Effective Instruction for STEM Disciplines

FROM LEARNING THEORY TO COLLEGE TEACHING

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Effective Instruction for STEM Disciplines

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We dedicate this book to our parents,
families, and all our students.

Foreword

When I first read this book as a manuscript, I was impressed. Here was a group of engineers willing to say that teachers in the science, technology, engineering, and math (STEM) disciplines ought to be looking at the research on learning and implementing it in their classrooms. They deliver this message clearly, unequivocally, and with compelling logic.

They aren't the first or only ones to point out the need for change. In a review of the research on active learning, Joel Michael (2006) of the Department of Molecular Biophysics and Physiology at Rush Medical College writes

> As scientists, we would never think of writing a grant proposal without a thorough knowledge of the relevant literature, nor would we go into the laboratory to actually do an experiment without knowing about the most current methodologies being employed in the field. Yet, all too often, when we go into the classroom to teach, we assume that nothing more than our expert knowledge of the discipline and our accumulated experiences as students and teachers are required to be a competent teacher. But this makes no more sense in the classroom than it would in the laboratory. The time has come for all of us to practice "evidence-based" teaching. (p. 165)

Engineers are precise and systematic, and these authors are no exception. They move through the research carefully, explaining in readable prose what has been documented and what those who teach in these disciplines ought to do about it. The changes they advocate are sensible and doable. The authors write cognizant of the realities of higher education—increasing class sizes, students not as well prepared as they once were, and students beset with pressures that often diminish the time and energy they can devote to study. They write knowing about those aspects of instruction teachers can control (like when and how to use PowerPoint) and those beyond their control (like the configuration of the rooms and labs where they teach). They also write with the voice of experience. They have tried the changes they recommend, and they are willing to admit that some of their first attempts were not as successful as subsequent ones.

It is unusual, but highly appropriate, in books on teaching and learning to hear the voice of experience coupled with careful study of the literature. The book then becomes what Michael calls for in his quote—a description of what "evidence-based teaching" looks like in the STEM disciplines. The description of teaching laid out in this book is encouraging because, although it calls for change, many of the changes are not all that radical. For example, these authors point to research documenting that taking an exam can be a significant learning experience. That requires faculty to reconsider the design of exam experiences and help students see their learning potential beyond how many points exams are worth. In another chapter, based on research, they recommend against telling stories when presenting concepts. Anecdotes may interest the students, but stories can distract and muddle the mental models students need to be creating. They offer sanguine advice illustrated with examples showing how problems currently assigned can be reformulated and used in problem-based learning activities. After reading the book, it's hard to understand why more faculty aren't making the changes consistent with research findings.

You will find this an eminently readable book. It makes educational research understandable—no small accomplishment, given that educational research, like research in so many of our fields, is written to inform research more often than practice. The authors write with voice—you can hear them talking, you can tell that they're college teachers themselves. They make their way through the topics in a conversational style with an occasional interjection of humor.

It is a book written by engineers who imagine that learning can be built much like the structures and circuits they construct. Even though learning construction may not be quite as definitive as electrical engineering, teaching can be designed so that it more directly and systematically promotes learning. This book shows how that happens and how to make changes in your teaching to better facilitate learning for students.

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Preface

Think back to when you were a new college professor—or ahead to that time if you are just starting. You have just finished your PhD, have accepted a teaching position at a college, and are about to face your first class. What do you do?

If you are like most other new professors, you reflect on what your professors did best and try to emulate those moments. That's the way it's usually done, and it's been done that way for hundreds of years. Spence (2001, pp. 12–13) said, "Plop a medieval peasant down in a modern dairy farm and he would recognize nothing but the cows. A physician of the 13th century would run screaming from a modern operating room. Galileo could only gape and mutter touring NASA's Johnson Space Center. Columbus would quake with terror in a nuclear sub. But a 15th century teacher from the University of Paris would feel right at home in a Berkeley classroom."

Think about that for a moment. Medieval peasants are an earlier version of today's farmers, who need to know a fair amount of chemistry and biology. If they don't know the pH of their fields and the concentration of nutrients and fertilizer, then it is hard to succeed. Farmers need to know enough biology to comprehend, for example, the life cycle of crop pests, or else failure is likely.

In the same way, modern physicians cannot succeed without understanding a large amount of biochemistry and biology. Modern astronomers and space scientists need a large store of knowledge about relativistic physics and mechanics, for starters. And anyone in command of a nuclear submarine needs to know an awful lot about nuclear physics and oceanography.

But what do college teachers need to know? Currently, we seem to assume that expertise in the discipline is sufficient and that it is not necessary to be aware of how people learn. We appear to believe that the knowledge amassed in educational psychology and cognitive science in the last quarter century or so can be ignored. In all those other fields—from farming to running a nuclear sub—the person in charge receives an education that includes background knowledge necessary for job success. But universities continue to hire faculty who have no awareness of the learning process.

In education we tend to do things the way they have been done—which is what makes Spence's (2001) idea simultaneously humorous and painfully true. Most college teachers teach the way they were taught. There is no requirement that a teacher in a college actually know anything about teaching or the relevant research in fields like cognitive science and educational psychology. Particularly distressful are comments like the following:

> The preparation of virtually every college teacher consists of in-depth study in an academic discipline: chemistry professors study advanced chemistry, historians study historical methods and periods, and so on. Very little, if any, of our formal training addresses topics like adult learning, memory, or transfer of learning. And these observations are just as applicable to the cognitive, organizational, and educational psychologists who teach topics like principles of learning and performing, or evidence-based decision-making. (Halpern and Hakel, 2002, p. 37)

> Most current approaches to curriculum, instruction and assessment are based on theories and models that have

> not kept pace with modern knowledge of how people learn. They have been designed on the basis of implicit and highly limited conceptions of learning. (Pellegrino, 2006, p. 3)

So, most importantly, college teachers need to be grounded in basic knowledge about how people learn. That is what we try to share in this book. This book presents and then explores a model for the learning process. The various parts of that model are based on findings in the cognitive sciences and educational psychology. For the most part, those findings come from work in the last 50 years as psychology has moved away from behaviorism to a mostly constructivist approach. Those findings together give a coherent picture of what takes place in the learning process. In examining the model, we can identify various instructional practices that aid student learning, thereby increasing effectiveness in the classroom. All three of the authors are experienced both in the practice of engineering and teaching engineering. That gives us a design perspective. In other words, we are accustomed to using basic knowledge in the sciences—buttressed by mathematical analysis—to inform the designs that we have produced. As engineering educators, we require our students to learn a vast amount of material in physics, mathematics, chemistry, and other basic sciences. Then, in the latter part of our curricula, we focus on getting students to apply that material to designing various items that have a purpose.

In science and engineering, if there is knowledge available we try to use what has been discovered in other fields (like physics and chemistry) when we design various devices. What is known about learning should be applied in the classroom similarly, and it should not take as long as it has taken in the past for that to happen. Application of basic research results happens dramatically faster in many other branches of science, and it seems rather peculiar that it has taken this long for those of us who teach—particularly in science, technology, engineering, and mathematics

(STEM) disciplines—to begin to move basic knowledge in these relevant fields to the practice of teaching.

The essence of engineering is design. In the process of design we apply knowledge from the areas of physics, mathematics, and various other sciences to produce a result. To us, it makes sense that course design and the design of classroom activities should implement knowledge from the areas of cognitive science and educational psychology to produce instruction that more effectively promotes learning. As we devised workshops involving course design, we wondered if courses could be designed as engineering artifacts were designed. In other words, we wondered if it was possible to apply knowledge of the learning process to the design of a course. We approached this as engineers and began reading the literature in educational psychology and cognitive science. We were particularly interested in work that formed a coherent model of the learning process and techniques that seemed to be based on that sort of model. This book presents our findings, and we indicate where we found different aspects of the model in the literature.

As we have stated already, those who teach should understand how students learn, regardless of the course level or discipline. However, this book applies particularly to teachers of the STEM disciplines. They are more accustomed to thinking in terms of models, so having a model of the process will help in understanding what to do and why something will or might not work.

A Look Ahead

One frequently raised objection is that teachers are doing pretty well despite their lack of knowledge of the learning process. In other words, we seem to manage using common sense approaches in the classroom. However, as Robert Bjork (2002) points out, many of the most effective classroom approaches and important results about how people learn are counterintuitive (p. 3). So, it may take some courage to implement some of the concepts in this book.

In the first chapter, we take some time to provide a rationale for the idea that there really is a problem with what we are doing. We are not surviving as well as we ought to or as well as we may think we are. The first chapter presents evidence that helps us to focus on some problem areas. Despite any good feelings we may have, all is not well, particularly within STEM disciplines.

In the next three chapters we look at a model of the human memory system (Chapter 2), how we perceive material and get it into working memory (Chapter 3), and the evidence that exists for the best ways to process material that is perceived to store that material in long-term memory (Chapter 4). Along the way we will encounter some concepts about just how that material is stored in memory; this will be useful as we consider how to achieve learning that results in long-term retention. In particular, we find strong evidence that active learning techniques very effectively promote long-term retention and improvements in learning.

In Chapter 5 we look at levels of learning interpreted through the lens of Bloom's taxonomy of educational objectives. This categorization gives us a way to classify students' levels of knowing, which are strong determinants of how effective we are in achieving long-term retention. Later in the book we note that various teaching techniques produce learning at different levels and that achieving different levels is important for long-term retention and "transfer."

Chapters 6, 7, and 8 together focus on various topics in active learning. We face a conundrum here because the evidence we encounter in Chapter 4 is not based on a really good definition of active learning. As we proceed through this sequence of chapters—beginning with some commonly advocated methods in Chapter 6 through to a discussion of problem-based learning (PBL) in Chapter 8—we attempt to refine the concept of active learning and regularly refer to concepts from Bloom's taxonomy.

In Chapters 9 and 10 we discuss the multifaceted concept of *transfer*, in which students apply what they learn in different contexts and situations to problems that might not be directly related. STEM teachers know full well that the material students learn today could be outdated in only a few years, so they want their students to be able to adapt to whatever is coming. There is a vast, and rapidly growing, literature on this topic.

Finally, in the last chapter we look at ways the concepts in the book can be used to improve your teaching. This is perhaps the hardest part. Effective techniques, some known for years, never seem to make it into many classrooms. In this final chapter, we address some of the issues that make it difficult for STEM faculty to implement changes.

Maybe you anticipate that some of the techniques you will encounter in this book are chancy—something you find interesting to read about but are wary of using in the classroom. Almost everything presented here has been used successfully by faculty both teaching now and previously. In the 1950s, for example, the engineering curriculum at Carnegie Institute of Technology (as Carnegie-Mellon University was known in those days) implemented many of the ideas in this book. Those faculty had a strong sense of what worked as well as the courage to use what they believed in. They built strong programs using these ideas, and those of us fortunate enough to experience that curriculum realize how powerful their approach was. You can build courses and curricula with that educational and motivational power—and you will have the added advantage of knowing why what you are doing works.

Questions About Teaching and Learning

It makes sense to begin a journey through a book knowing where you are starting. To that end, take several minutes and answer the following questions we assembled by circling your answers. If you think two or more answers could be correct, choose the answer you think is best or the most commonly found result:

1) When a student learns
   a) A copy of what is in the instructor's mind is the goal for what should be in the student's mind after the instruction.
   b) Information is transmitted from the instructor to the student.
   c) Students retain a processed version of the material perceived by the student.
   d) None of the above options are true.
2) Which of these statements are generally true?
   a) Competition pushes students to achieve higher levels of learning than cooperation.
   b) Students master material more effectively if they work independently rather than in groups.
   c) Students must learn the underlying facts, formulae, and theories before being asked to solve real problems.
   d) Lecturing remains the most common instructional method in higher education because it is one of the most efficient methods of delivering information.
3) When students learn a set of material
   a) They either know or don't know the material.
   b) They may be able to explain the material but not be able to apply it.
   c) They may be able to apply the material but not be able to explain it.
   d) None of the above options are true.
4) A clear, logically presented lecture
   a) Leads to deeper understanding than group exercises on the same material.
   b) Allows the instructor to cover more material in the allotted time because students learn faster and better.

c) Produces learning equivalent to the best active learning methods.

d) Does not need to be supplemented with hands-on activities.

e) None of the above options are true.

5) Good teachers

a) Must have a deep understanding of the material.

b) Can teach any material.

c) Have knowledge of the conceptual barriers to learning a particular set of material.

d) Primarily enhance learning by developing clear and logical lectures.

e) Improves their lecture when students fail to learn adequately.

f) None of the above options are true.

6) Learning increases as

a) Students reread the material.

b) Lecture time increases.

c) Activity time increases.

d) None of the above options are true.

These questions lead to insights regarding how instructors think about the concepts, and answers often reveal some interesting misconceptions about the learning process. In the numerous workshops we have given for faculty in engineering and science, we have posed those questions. A tabulation of attendees' responses (in percentages) is given herein, along with our comments. Note that participants in these workshops may have been predisposed to active learning methods, which could have influenced these results.