Engineering Education: A Tale of Two Paradigms*

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ABSTRACT

Engineering education is in a turbulent period. Chronic industry complaints about skill deficiencies in engineering graduates, high attrition rates of engineering students with good academic performance records, the worldwide adoption of outcomes-based engineering program accreditation, and findings from both cognitive science and thousands of educational research studies showing serious deficiencies in traditional teaching methods have all provoked calls for changes in how engineering curricula are structured, delivered, and assessed. As might be expected, many academic staff members and administrators are less than enthusiastic about the proposed changes, arguing that the traditional system functions well and needs no radical revision. The ongoing debate involves four focal issues: how engineering curricula should be structured, how engineering courses should be taught and assessed, who should teach, and how the teachers should be prepared. This paper outlines two conflicting educational paradigms and the position on each of these four issues that each one reflects—the traditional paradigm, which has dominated engineering education since its inception, and the emerging alternative—and offers predictions about the eventual resolution.

1. INTRODUCTION

Pressures to reform engineering education have existed since the field first began, but a particularly intense series of them arose in the 1980s and still continues.

- Interest in engineering careers has steadily declined among secondary school students, which coupled with the traditionally high attrition rate from engineering curricula raises concerns about whether enough engineering students will graduate in the next decade to meet industry's needs.
- Employers of engineering graduates complain that their new hires lack high-level analytical and critical thinking skills, communication and teamwork skills, and understanding of engineering and business practice.
- Cognitive science and extensive educational research have repeatedly shown that traditional lecture-based instruction is ineffective at promoting learning and high-level skill development, both in general and specifically in engineering education.
- The United States, much of Europe, and countries that are signatories of the Washington Accord have adopted outcomes-based program accreditation systems. These systems shift the focus of accreditation from documentation of what has been taught to assessment of what students have learned and remediation of shortfalls in targeted learning outcomes.

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- Significant potential benefits of technology-assisted instruction and distance education have been demonstrated.
- University administrators and staff members have become aware that traditional engineering jobs will increasingly be done in the future by either computers or engineers in countries with low labor costs. To be competitive, future engineers will need to be equipped with skills that have previously not been emphasized in engineering curricula, including critical and creative thinking and entrepreneurship (Felder, 2006a).

Responses to these pressures in the engineering education community have been forthcoming, but progress has been slow. If you walk down the hall of an engineering building at most universities and glance into classrooms, you would still be likely to find professors teaching the same topics that were taught three and four decades ago in the same way they were taught then. Not in all classrooms, however: in some (and at a few institutions, many) of them you would see dramatic differences.

There are thus two competing paradigms for engineering instruction: the traditional one, which has dominated engineering education for at least a century, and the emerging one. This paper first outlines these two schools of thought and then contrasts their positions on four focal issues:

1. How should curricula be structured?
2. How should classes be taught?
3. Who should teach?
4. How should staff be prepared to teach?

What is presented is a brief overview of these issues, not a comprehensive discussion of the historical background and methodologies of the traditional and emerging responses to those questions, the obstacles to implementation of the new methods (the author knows from personal experience that they are anything but easy), and examples of their successful implementation. To cover all of that would require a book. Fortunately, one has been written: readers who wish far more elaboration than they will find here should consult Sheppard *et al.* (2008), along with the articles and books cited in the references at the end of the paper.

2. TWO APPROACHES TO KNOWLEDGE, LEARNING, AND TEACHING

The traditional philosophical view of knowledge is *positivism*, which holds that objective reality exists and is knowable through scientific examination of evidence of the senses. The positivist researcher's goal is to carry out objective and unbiased studies to arrive at The Truth. The positivist educator's job is to present material as clearly as possible, the students' job is to take it in and understand it, and their failure to do so indicates either their lack of aptitude or diligence or the instructor's lack of teaching skill. (Many instructors don't admit the possibility of the last option.)

The alternative view of knowledge is *constructivism*, which claims that whether or not there is such a thing as objective reality, human beings can never know what it is. People take in information through imperfect sensory organs and either filter it out quickly or incorporate it into their existing mental structures; in effect they construct their own reality, either individually (*cognitive constructivism*) or collectively with others (*social constructivism*). The constructivist educator has a much more difficult task than the positivist. For anything but simple factual knowledge that can be learned by rote memorization, direct transmission of information that students absorb and understand in its entirety simply doesn't happen. Whether or not difficult concepts and structures and mechanisms are learned and understood doesn't just depend on how accurately and clearly the instructor explains them and on how intelligent students are and how hard they work (although those factors are still vitally important), but also on such things as the students' prior knowledge, conceptions, and misconceptions about the course content, the level of their interest in the subject and their view of its relevance to their needs, and the degree of compatibility between their learning style (the way they characteristically take in and process information) and the instructor's teaching style. *Constructivist education* (aka *learner-centered teaching*) seeks to take those factors into account when designing instruction, presenting new information in the context of what students already know and helping them to develop understanding and skills through activity and reflection rather than making them passive recipients of information.

John Dewey (who in the late 19th century foreshadowed most constructivist methods that don't involve computers), Jean Piaget (who established the principles of cognitive constructivism), and Lev Vygotsky (who did the same for social constructivism) laid the theoretical foundations of learner-centered teaching, and modern cognitive science and extensive educational research have clearly demonstrated its superiority over traditional teacher-centered instruction for virtually any targeted learning outcome [Ambrose *et al.,* 2011; Bransford *et al.*, 2000; Prince, 2004; Sousa, 2006; Svinicki & McKeachie, 2011]. Nevertheless, the traditional paradigm is still alive and well in engineering education at most institutions around the world. The tension between these two approaches to teaching and learning is reflected in every aspect of curriculum and course design, delivery, and assessment. The remaining sections survey some of the principal differences between the traditional paradigm (denoted by **T**) and the emerging paradigm (**E**).

3. HOW SHOULD ENGINEERING CURRICULA BE STRUCTURED?

T: *Deductive (Fundamentals → Applications)*. Begin the first year with basic mathematics and science, teach "engineering science" in Years 2 and 3, and get to realistic engineering problems and engineering practice in the capstone course.

E: *Integrated*. Introduce engineering problems and projects starting in Year 1, and bring in the math and science (and communication and economics and ethics) in the context of the problems and projects.

The traditional organization is what might be called the "trust me" approach to education, as in "*You may have no idea why I'm teaching you all these theories and derivations and mathematical models and algorithms now, but trust me, in a year or four years or after you graduate you'll see how important they are*." As any cognitive scientist will tell you, "this will be useful some day" is a really poor motivator of learning. The emerging paradigm infuses the entire engineering curriculum with real engineering problems and introduces fundamental material on a need-to-know basis in the context of solving those problems. Among other benefits, the latter approach gives engineering students exposure to real engineering (as opposed to pure and applied science) before the final year of their schooling.

T: *Curricula and courses emphasize content.*

E: *Curricula and courses balance content and skills (analytical and critical and creative thinking, problem solving, problem formulation, technology, teamwork, communication, entreneurship, foreign languages and cultures,…)*

The fact is that the "content" of engineering practice other than basic principles is changing far too rapidly for engineering curricula to keep pace with. Much of what we teach our students today is likely to be obsolete or irrelevant to what they will need to know when they enter the workforce or soon afterwards. Instead of constantly trying to jam more content into our courses in a futile effort to keep up, we should therefore focus on teaching basic principles and self-directed learning. When the students leave us, they should be equipped to figure out what they need to know when they face new challenges, identify sources of the needed information and learn from them, find colleagues with complementary areas of expertise and team effectively with them, do the analytical, critical, and creative thinking required to meet the challenges, and communicate the solutions clearly and persuasively. Those skills will never become obsolete but will continue to serve the students throughout their careers.

T: *Courses are compartmentalized, self-contained, and taught by an individual instructor.*

E: *Courses are horizontally integrated across subjects and disciplines and/or vertically integrated across years of the curriculum.*

In practice, unlike in school, problems rarely come neatly packaged within the boundaries of a single course subject (thermodynamics, hydrology) or even a single discipline (civil engineering). To solve real problems invariably requires pulling together material from several different subjects and disciplines, both technical (engineering and science) and nontechnical (economics, business, communications,...).

Traditionally, the idea that the material taught in one course has important applications in most other courses is rarely brought up in engineering courses, and so it does not become part of the students' thinking. Every experienced instructor knows what happens if you bring up something in a heat transfer course that is normally taught in a thermodynamics course: mainly blank stares, and if pressed, most students will vigorously deny that they have ever seen anything like it. In the emerging paradigm, the connections between subjects and disciplines are made explicitly clear, sometimes in lectures and sometimes in assignments.

T: *Design is taught in the capstone design courses.*

E: *Design is taught throughout the curriculum.*

First-year engineering students are perfectly capable of designing devices and processes after getting some basic instruction. Their work will obviously be at a lower level of sophistication than they can produce in their fourth year, but they will be able to carry the design knowledge and skills they acquire into subsequent courses and steadily become better engineering designers. Now when they enter their final semester, they will be capable of tackling design challenges that traditional capstone course instructors would never dream of assigning to undergraduates.

4. HOW SHOULD CLASSES BE TAUGHT?

T: *Content is determined by the syllabus* ("*I will cover...*").

E: *Content is determined by learning objectives* ("*The students will be able to...*")

A list of topics to be covered conveys very little useful knowledge to students or instructors about exactly what will be taught in a course, including how deeply the instructor will delve into each topic and what kinds of thinking and problem-solving skills the students are expected to acquire. If instructors instead write *learning objectives* that specify all the things the students should be able to *do* (explain, calculate, derive, model, design, critique,...) if they have learned what the instructor intends to teach, everything changes. The students get a clear understanding of what knowledge and skills they are expected to acquire; the instructor can make sure that all of the lessons, activities, assignments, and exams are pointing toward the same goals (*constructive alignment*), and instructors of subsequent courses know what they can presume about the knowledge and skills of their entering students (Felder, 2006b).

T: *Teaching style addresses only one learning style.*

E: *Teaching style addresses a broad spectrum of learning styles (visual/verbal, concrete/abstract, active/reflective, sequential/global,...).*

Students do not all learn in the same ways or respond identically to specific teaching methods. Those with different learning styles tend to have different strengths, all of which can be vitally important in engineering practice. Instruction that addresses the needs and preferences of only certain types of learners (as traditional engineering instruction does) weeds out students who would make excellent engineers. On the other hand, balanced instruction that alternately addresses the needs and preferences of opposite learning styles gives all students with the basic ability and interest to succeed in engineering a good opportunity to do so. All students are taught sometimes in a manner compatible with their learning style, so they are not too uncomfortable to learn, and sometimes in the opposite manner, so they will get practice and feedback in important skills that they would be perfectly content to neglect if given the option (Felder & Brent, 2005).

T: *Deductively: Principles → formulas & algorithms → applications.*

E: *Inductively: Instructor presents or students discover principles, formulas, and algorithms in the context of problems or projects.* Variations of inductive learning include guided inquiry, problem-based learning, and project-based learning.

The same reasoning that justifies an inductive curriculum also applies to teaching individual courses inductively. Rather than deductively presenting all of the theories and derivations and analytical methods first and then showing applications, the instructor starts with challenges—questions to be answered, projects to complete, or real-world problems to be solved—and teaches the course material (or helps the students teach themselves) in the context of the challenge.

Extensive research has demonstrated the effectiveness of inductive teaching in promoting deep learning and conceptual understanding (Prince & Felder, 2006). Implementing inductive teaching (especially problem-based learning) is not trivial, however, and instructors should first read about the approach and/or get some training rather than just plunging in and learning from their mistakes.

T: *Most in-class activity in non-lab classes is done by the instructor* (*lecturing and occasionally asking questions).*

E: *Active learning is used, with the burden of activity in all courses being shared by the instructor (lecturing, asking and answering questions) and the students (discussing, explaining, brainstorming, questioning, reflecting, computing,…*).

A vast body of cognitive science and empirical educational research has established that people acquire nontrivial knowledge and skills only through practice, reflection, and feedback, not by watching and listening to someone telling them what they are supposed to know (Prince, 2004). *Active learning,* in which students in class work individually or in small groups on short course-related exercises, has been repeatedly shown to produce substantially greater learning than the traditional lecture-dominant approach. Unlike most inductive methods, active learning is fairly easy, and is almost guaranteed to work as long as the exercises are short (as little as 10 seconds up to a maximum of 2–3 minutes) and challenging (asking students to get in groups to answer a trivial question is a waste of class time), and at least some of the time the instructor calls on individuals for the first few responses rather than calling for volunteers every time (Felder & Brent, 2009).

A relatively new approach to active learning involves the so-called *flipped classroom*, in which students study material before coming to class (often by watching on-line lectures and possibly answering and asking questions about them electronically, sometimes by working through on-line multimedia tutorials) and then spend the class time engaged in activities that reinforce and extend the material in the lectures and tutorials (Peer Instruction Network, website).

T: *Homework and tests involve exclusively convergent (single-answer) problems*.

E: *Homework and tests involve convergent problems, divergent (open-ended) problems, and troubleshooting, interpretation, and problem formulation exercises*.

Relatively few real problems, as opposed to academic problems, have the form "Given this, calculate that," where there is a unique answer and the task is to find it. Real problems are sloppy, often poorly defined, and don't come neatly packaged with exactly the information needed to solve them, and if there is a correct or optimal answer it usually begins with "It depends." Since that is the kind of problem our graduates will face throughout their careers, it makes sense to start teaching them to deal with such problems while they are still with us. Felder (1987, 1988) suggests a large variety of open-ended problems that can easily be adapted to any engineering course.

T: *All homework outside of projects and labs is done individually. Working together is considered cheating*.

E: *Some homework is done individually, some cooperatively (with measures taken to assure individual accountability for all the work)*.

Most engineers—in fact, most members of any profession—will do a substantial part of their work in teams, and until they reach a senior position they will have little or no say regarding the team composition. Their ability to work well with their team members, regardless of their differing skill levels, work ethics, and personality traits, is likely to affect their performance evaluation more than their technical skills do. Since teamwork skills (including communication, project and time management, leadership, and conflict resolution skills) are rarely taught before college; providing guidance, practice, and feedback in those skills should be part of the engineering education curriculum.

The best way to provide instruction in teamwork is to use *cooperative learning*, an approach to team assignments that includes positive interdependence (the team members are forced to rely on one another), individual accountability (each team member is held accountable both for the work that he or she had primary responsibility for and the work that everyone else on the team did), and several other criteria. Felder & Brent (2007) define cooperative learning, suggest different things engineering students can profitably be asked to do in teams, survey the research base that demonstrates the effectiveness of the method for addressing almost every conceivable learning objective, and outline strategies for making cooperative learning as effective as possible.

T: *Teaching evaluation is based on student ratings.*

E: *Teaching evaluation is based on student ratings, peer ratings, self-ratings, and what students learn ("outcomes-based assessment").*

At most universities, student ratings are collected at the end of every course, the ratings are compiled, and copies go to the instructor and into the instructor's personnel file to help inform decisions regarding promotion, tenure if the instructor is eligible for it, merit raises, and teaching award nominations.

Including student ratings in comprehensive assessments of teaching performance is entirely appropriate. There are some aspects of teaching that students are in a unique position to judge, such as the instructor's clarity, attitude, punctuality, availability, etc. Moreover, thousands of research studies have shown that student ratings are consistent with other assessments of teaching, and that criticisms frequently leveled at them (they're popularity contests, the high ratings go to the easy graders, and so on) have little basis in reality (Felder & Brent, 2008).

There are, however, some aspects of teaching that students are in no position to judge. They do not know, for example, whether the instructor is teaching the right material to prepare them for subsequent courses, or if the material is up-to-date, or if appropriate methods are being used for instruction and assessment. Only peers are capable of making those judgments, and so a comprehensive teaching evaluation should always include peer review along with student ratings. Not the usual form of peer review, however, in which a staff member observes a colleague's class session and jots down notes on whatever happens to catch his or her attention, but a well-structured system with multiple raters making at least two observations and using pre-defined and agreed-upon criteria of what constitutes good teaching as the basis of their judgments, and separately rating course materials (syllabus, learning objectives, handouts, visuals, assignments, and tests) (Felder & Brent, 2004). Learning outcomes should also be part of a comprehensive evaluation of teaching (Felder & Brent, 2003): if most students are not learning what the course is designed to teach them, then no matter how highly the instructor might be rated by his or her students and peers, something is clearly wrong with the instruction.

T: *Courses are taught by professors lecturing in classrooms or auditoriums on campuses.*

E1: *Courses are taught by professors lecturing on TV monitors.*

E2: *Courses are taught using interactive multimedia tutorials and other technology-based tools.*

Instructional technology is a two-edged sword. To the extent that it promotes student activity and interactivity (as in E2), it enhances learning; to the extent that it increases passivity (as in E1), it detracts from learning (Felder & Brent, 2000).

There are many things technology can do better than instructors in a traditional classroom. They include engaging students with interactive tutorials that present information, ask questions about it, and provide affirmation or corrective feedback on the student's responses; showing complex schematics and three-dimensional surface plots and video clips; and involving students in hands-on experimentation and exploration using simulations of laboratory or engineering processes. Learning is enhanced when instructors use technology in any of those ways, but it is diminished by having students sit passively through PowerPoint shows or videos of complete lectures. Meaningful learning results from activity and reflection and not from simply watching and listening.

5. WHO SHOULD TEACH?

T: *Ph.D.'s specializing in frontier disciplinary research.*

E: *People specializing in one or more of four diverse forms of scholarship* (Boyer, 1990).

1. *Scholarship of Discovery*: frontier research
2. *Scholarship of Integration*: applied research that builds on and extends frontier research
3. *Scholarship of Application*: applied research that directly benefits society
4. *Scholarship of Teaching and Learning*: conducting educational research and using the results to improve teaching and learning.

It is vital for engineering schools to maintain strong frontier research programs, since in many of the world's developed countries basic engineering research has all but been abandoned by industry. First-class frontier researchers who are also good teachers should continue to be the mainstay of faculties at research universities. It is also important, however, for some staff members—possibly in collaboration with researchers from other disciplines—to conduct applied research, building on the discoveries of the frontier researchers to benefit industry and/or society. In addition, someone in every academic department should be an expert on pedagogy—knowing the methods we have described and skilled at using them, reading the education literature, attending teaching conferences, developing new instructional materials and methods and importing and adapting materials and methods developed elsewhere, and sharing them with colleagues who are not teaching specialists but are willing to try new techniques to make their teaching more effective.

All of the functions served by those diverse staff members are equally important in the university mission. It is only fair for staff members who engage in each of them to be treated equitably by the university, with performance evaluations and opportunities for promotion and advancement based only on how well they perform their designated functions and not on which functions they perform.

6. HOW SHOULD FACULTY MEMBERS BE PREPARED TO TEACH?

T: *Not at all.*

E: *With courses on teaching for graduate students; staff workshops, seminars, learning communities; and mentorships.*

College teaching may be the only highly skilled profession whose practitioners are not routinely given some training before or after they enter it. The presumption is that if you have a degree in a subject you must also know how to teach it. As every former and current college student knows, this presumption is seriously defective. Effective instructional development for both current and future academic staff can take years off the usual 4–5 year learning curve for most new staff members to become as effective in teaching as they are capable of being.

When universities have instructional development programs, they are frequently conducted for staff in all disciplines by facilitators with no STEM background or knowledge. The programs focus on learning theories and general pedagogy without providing specific examples of how the techniques being described can be applied to technical courses. Participating engineering staff members come away with very little information they can use, and the 4–5 year learning curve follows. Felder, Brent, and Prince (2011) survey STEM-specific instructional development programs around the world that do a much better job of equipping staff to do the kind of teaching we have described in this paper.

7. REMAINING QUESTIONS

- *Can we afford to do all that?*
- *Can we afford not to do it?*

Some of the emerging practices listed in this paper require no resources to implement**.** If instructors want to write learning objectives or use active learning, for example, after some preliminary reading they can just do it. Other suggestions, such as establishing STEM-specific instructional development programs or mentorships, involve costs (albeit trivial ones in the context of engineering school budgets). In this age of perpetual budget crises, many administrators are reluctant to allocate any more funds to nonessential tasks than they are forced to allocate, and they do not consider instructional development essential.

There are also costs associated with sticking to traditional instruction, however—they may be less easily quantified, but they are real and steep. For one, outcomes-based accreditation systems almost preclude staying with business as usual, and if a program gambles that its evaluators will not take the new criteria seriously it seriously risks losing accreditation.

More importantly, engineering schools are finding it increasingly difficult to attract and retain enough students to meet anticipated demands for engineers, and growing numbers of departments are in danger of falling below the critical enrollments they need to survive financially. The most prestigious research universities will continue to attract students on the basis of their reputations, but other schools will be forced to compete for a dwindling pool of qualified students. The schools that can describe active, student-centered, technology-rich instructional environments in their brochures and demonstrate such environments to visitors, and who train staff members to create such environments and reward those who do so successfully, will succeed. The schools that fail to do so may not.

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