and the students to monitor progress. Formative assessment gives the students rapid feedback. To be effective in getting students past erroneous preconceptions, feedback of experimental events occurring in real time must be fast – that is within 20 to 30 minutes (HPL, pp. 179-180). Provide time for revisions.
> **Community centered.** The context of learning is important. Combined argumentation plus cooperation enhances cognitive development.

How do you find time to do this? First, control *content tyranny* (Wankat, 2002, pp. 66-68). Content tyranny occurs when you let the need to cover content control the teaching and learning processes in the course. Delegate some of the learning responsibility to the students. Don't try to cover everything in class. Require the students to learn some of the material on their own. If material is well explained in the textbook or a web site, this is easy; otherwise, you may need to prepare some handouts or a web page. To encourage more of your students to learn on their own, you will need learning objectives, homework assignments and test questions on this material. After you have followed through and asked the questions on a test, most of the students will believe you are serious. Another proven approach is to use longer class periods such as recitations or studio classes where the students work in groups on problems. These longer class periods provide time for deliberate practice and allow for immediate feedback. On-line computer tutorials can also be used to provide deliberate practice and immediate feedback.

Since most professors have not taught using active learning with attention to learning principles in the past, we will need to be creative in developing effective approaches. Resources on cooperative learning (Johnson et al, 1991, 1998; Wankat, 2002, pp. 94-104; Wankat and Oreovicz, 1993, pp. 121-128) and Problem-Based Learning (Wankat, 2002, pp. 104-112; Woods, 1994) can help teachers learn these techniques. Even better is to take one of the excellent teaching workshops offered within the engineering education community.

Transfer

Transfer is applying content learned in one area to help learn knowledge and application skills faster in a new area (HPL, pp. 55-77). Because technology is changing very rapidly engineering and technology graduates will have to be proficient at transfer. An engineering or technology education cannot teach the students everything they will need to know for a forty-year career. In order to be able to transfer knowledge to new areas when they graduate, our students need practice, feedback and more practice while they are students.

Teachers can improve transfer by first making sure that students clearly understand the basic material. There will be no transfer of knowledge if the original material was not learned. Second, the teacher can show the potential for transfer while teaching the original material by mentioning other applications of the knowledge, using multiple contexts for examples, and doing what-if problems. Use transfer in your teaching by telling students that since there are similarities with what they have studied previously, you will spend significantly less time on the new material. This gives the students a chance to practice transfer.

Providing explicit coaching and asking the students leading questions (e.g., "What have you studied that looks like this?), will improve transfer. Coaching can take advantage of a psychological principle known as the *zone of proximal development (ZPD)* (HPL, p. 80). Although students may initially have a very narrow range of skills that they can do without help, they have a much broader range of skills (the ZPD) that they can do successfully with coaching. Success within the ZPD will increase the range of skills that they can successfully apply without help. For example, beginning students may be overwhelmed by a case study if they are expected to do it without help. If they are guided through it, perhaps with a guided design technique (e.g., Wankat and Oreovicz, 1993, pp. 176-178), they can be successful and in the process learn how to do case studies.

Transfer of knowledge from what they have learned about mass balances can help students learn energy balances in the second half of the CHE 205 course discussed earlier. First, I make sure they learn mass balances well. During the mass balance section I note that the general balance equation (1) is valid for balancing other items. The teaching sequence to use transfer then proceeds in steps. Start the energy balance section by having the students grapple with writing an energy balance before any lectures on the topic. With coaching they should be able to write equation (1). Then have the students write, with coaching, terms (in words) that are similar to the mass balance terms in the energy balance. After this, start the lecture by filling in the terms in the word form of the energy balance that are not analogous to terms in the mass balance. Finally, when the students understand what the energy balance does, put each term into equation form. Of course, continue to do examples, require deliberate practice, assign homework and provide feedback.

Memory

Memory is important for applications and problem solving (HPL, pp. 31-43). People have the ability to store 7 ± 2 items in their short-term memories – which represents their working memory. Since experts cluster or "chunk" items, they may seem to store a lot more than nine items in memory. Consider the twelve-digit number,

189819411812

As twelve unrelated digits this is too many to remember in short term memory. However, *if* one recognizes the pattern that the digits are formed into years,

1898 1941 1812

then it is relatively easy to remember three years (particularly since they are years the United States went to war). The trick is to *help students recognize significant patterns*. Start by coaching – explicitly show them the patterns. Have them practice and then move on to expecting them to find the patterns without coaching.

Experts also use long-term memory differently than novices. Experts organize their knowledge based on core concepts and guiding principles. Novices tend to use shallow or surface similarities to classify ideas. For example, experts would classify mechanics problems based on the principles that can be used to solve them. Novices are likely to classify them by surface similarities such as problems with pulleys. Experts also "conditionalize" their knowledge – that is they store the rules for when the knowledge is likely to be useful (HPL, p. 43). Novices don't do this. Professors can help by providing hierarchies for remembering information and by giving the students the specific conditions of use.

Professors need to strike a balance between providing students practice of known methods and having them choose which method to use. When students are first learning to use various techniques, they are more likely to be successful if they are explicitly told what technique to use (e.g., Use the method in section 5.4.3.). But in order to conditionalize their knowledge they must also have practice in selecting the appropriate method (e.g., Solve these four problems from chapter 5, or solve these four mechanics problems).

Student Motivation

The vast majority of engineering and technology students are very intelligent. The secret ingredient that separates one student from another is motivation. Motivation affects:

- The time students will spend learning content.
- The probability that assignments will be completed on time.
- Students' attendance rates.
- Students' attention while in class.
- The amount they learn.
- Their course grades
- Their satisfaction with the course.
- Their evaluations of the course and of the professor.

Yes, motivated students rate their courses and professors higher than unmotivated students (Wankat and Oreovicz, 1993, p. 315). Students are likely to be more motivated if they have a learning orientation as compared to a performance orientation ("I just want the grade") (HPL, p. 61). Professors can help a little bit by emphasizing learning instead of grades and by making sure that there is sufficient time for homework and exams so that learning-oriented students are not penalized (it takes more time to reason through a problem than to write down memorized formulas).

There are techniques that professors can use in class to help motivate some students (HPL, pp. 61-62). Since sharing and a perception of contributing to a group are motivating, cooperative small groups will motivate many students. Most students, particularly those in engineering and technology, are motivated by useful material. Make sure that the students are aware of how the material can be used. Challenges and deadlines from outside groups or outside experts are motivating. Since many students believe that outside experts and practicing engineers will tell them the important stuff, they listen more closely and are more likely to do what they are told. This phenomenon can be used in case studies and design by occasionally bringing in an outside expert. Students are motivated by understanding, success, and a sense of efficacy (a sense that one can do and accomplish things). Make sure that almost everyone can understand and be successful at the beginning of each new section. The initial use of impossibly difficult problems to "challenge the smart students" can backfire by demotivating almost everyone else. Outside of the normal course, most students will be motivated by co-op or internship assignments, tutoring others and undergraduate research.

Unfortunately, it is often easier to demotivate students than to motivate them. Avoid such demotivating actions as ignoring, blaming or belittling students (Wankat, 2002, pp. 137-139).

Improving Teaching

Excellent teachers are made, not born. Although professors need to know the content to teach well, content experts are not automatically good teachers (HPL, pp. 241-242). On the other hand, general teaching skills are not sufficient either (HPL, 157). Excellent teachers have a combination of content knowledge, general pedagogical skills and *pedagogical content knowledge* for their discipline.

Pedagogical content knowledge is a detailed understanding of how to teach the specific content of the discipline (HPL, pp. 155-157). Thus, professors need to know the following:

- A hierarchical organization of knowledge that will aid recall and application for problem solving.
- The student's existing knowledge and misconceptions, and how to tap into this pre-existing knowledge and combat the pre-existing misconceptions.
- Typical student difficulties and misconceptions during the learning process.
- Learning strategies that students may use or should be taught.
- How to assess student progress.
- Appropriate metacognitive strategies and how to weave them into the content.
- Appropriate use of technology (ranging from blackboards to overhead projectors to computers and the Internet) to satisfy learning principles (see HPL, pp. 206-227 for more information).

My detailed examples in this paper are mainly from my own teaching in chemical engineering since this is the area where I have pedagogical content knowledge.

Most engineering and technology professors have obtained their detailed content knowledge through years of study as an undergraduate, graduate student, and often a reflective practicing engineer. The vast majority of these professors understand their content at a level that is more than adequate. Since few engineering and technology professors are trained in general and discipline-specific pedagogy, this is where problems arise.

Although they are not experienced, young professors do have several advantages. They are closer in age to their students and usually remember what it was like to be a student. They are enthusiastic and haven't been burned by the tricks college students will try. They are usually very up-to-date with the latest content knowledge and computer techniques. Their challenge is to rapidly learn general and content-specific pedagogy.

Ideally, graduate students who wanted to teach would all serve as teaching assistants, take a course in pedagogy, and have a supervised teaching internship (Wankat, 2002, 196-202). Since this rarely happens, new professors need to supplement their education. Take courses or workshops on teaching, particularly one of the excellent workshops offered within the engineering education community. The National Effective Teaching Workshop that is held in conjunction with the annual meeting of the American Society for Engineering Education (ASEE) has earned a reputation for producing award winning teachers. Talk to experienced professors at your school about both general and content-specific pedagogy. Take the risk and ask an experienced (and friendly) professor to sit in on your class and provide feedback. Then try revising what you do. Independent reading in ASEE *PRISM*, the *Journal of Engineering Education*, the *Journal of SMET Education*, and other educational journals is helpful. The books referenced in this article are also good sources and they contain a large number of references in the educational literature. Then experiment and practice; obtain feedback from students, other professors, or teaching development experts; reflect on what worked and didn't work; revise your methods and try again.

More experienced professors need to work to retain their enthusiasm and avoid boredom and burnout. One of the best ways to do this is to keep trying new things to keep at least a moderate level of challenge in teaching. The new challenges can be either new courses or the use of new teaching techniques including the use of technology. Jumpstart your learning about these new techniques by attending a teaching workshop, an ASEE meeting, or the sessions devoted to education by your professional society. Talking to colleagues interested in education can provide the motivation needed to start changing your teaching.

One of the best ways to maintain rapport with students is to become a student again. Being a student reminds professors what it is like to not "know" and to struggle to learn. Plus a little humility will not hurt most professors' teaching. The topic you study is not critical, and there are advantages of learning outside your discipline. Learning in a new discipline is much closer to the experience of your students, it can be a more effective antidote to boredom than studying within your discipline, and you are more likely to observe the teacher using teaching methods that are not employed in your discipline. Teaching improvement can and should continue throughout one's career.

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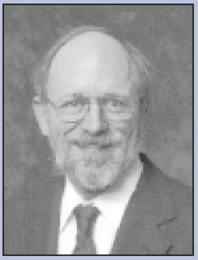

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