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Engineering Education and the Development of Expertise

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BACKGROUND
Although engineering education has evolved in ways that improve the readiness of graduates to meet the challenges of the twenty-first century, national and international organizations continue to call for change. Future changes in engineering education should be guided by research on expertise and the learning processes that support its development.

PURPOSE
The goals of this paper are: to relate key findings from studies of the development of expertise to engineering education, to summarize instructional practices that are consistent with these findings, to provide examples of learning experiences that are consistent with these instructional practices, and finally, to identify challenges to implementing such learning experiences in engineering programs.

SCOPE/METHOD
The research synthesized for this article includes that on the development of expertise, students' approaches to learning, students' responses to instructional practices, and the role of motivation in learning. In addition, literature on the dominant teaching and learning practices in engineering education is used to frame some of the challenges to implementing alternative approaches to learning.

CONCLUSION
Current understanding of expertise, and the learning processes that develop it, indicates that engineering education should encompass a set of learning experiences that allow students to construct deep conceptual knowledge, to develop the ability to apply key technical and professional skills fluently, and to engage in a number of authentic engineering projects. Engineering curricula and teaching methods are often not well aligned with these goals. Curriculum-level instructional design processes should be used to design and implement changes that will improve alignment.

KEYWORDS
deep learning, expertise, motivation

INTRODUCTION

In response to calls for change from national and international organizations, engineering education has evolved in a number of ways that enhance the learning of students. One of the major responses has been the incorporation of more team-based, project-driven activities. However, recent reports on engineering education make clear that additional enhancements are needed to prepare engineering graduates to meet the challenges of the twenty-first century (e.g., Jamieson & Lohmann, 2009; Sheppard, Macatangay, Colby, & Sullivan, 2009). One of the keys to preparing students to meet these challenges is to help them build knowledge and skills that they can readily adapt to address the novel, complex problems that they will encounter. Fortunately, the literature on learning provides rich information on the characteristics of learning experiences that build such adaptable knowledge and skills.

The literature on expertise, and the learning processes that support its development, is particularly salient because undergraduate engineering education lays the foundation upon which expert engineering practice can be built. In the next section we discuss two key ideas from the literature on expertise. The first is the importance of structuring knowledge in a domain around key concepts and principles of the field to facilitate students' abilities to access and transfer knowledge to new and novel situations. The second is the central role of motivation in enhancing students' levels of performance in educational settings. Findings from studies on instructional practices that encourage the use of deep approaches to learning and on the role of motivation in learning are thus relevant to our discussion.

Drawing upon these sets of literature, we will:

- Relate key findings from studies of the development of expertise to engineering education.
- Synthesize the literature to provide a list of instructional practices that support the approaches to learning required for the development of expert levels of performance.
- Provide examples of learning experiences from mathematics, science, and engineering education that are consistent with these instructional practices.

We will then draw upon studies of dominant teaching and learning approaches in engineering to discuss some of the major challenges to transforming engineering programs. We will conclude with a summary of the paper and suggestions for future research.

THE DEVELOPMENT OF EXPERTISE

The study of experts in a wide range of fields has led to a number of observations about what makes experts expert and how they differ from novices. Bransford, Brown, & Cocking (1999) recommend that these observations define the goals for teaching and learning. Following this recommendation, we focus our discussion on learning experiences that are consistent with what is known about the development of expertise.

It is important to note that we do not mean to suggest that any single experience can lead to the development of expertise, but rather that each experience should contribute to the maximum extent possible to growth toward expertise.

Studies of experts and novices show that the knowledge of experts and novices differ quantitatively and qualitatively. Of course experts have much greater quantities of knowledge in the domain of their expertise than novices. But even more importantly, the knowledge of experts is organized based on a deep understanding of the domain. In technical fields such as engineering, expert knowledge is organized around key concepts, e.g., mass, force, and general principles, e.g., Newton's Laws. By contrast, students new to a field of study tend to make superficial connections rather than organizing their knowledge around fundamental concepts and general principles. Studies of learners' abilities to apply their knowledge to novel problems, a process often referred to as transfer of learning, have clearly shown that for knowledge to be transferred it must be based upon general principles. Disconnected or poorly organized knowledge obtained by rote learning is unlikely to transfer whereas knowledge organized around general principles is more likely to do so (Bransford et al., 1999).

Experts organize their knowledge in ways that include "specifications of the context in which it is useful" (Bransford et al., 1999, p. 31), which allows them to easily recall it. Knowledge that is linked to the context(s) in which it is useful is referred to as "conditionalized." Bransford et al. (1999) emphasize the need to create learning environments that explicitly lead students to develop conditionalized knowledge rather than leaving it to students to learn the conditions under which knowledge and skills can be applied.

Another key finding of the research on expertise is that "everyone, even the most talented individuals, needs to invest 10 years of active engagement in a domain to become expert." (Ericsson, 2010, p.412). The duration of active engagement required to achieve the highest levels of performance has been estimated at 10,000 hours (Ericsson, Krampe, & Tesch-Römer, 1993). In the typical engineering program, students might work an average of six hours per week per course, applying and practicing what they are learning. If a course lasts for 15 weeks and the degree program has a total of 40 courses, then the total time spent on application and practice would be about 3,600 hours. The number of hours spent by a typical student in truly active engagement, however, is likely to be far less than 3,600 hours. Thus, to maximize the impact of time spent in practice and application, it is imperative that we design the most effective learning experiences that we possibly can.

The research on the development of expertise also indicates that only practice performed with the intention of improving a skill will lead to the development of expertise. Practice performed with the intention of improving a skill is referred to as "deliberate practice"; this type of practice requires that the individual be highly motivated to learn and improve. The two key processes in deliberate practice are identifying which knowledge and/or skills needs to be improved and selecting a learning approach that will lead to the desired improvements. (These processes are "meta-cognitive" and are addresed in the next section.)

Ambrose, Bridges, DiPietro, Lovett, and Norman (2010) discuss the need for two types of practice—practice that develops individual skills, which they referred to as "component" skills, and practice that requires skills to be integrated to address more challenging, realistic problems. In order to develop expert levels of competence, students must be able to apply component skills easily and fluidly. However, as noted by Ambrose et al., "acquiring component skills does not by itself prepare students to perform complex tasks" (p. 103). Further as Boshuizen (2010) states "integration is not an automatic process" (p. 382). Thus, to help students proceed along their pathways to expert performance, the curriculum must provide multiple opportunities for them to practice their skills on authentic tasks that require the integrated application of various knowledge and skills.

Research on the development of expertise indicates that progress toward expert performance requires thousands of hours of deliberate practice that develops conceptual knowledge and components skills as well as the ability to apply the knowledge and skills to authentic problems. In engineering education, it falls to the instructors to design and sequence the learning experiences that will promote such deliberate practice. Instructors must also arrange learning experiences that help students learn to identify the knowledge and skills needed for expert practice, as well as to develop that knowledge and skill set.

CHARACTERISTICS OF EFFECTIVE LEARNING EXPERIENCES

We will use the term *effective learning experiences* to describe learning experiences that best support the development of expert professional practice. We define effective learning experiences as those that support the development of deep understanding organized around key concepts and general principles, the development of skills, both technical and professional, and the application of knowledge and skills to problems that are representative of those faced by practicing engineers.

The types of learning approaches that lead to deep understanding of the concepts and principles of a domain are referred to as "deep approaches to learning" in much of the literature on learning. This substantial body of literature began with a study of how students read materials when they expect to be asked questions about them afterwards (Marton & Säljö, 1976; Svensson, 1977). Those studies revealed that some students read text with the intention to understand it, whereas other students focus more on the text itself. Differences in intentions lead students to use different learning strategies as they read. The learning strategies used by students whose intention is to understand are described as "deep"; the set of learning strategies used by the other students are described as "surface".

In their review of the literature related to deep approaches to learning, Entwistle and Peterson (2004, p. 415) identified a number of strategies to promote deep approaches to learning including: relating ideas to previous knowledge and experience; looking for patterns and underlying principles; checking evidence and relating it to conclusions; and examining logic and argument cautiously and critically.

Vermunt (1996) identified additional deep approaches to learning used by students who he described as "application oriented." These students "mainly pay attention to those parts of the subject matter that have practical relevance" (p. 42). Application-oriented processes include (p. 42): searching for relations between the subject matter and the reality to which it refers; trying to apply in practice what has been learned in a course; and seeking to fill in abstract lines of reasoning with concrete things.

Results from the National Science Foundation (NSF)-sponsored Center for the Advancement of Engineering Education provide evidence from engineering students about the characteristics of significant learning experiences. The characteristics, based on interviews with students that asked them to discuss their most significant learning experience, are consistent with the studies of deep approaches to learning. The characteristics of significant learning experiences for engineering students included integrating diverse knowledge and applying knowledge and skills to real-world problems (Atman et al., 2010).

The early work on deep approaches to learning gave rise to a substantial body of research that investigates the relationships between teaching approaches and students' learning strategies. Some of the key findings of this research are that:

- Deep learning approaches were correlated with learning experiences that stress "conceptual connections between the content of the learning domain" (Wierstra Kanselaarl, Van der Linden, Lodewijks, and Vermunt, 2003, p. 514) and that were "student oriented." The term "student-oriented" describes learning in which students were active and exercise a high degree of self-regulation (Wierstra et al., 2003).
- Surface learning approaches that support reproduction of content were correlated with learning experiences that emphasized "memorizing facts and that give students few incentives toward active participation" (Wiestra et al., 2003, p. 515). They were also correlated with teaching approaches that focused on transmission of knowledge (Trigwell, Prosser, & Waterhouse, 1999).
- When students experience instruction focused on knowledge transmission, their "use of deep approach is likely to decline through the period of the course of study" (Kember & Gow, 1994, p. 67). The inverse is also true: the use of teaching methods that facilitate use of deep approaches to learning will discourage the use of surface approaches.

These learning approaches focus on how students process information and are therefore cognitive in nature. Deep approaches to learning also require that learners use metacognitive strategies to manage their learning processes. Key strategies include monitoring whether learning is happening as planned, reflecting on the cognitive strategies used, diagnosing the cause of difficulties if learning is not happening, and adjusting learning activities accordingly (Vermunt & Vermetten, 2004). Such processes are essential if learners are to be able to engage in the deliberate practice that is the key process in developing expertise.

Studies investigating the effects of explicit instruction aimed at helping students to develop strategies for learning in a domain and for regulating their own learning suggest additional characteristics of effective learning experiences. Vermunt and Vermetten (2004) summarize the results of these studies. Two of the key findings they report are: that providing specific instruction on key self-regulation skills improves those skills, as well as exam performance, in courses in computer science and business economics (Volet, McGill, & Pears, 1995; Masui & DeCorte, 1999); and that participation in working groups aimed at improving learning and regulation strategies did improve both, as well as exam performance (Schatteman, Carette, Couder, & Eisendrath, 1997).

In creating effective learning experiences that encourage students to engage in deep approaches to learning and to integrate their knowledge and skills in solving complex problems, we must attend to motivation, especially because deep approaches to learning and integrated application of knowledge and skills place a higher cognitive demand on students than surface approaches. Pintrich (2003) provides an excellent summary of research on the role of motivation in learning and guidelines for designing effective instructional environments. Key points from his article include:

- Research on both personal and situational interest indicates that "higher levels of both are associated with more cognitive engagement, more learning, and higher levels of achievement." (p. 674) Instructors should therefore provide "stimulating and interesting tasks, activities, and materials, including some novelty and variety in tasks and activities" and "display and model interest and involvement in the content and activities" (p. 672).
- In general, "… students who believe that they have more personal control of their own learning and behavior are more likely to do well and achieve at higher levels

than students who do not feel in control …" (p. 673). Based on this finding, instructors should provide "feedback that focuses on the processes of learning, including use of strategies, effort, and the general changeable and controllable nature of learning…" (p. 673).

- "Students who believe they are able and that they can and will do well are much more likely to be motivated in terms of effort, persistence, and behavior than students who believe they are less able and do not expect to succeed" On this point, Pintrich noted that "learning tasks that are within the range of competence for students, allow them to use their prior knowledge and expertise, and thus feel confident and competent (p. 671)." In an effort to prevent students from overestimating their ability and exerting too little effort " it is more important that students understand what they can and can't do and have accurate and realistic feedback that can help them acquire the expertise needed to learn." (p. 672)

Ambrose et al. (2010) provide a summary of practices that are likely to enhance motivation focusing on three factors: students' perception of the value of the learning experience, students' expectations that they can create and execute a plan to succeed at a given learning task, and students' perceptions of how well the learning environment set by the instructor supports their learning. The optimal situation occurs when all three factors are positive resulting in a highly motivated student; other combinations lead to negative effects on motivation. To increase the perceived value of a learning experience, Ambrose et al. (2010) suggest providing authentic tasks and making connections to students' academic life and their intended professions. To increase the likelihood that students will have positive expectations, Ambrose et al. recommend ensuring that objectives, assessment, and instruction are well aligned, designing assignments with an appropriate level of challenge, and providing timely and constructive feedback.

As Ambrose et al. (2010) noted, it is important that instructors challenge students with tasks at an appropriate level. It is also important that instructors provide sufficient supports to ensure that students can successfully integrate their knowledge and skills to complete those tasks. Providing assistance to students as they take on new complex tasks is often referred to as "scaffolding," an analogy to the scaffolding that is used in construction of a building. As students become better at the process of integrated application of their knowledge and skills, less and less scaffolding is needed, so it can be removed gradually as students progress. This process of purposefully removing the scaffolds as students learn is often referred to as "fading."

The findings reviewed in this section can be synthesized into a set of instructional practices, presented in Table 1, that are most likely to lead to effective learning experiences for students. The instructional practices include elements related to motivation, self-regulation, teaching, and assessment. (The article by Johri & Olds (2011) in this issue presents a summary of different theories of learning and how they relate to the design of learning experiences.)

Examples of Effective Learning Experiences

In this section we present some examples of instructional methods in engineering, science, and mathematics that include one or more of the practices summarized in Table 1. There are a number of references that provide additional examples such as *Engineering*

TABLE 1
Instructional Practices that Create Effective Learning Experiences

Affective

- Arouse interest for students of contrasting abilities and goals.
- Provide stimulating, interesting, and varied assignments that are within the range of students' abilities but challenge them to reach for the top of that range.
- Make connections to students' interests and intended careers.

Meta-cognitive

- Build self-regulative abilities by explicitly teaching students about them.
- Promote reflection to enhance attention to meta-cognitive aspects of learning.
- Provide timely and constructive feedback on the learning processes so students understand what they know and can do well, and what they need to improve.

Cognitive

- Engage students' prior knowledge through selection of learning tasks that are at appropriate levels of difficulty.
- Promote deep engagement with content through assignment design and tasks that require meaningful interaction with peers.
- Require students to integrate their knowledge and skills to complete increasingly complex assignments.
- Provide support to "scaffold" student learning, especially for assignments that require integration of knowledge and skills.
- Use assessments that make students' thinking processes apparent so their level of understanding can be assessed.
- Provide timely and constructive feedback that focuses on development of all elements required for expert-like performance: conceptual understanding, component skills, professional skills, and the integration of knowledge and skills.
- Use summative assessment techniques that evaluate and reward all elements required for development of expert-like performance.

Education: Research and Development in Curriculum and Instruction (Heywood, 2005), "Pedagogies of Engagement" (Smith, Sheppard, Johnson, & Johnson, 2005), and "Inductive Teaching Methods" (Prince & Felder, 2006).

We selected examples of learning experiences that support the development of expert practice but are not yet common in engineering education. Based on these criteria, we chose not to discuss the use of design projects or service learning, methods that are now widely used in engineering education. *Educating Engineers* by Sheppard et al. (2009) and "Engineering Design, Thinking, Teaching, and Learning" by Dym, Agogino, Eris, Frey, & Leifer (2005) provide good overviews of design as a teaching approach. The edited volume, *Projects that Matter:*

Concepts and Models for Service Learning in Engineering (Tsang, 2007), discusses the pedagogical foundations of service learning and provides examples of models for its implementation in engineering education. "Engineering Projects in Community Service" (Coyle, Jamieson, & Oakes, 2006) and the work of Baillie (2010) and colleagues in Engineering and Social Justice are good examples of the current use of service learning in engineering education.

In most cases, the engineering examples that we were able to locate have not yet been subjected to the rigorous levels of assessment typically found in evaluations of educational approaches in science and mathematics. As these approaches are more widely used in engineering education, more evidence of their effectiveness will be forthcoming. They are nonetheless notable because they incorporate elements of instructional practices that are likely to lead to learning that supports the development of expert professional practice.

Enhancing Conceptual Understanding

The development of deep conceptual understanding in a domain is a necessary condition for the development of expertise. Unfortunately, students often fail to develop such conceptual understanding due to the nature of the learning experiences that they encounter.

Students' failure to gain conceptual understanding of material from traditional approaches to instruction has been most substantially documented in studies of Newton's laws of motion using the Force Concepts Inventory (FCI) (Hestenes, Wells, & Swackhamer, 1992; Savinainen & Scott, 2002). The finding that led to substantial changes in physics instruction was that "no large gains from pre-test to post-test have been seen with conventional instruction." (p.48) Here, conventional instruction entails lecture and problem-solving sessions with a focus on solving traditional, textbook types of problems that lead to the development of algorithmic problem solving approaches.

A seminal paper by Hake (1998) demonstrated that "interactive engagement" approaches to teaching physics led to substantial improvement in conceptual learning. Hake defined interactive engagement as "designed in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors" (p. 65). Thus, teaching for interactive engagement entails several key characteristics of teaching to promote deep approaches to learning: the learning is focused on development of conceptual understanding, students' interest is activated by the nature of the activity and the questions asked, students engage in reflection using prior knowledge and they get immediate, formative feedback on their understanding.

One of the most extensively documented approaches to interactive engagement in physics instruction is a peer teaching method implemented by Mazur and colleagues at Harvard. Crouch and Mazur (2001) provide a summary of the first 10 years experience with peer teaching including the evolution of their approach based on results of assessment of the effectiveness of the method. They describe peer instruction as a modification of "the traditional lecture format to include questions that engage students and uncover difficulties with the material." The pedagogical goal of peer teaching is to "require each student to apply core concepts being presented and then to explain those concepts to their fellow students." The approach was initially used in introductory physics courses for non-majors at Harvard, but was eventually used in upper level courses and also at other institutions.

As originally implemented, the key elements of the peer instruction method as practiced by Mazur are: (1) Students must complete readings before coming to class in order to free up class time for peer instruction. Students complete reading quizzes before coming to class and they receive course credit for doing so. (2) Class is divided into a series of short presentations, each focused on a central point. (3) After each short presentation, students are presented with conceptual questions which probe understanding of the ideas just discussed in class. (4) Students are given a few minutes to formulate their answers individually and then they are to explain their answers to the other students sitting around them. The instructor encourages students to provide the reasoning behind their answers. (5) The students are polled for their answers. (6) The instructor discusses the answers and then moves to the next topic. (7) Students do not receive direct credit for their answers, but they do receive credit for consistently participating. Exams contain a significant number of conceptual questions, which also provides incentives to participate.

Crouch and Mazur provide a time series plot of the normalized gains in FCI scores of students in introductory calculus-based physics at Harvard over an eight-year period. Normalized gain is defined as the difference in post-test and pre-test scores divided by the maximum possible gain, i.e., 100% - pre-test score. During this time, the peer instruction method was being enhanced based on formative assessment. The first year in the time series was for students taught with traditional methods. That class showed a normalized gain of 0.23. The first year of interactive engagement resulted in a normalized gain of approximately 0.5, more than twice that of the traditional instruction. Subsequent years in the time series show even larger gains as the peer teaching method was refined. These results are consistent with many other studies of peer teaching that show substantial and significant positive effects, see e.g., Springer, Stanne, and Donovan (1999).

Crouch and Mazur report three major refinements to the peer instruction method: (1) Reading quizzes were replaced with Web-based assignments designed to have students think about the reading. (2) Cooperative learning activities were introduced into discussion sections. Roughly half of the total class time is devoted to conceptual understanding and hands-on activities. (3) Cooperative problem solving was introduced into the portion of the discussion sections devoted to problem solving. It is preceded by the instructor solving a similar problem that is "chosen to be challenging without being tedious" (p. 974).

Peer instruction methods would seem to have great potential for engineering education. Indeed some programs are now applying them systematically. For example, Rowan University's engineering faculty has used peer instruction in Statics classes (Chen, Kadlowec, & Whittinghill, 2005). The availability of student response systems (SRS) can facilitate the use of interactive engagement and enhances the ability to quickly see student responses. Hong Kong University of Science and Technology was one of the first institutions to make available SRS instructional technologies in all of their classes, doing so for more than a decade (Cue, 1998).

Improving Analysis Skills

As students begin to do engineering analysis in a given domain, such as thermodynamics, they often fall into algorithmic approaches to solving what looks to them like a wide variety of problems. A student might see something as a "pump problem" or a "turbine problem." Such categorizations probably arise from attending to surface problem features (e.g., it's a pump) rather than the deep conceptual principles. An expert in that domain, however, would see most of these problems as a single type involving conservation of energy. In this section, we summarize two examples of learning experiences that have been shown to move students away from algorithmic problem solving towards more expert-like behavior in their problem-solving: context-rich multifaceted problems and model-eliciting activities.

Context-rich, multifaceted problems. Using context-rich, multifaceted problems has been advocated by several groups as an approach to having students develop more sophisticated problem solving skills than those developed when solving typical textbook exercises. This approach supports the development of key skills and the ability to apply conceptual knowledge both of which are needed to address the complex problems typical of engineering practice. Thus, this learning experience acts as a bridging strategy from textbook problems to realistic problems. The contexts of the problems can be chosen to link to students' interests and career plans, increasing students' motivation as well.

Ogilvie (2009) describes multifaceted problems as problems that "lie somewhere between well-structured problems found in textbooks and large, ill-defined, open-ended challenges in the degree-of-difficulty these pose to students" (p. 3). A key characteristic of multifaceted problems is that they require students to integrate multiple concepts to construct a solution. Thus, students cannot use usual strategies of seeking examples in textbooks to identify the particular algorithm to solve the problem.

Ogilvie (2009) presents the following example of a multifaceted problem related to thermodynamics:

> You are in charge of drinks at a picnic that will start at 3pm. You place ice inside a cooler at 6am, when the temperature outside is 10°C. The day is forecast to warm up steadily to reach 30°C by 3pm. Estimate how much ice you will need (p. 3).

Because students are likely to have little experience in solving such problems, teaching in the course should include specific instruction on how to approach these problems. The complexity of the problems makes them well-suited to group problem solving activities.

In describing his use of context-rich, multifaceted problems in an introductory physics course, Ogilvie (2009) indicates that he uses these strategies. The problems serve as a "capstone" experience for each of the main sections of the course; over the course of the semester the students solve six such problems. The instructor solved several of these problems during class to model strategies that students could apply in their own problem solving. The students worked in groups of two or three to solve the multifaceted problems during recitation with support from a graduate teaching assistant (GTA). The GTAs received training on how to use questions that prompted thinking by the students rather than giving direct answers.

In addition to solving context-rich, multifaceted problems in recitation, students had to solve this type of problem on two group exams. They were graded on their use of appropriate strategies, e.g., "representing the problem with a diagram and their description of ongoing monitoring of the progress of the solution" (Ogilvie, 2009, p. 4).

The approach described by Ogilvie is well aligned with the characteristics of effective learning experiences listed in Table 1. It offers students a challenge that forces them to use their prior knowledge in new ways. It also presents problems in more realistic contexts that enhance the interest of students and uses collaborative approaches that encourage deeper engagement.

Ogilvie evaluated the impact of this approach on students' analysis strategies by collecting students' reflections at the beginning and end of the semester in response to the following questions:

> Please reflect on how you approach physics problems. What methods do you use? What mistakes do you have to watch for? And are these approaches similar to skills that you will need in your future studies or career? (p. 4)

Two hundred sixteen students submitted both reflections. Their responses were analyzed by Ogilvie and an experienced colleague based on a scheme that divided the problem solving approaches students described into two categories: "limiting" and "expansive." Limiting strategies included equation matching, listing knowns and unknowns, and using prior examples. Expansive strategies included thinking about re-representing the problem with a diagram, thinking about concepts first, using qualitative analysis, and identifying sub-problems. The major conclusion from the analysis is that using the multifaceted problems led to significant and substantial increases in the number of students who described themselves as using expansive strategies in solving problems.

Model-eliciting activities. Model eliciting activities (MEAs) that promote deep approaches to learning were first developed in mathematics education (Lesh & Doerr, 2003). MEAs are being adapted to engineering education by several groups, see e.g., Diefes-Dux and Imbrie (2008) and Moore et al. (2008). The overall goal of MEAs is to facilitate the development of conceptual foundations of knowledge that will support deeper understanding (Lesh et al., 2000). Diefes-Dux, Verleger, Zawojewski, and Hjalmarson (2009) define MEAs as "open-ended, realistic, client-driven problems set in engineering contexts requiring teams of students to create a generalizable (shareable, reusable, modifiable) mathematical model for solving the client's problem." One of the distinguishing features of the MEA approach is that it incorporates multiple points of formative feedback and iteration to help students develop strategies and methods to solve such problems (Verleger & Diefes-Dux, 2008).

The design of the problems themselves is guided by six principles from Lesh, Hoover, Hole, Kelly, and Post (2000): (1) Reality: the activity provided should occur in "real life"; (2) Model construction: the activity must create the need to develop, revise, refine, and extend a mathematical model; (3) Self-assessment: students should determine themselves if their solution meets the criteria for success, often described as needs of a client; (4) Model documentation: the documentation required of the students should reveal their thinking; (5) Generalizability: the activity should guide students to develop their model in a way that will allow others to not only use it to solve the immediate problem but also use it for their own purposes; (6) Effective prototype: the activity should involve learning processes and knowledge that students will use in their academic and professional careers.

MEAs encourage deep engagement by demanding production and justification of a mathematical model. The problems are cast in a realistic context that should enhance student interest and motivation. The method also helps students to develop the ability to assess their progress toward a successful solution, an important meta-cognitive skill. (MEAs can be considered a specific type of problem-based learning, which we address directly in the next section.)

Purdue University began the process of integrating MEAs in a required first-year engineering class in 2002. Diefes-Dux and Imbrie (2008) describe the implementation process, which continues today with cycles of assessment and improvement. The overall goal for the implementation of MEAs was to "bring engineering content and contexts into the first-year to help students better understand the nature and practice of engineering and to better prepare students for the sophomore year while addressing a number of ABET criteria" (p. 56). The learning objectives for the course that are fulfilled through the use of MEAs were: develop a logical problem solving process, translate a written problem statement into a mathematical model, solve fundamental engineering problems using computer tools, and work effectively and ethically as a member of a technical team.

The implementation presented many challenges because the enrollment of the class is typically in excess of 1,400 students. The class format includes two 50-minute lectures and one 110-minute laboratory session. The MEAs are used in the laboratory sessions, which are guided by graduate teaching assistants who have been carefully prepared to implement and assess MEAs effectively and consistently.

The students receive the MEA initially in the form of a memo from a client to help them engage the problem. The memo includes questions that are intended to help orient individual students to the problem and to assist them in organizing their knowledge related to the problem. The MEA problem statement is open-ended so students must define the problem that must be solved to meet the needs of the client and define a plan of action to meet those needs. The underlying problem is sufficiently complex that the teams will have to go through several iterations to revise and refine their model so that it will be useful to the client. MEAs developed at Purdue include Aluminum Crystal Size (Diefes-Dux, Hjalmarson, Zawojewski, & Bowman, 2006), Campus Lighting Design, and Nano Roughness (see appendices of Zawojewski et al., 2008)

Extensive assessment was conducted throughout the implementation process; much of which is presented in Zawojewski, Diefes-Dux, and Bowman (2008). Assessment methods included direct observation of team performance and assessment of student work as well as surveys and interviews with students, teaching assistants and instructors. Improving the assessment of student work to provide meaningful feedback remains an on-going activity (Diefes-Dux et al., 2009).

Developing Complex Problem Solving and Professional Skills

Development of sophisticated analysis skills is a prerequisite of expert professional practice, but they alone are not sufficient to be an expert in solving complex problems. Developing the additional skills necessary such as the ability to identify the nature and relevant context of the problem, what knowledge is needed to address it, and what methods are best suited to solve the problem can only come with practice in solving complex problems. In many engineering curricula, students will have a chance to practice these skills only in the capstone experience in the final year of study. Work completed by Atman et al. (2010) has demonstrated that even two design experiences do not improve students' ability to consider broader context in their design process. Thus, it is clear that students would benefit from a greater number of opportunities to address authentic problems. The use of Problem-based Learning (PBL) is one approach that can be used to allow students to practice complex problem solving throughout their academic studies.

The basic flow of a PBL process is as follows: (1) Student teams are presented with a complex, ill-structured problem. (2) Students work to define the problem and to identify what they know that is relevant to the problem. They also identify what they need to know and how they will learn it. (3) Students engage in learning independently and then come together as a team to share learning and to use their existing and new knowledge to formulate solutions. They assess the quality of their proposed solutions and decide what additional learning is needed to select and refine their solution. (4) The cycle is repeated until the students arrive at an acceptable solution, which they then present in written and oral forms.

A significant difference between a typical capstone experience and a PBL experience is that students engaged in a PBL process will also be asked to reflect on their learning and team skills with the explicit goal of improving these skills. This aspect of PBL incorporates the meta-cognitive characteristics of effective learning experiences. As with peer learning, PBL is used in a wide range of disciplines and its positive effects on learning are well documented, see e.g., Walker and Leary, 2009.

A number of engineering programs around the world have made a commitment to the integration of PBL across courses. The first such program to do this was Chemical Engineering at McMaster University in Canada with an effort that began in the late sixties (Woods et al., 1997). That work was followed by a few others in the U.S. and Europe including Worcester Polytechnic Institute (Hazzard, 1975, Grogan, Schachterle, & Lutz, 1988), Aalborg University, Linkoping, Roskilde, & Maastricht. More recently, a number of engineering programs in Australia have rebuilt their curricula around PBL including Civil Engineering at Monash (Hadgraft & Grundy, 1998) and at the University of Southern Queensland where traditional courses on computers, instrumentation, and numerical analysis were replaced with PBL courses (Brodie, 2007) as well as Chemical Engineering at the University of Queensland, Central Queensland University (CQU), University of South Australia, Victoria University (VU), and RMIT University (Hadgraft & Muir, 2003). The approach to integrating PBL into the curriculum at Aalborg University is the best documented in the literature (e.g, De Graaff & Kolmos, 2003; Kolmos, 1996) and will serve as the primary example of the use of PBL at the course level.

At Aalborg, student teams for PBL contain up to seven students; the number of students in the team gets smaller as the students progress through their studies. Every semester the teams produce a major project report, on the order of 70 pages in length. For their PBL project the teams have two supervisors. One serves as a technical expert in the broad domain of the project and serves as the main supervisor. The second supervisor supports understanding of the broader context of the problem and serves as the primary advisor during the writing phase of the project. In addition to the PBL experience, students typically are taking several courses. Some of the courses focus on building the skills required for PBL while other courses are intended to build knowledge in specific subjects such as mathematics, science, or engineering.

In some cases students are given a choice of projects. For example, first-year students can choose among projects related to mathematics such as: bird flu, how to measure spread scenarios, DNA-micro array techniques in support of diagnosing diseases, and Google's page rank system (Christensen, 2008). Each project is summarized in a one-page description. Once a team chooses a project, they begin defining their strategy for addressing the project and preparing the final report, in close collaboration with the two supervisors.

Christensen describes each of these problems and how the students approached them. For example, in the bird flu project, the team of seven students decided to address the issue of how many people would become ill and die if the disease reached Denmark. To answer this question, the students had to engage not only mathematical knowledge but they also had to find answers to questions like "How does the bird flu spread?" and "How effective is Tamiflu® in preventing it?" The students actually reframed the question that they wished to address and focused on the possible overreaction of the public to the threat of bird flu. They used their mathematical models and a range of assumptions to formulate "realistic" and "worst case" scenarios. Thus, this problem statement led the students to learn a good deal about the spread of disease and consequences of predictions made using their mathematical tools.

Employer evaluations comparing Aalborg graduates to students from the Technical University of Denmark (DTU), which does not make extensive use of PBL, show clear superiority on a number of criteria (Kjærsdam, 2004). Forty-one percent of respondents evaluated Aalborg graduates as good or very good at project and people management versus just 9% for DTU. Aalborg graduates were also rated higher in innovative/creative skills (81%/59%). Graduates of the two programs received equivalent ratings on quality of engineering and technical skills (86%/85%). Thus the intensive focus on PBL seems to have enhanced the Aalborg graduates' ability to apply their knowledge to solve complex problems creatively and collaboratively.

Enhancing Learning from Experimentation

Students' understanding of a domain can be enhanced when they engage in laboratory experiments. Unfortunately, traditional labs where students follow prescribed procedures often fail to engage students in the deep learning processes that lead to conceptual understanding. An inquiry-based laboratory is one alternative approach that can address this shortcoming. For additional discussion of the challenges and potential of learning in laboratories, readers can refer to Sheppard et al. (2009) and Hazel and Baillie (1998).

Inquiry-based learning is described in the National Science Education Standards (National Academies, 1996) as:

> … making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations. (p. 23)

In inquiry-based laboratories, students learn to design and conduct experiments to answer questions, often of their choosing, as opposed to traditional laboratories where they follow procedures to arrive at pre-determined results. Thus, these experiences challenge students to regulate their own learning and to apply their knowledge and skills to realistic problems.

A substantial body of literature exists on the use of inquiry-based learning in science education. Results from these studies indicate that inquiry-based approaches in laboratory courses can improve ability to design experiments and analyze data (Miles and Burgess, 2003), enhance conceptual knowledge (Wallace, Tsoi, Calkin, & Darley, 2002), and increase interest in subject matter (Howard & Miskowski, 2005). Only a few examples of the use of inquiry-based approaches in engineering laboratories were found in the literature. We will summarize two of them here: Lisenmeier, Kanter, Smith, Lisenmeier, and McKenna (2008) to illustrate the use of inquiry in a pre-laboratory and Flora and Cooper (2005) to illustrate the use of student-defined experiments.

The study by Lisenmeier et al. (2008) was conducted in a biomedical engineering physiology course. The goals of the study were to "enhance students' ability to learn and transfer concepts in metabolism" (p. 213). Their approach to achieving these goals was to introduce a new laboratory module that required students to apply their knowledge and laboratory skills to answer the question: "How much food is needed by an astronaut per day for a two week space mission in order to satisfy metabolic demands and not gain or lose weight?" (p. 213). The authors refer to this question as the "challenge." Thus, their basic pedagogical approach was inquiry-based. In the course of answering this question students were challenged to "reason from the biochemical to the systems level" and to "make measurements of their own metabolic rate" (p. 213).

The study used an experimental design that compared the performance of students in the inquiry-based laboratory to students in a control group. There were three rounds of data collection in three separate offerings of the course. Both groups experienced a 1.5 hour pre-lab discussion and the lab itself, which required 2.5 hours; all students in both groups had to submit individual lab reports that explained their findings and made recommendations for the astronaut's diet. The experience in the remainder of the course such as lectures, exams, and homework, was identical between the two groups with one exception. In the third round of data collection, the students in the inquiry-based group received a short homework assignment designed to prompt reflection on some key issues after completing the pre-lab.

During the pre-lab discussion for the inquiry-based group, the instructor used guided discussion to allow the students to discover and/or recall the key content knowledge required to answer the challenge question on the astronaut's diet. The discussion led students to discover and/or recall key concepts and theory. At the end of the pre-lab, students received a handout summarizing the key points of the discussion. The handout was prepared ahead of time because the instructor guided the discussion to ensure that the required information arose from the discussion. In contrast, the control group received the handout at the beginning of the pre-lab and followed along as the instructor expanded upon and explained the handout.

During the lab session students in both groups had access to the necessary equipment to make the measurements of oxygen consumption. The instructor guided the inquiry-based group to answer questions that arose as they implemented the experiments. For the control group, the instructor simply answered the groups' questions without attempting to prompt them to find their own answers.

Assessment of the impact of the inquiry-based approach to the lab was based on evaluation of student answers to pre-test questions on a mid-term exam, post-test questions on the final exam, evaluation of the lab reports, and a survey to gauge students' response to their experiences. For direct measures of knowledge gained from pre/post-test and discussion in the lab reports, the two groups were essentially equivalent. However, for the third round of data collection with the additional reflection assignment, the inquiry-based group was able to list more factors that determine metabolic rate (effect size $= 0.70$, $p = 0.007$). On a final exam problem intended to measure ability to apply the knowledge gained to a new problem, the inquiry-based group showed a statistically significant improvement over the control group (effect size $= 0.43$, $p = 0.047$). The knowledge elements required for successful completion of the problem were: a mass balance for CO_2 production, the stoichiometric relationship among glucose, oxygen and CO_2, and the conversion of volume of CO_2 to kilocalories.

Flora and Cooper (2005) summarize their study of the effectiveness of inquiry-based experiments in Introduction to Environmental Engineering, a junior-level course, compared to traditional experiments. In the inquiry-based experiments student teams designed and conducted experiments of their choosing. The inquiry-based experiments are done in the last four weeks of the semester; the course also includes several traditional labs in the earlier portion of the semester. Course enrollments were approximately 20 students over the five-year period of the study. Introduction to Environmental Engineering is part of the civil engineering curriculum; it enrolls primarily civil engineering students but students from other engineering majors and from some science majors also take the course.

The instructors set several intermediate goals for the design experiments throughout the semester to ensure that students would make adequate progress. Each team had to select the topic for their inquiry-based experiment by the third week of the semester. The teams were asked to brainstorm about current local environmental topics and then to investigate them using the journals and the internet. During this period, the instructors had extensive discussions with the students to ensure that the experiment could be performed with the analytical equipment that was available. Topics that teams selected for investigation included: effectiveness of hog waste lagoons, indoor air quality, water quality in local high schools, and acid mine drainage. During weeks four to six, the students formulated their experimental procedures. In the seventh week, the teams submitted a formal memo describing the problem statement, experimental procedures, required materials, and expected results.

At the end of the semester, students received a questionnaire asking them to evaluate their experiences in the inquiry-based and traditional labs. The survey used a five-point Likert scale, which was scored with a scale from 2 for strongly agree to -2 for strongly disagree. Key findings from the survey indicated that, compared to traditional labs, the inquiry-based labs helped students to better understand basic environmental concepts (Average response = 0.69); better visualize the application of theory learned in the class (Average response = 0.76); and better understand how to design and conduct experiments (Average response = 1.05).

Integrating the Liberal Arts and Engineering

A recent book entitled, *Holistic Engineering Education: Beyond Technology*, (Grasso & Brown Burkins, 2010) describes a model for the education of engineers who are prepared to meet the challenges of the twenty-first century. The holistic approach to engineering education is a "more cross-disciplinary, whole systems approach to engineering that emphasizes contextualized problem formulation, the ability to lead team-centered projects, the skills to communicate across disciplines, and the desire for life-long learning of the engineering craft in a rapidly changing world" (Grasso & Brown Burkins, p. 1). Holistic engineers are defined as those who "understand complex interdisciplinary systems" and "bring the power of engineering thought to issues spanning and connecting technology, law, public policy, sustainability, the arts, government, and industry" (p. 1).

One element of holistic engineering education is the intimate integration of liberal arts and engineering, which supports the ability to understand problem context and to communicate across disciplines. There are a growing number of examples in the literature on approaches to achieve this integration including work at Smith College (Christ, 2010), Union College (Traver & Klein, 2010), and Binghamton University (Catalano et al. 2010).

Among the examples of the integration of the liberal arts and engineering at Smith is one that involves the integration of the work of the French philosopher, Foucault, into an introductory thermodynamics course (Riley & Claris, 2006). This work is part of the effort to use pedagogies that "empower students through active engagement and self-reflection" (Riley & Claris, 2006, p. 1), methods that are consistent with the practices presented in Table 1. Among the learning objectives related to the use of Foucault's writings in the course are to: "Stimulate critical thinking about the course, lay groundwork for connections made later about the history of thermodynamics, and course content including the second law, and give students an opportunity to reflect on engineering and society, science and truth, etc" (Riley & Claris, 2006, p. 2).

The specific excerpt of Foucault's work on power/knowledge that was selected for the class dealt with the role of science in establishing what is accepted as "truth" by society as well as the role of political forces that can control the production and transmission of scientific findings. This particular excerpt was selected to allow students to "question the politics of what questions are considered in science and how society decides what counts as truth, and thus stimulate critical thinking about the course content."

A variety of assignments were used throughout the class to help students reflect in an integrative manner about the meaning of Foucault's writing and its implications for the field of thermodynamics and the class itself. An in-class discussion asked the students to reflect upon power/knowledge relationships related to the ideal gas law, which many considered an absolute truth prior to encountering real-gas equations of state. Important points that arose in the discussion included whether the real-gas equations of state were more "true" than the ideal gas law and the "strong preference science has for an elegant equation that can summarize complex physical relationships concisely and mathematically" (Riley & Claris, 2006, p. 8). The former led to a discussion of the importance of understanding the role of approximation in engineering analysis and the latter set the stage for a planned discussion about the development of the concept of entropy and Foucault's work.

Other assignments included a reflective essay on the relationship of knowledge and power in the context of the thermodynamics course and also in students' personal experience. One student made a connection between what we choose to learn and its potential to impact others: "The concepts we learn as students are most likely the ones we will later on be most comfortable with as engineers. This means that the choice of concepts has power not only over individual students, but also over the people whose lives our engineering will influence" (Riley and Claris, 2006, p. 8).

An examination question was used to evaluate the extent to which students had the ability to apply what they had learned from using Foucault's works in course assignments. The students were asked to critique a passage from the textbook that presented "entropy analogies that are thermodynamically questionable and have social implications" (Riley & Claris, 2006, p. 11). To evaluate the course, the instructor also used focus groups to assess effectiveness of the integration of Foucault's work into the course.

Overall the evidence suggests that many students in the class made good progress towards meeting the learning objectives related to the integration of Foucault's work. The focus group discussions led to two main themes related to the extent to which the students perceived the assignments as effective for their learning. A majority of participants in the focus groups indicated that they saw critical thinking as an important part of the class and that they felt that they had improved on this skill as a result of the class. A smaller number of participants in the focus groups felt that the work on Foucault detracted from the important content in the class, namely thermodynamics. One student from this group put it as follows: "If I wanted to be writing essays all the time, I would take an English class. This class was good if you wanted to be well rounded and if you want to be a good writer but I don't think that's the right class for it because I feel I have hard enough of a time trying to understand the material, I want more examples and not more essays to write" (Riley & Claris, 2006, p. 12).

This group of students may or may not have grasped the importance of critical thinking and integrating knowledge for engineers, or perhaps they did not find the argument for their presence in the course to be convincing. In either event, their unfavorable opinions of the approach demonstrates one of the challenges that instructors will face as they begin to use instructional practices that move away from traditional approaches to teaching—resistance from some of their students.

In this section, we have summarized a set of instructional approaches that support the development of expert practice, but that are not yet common in engineering education. In the next section, we turn to the topic of transforming engineering curricula to include greater numbers of such instructional practices. We also discuss some of the challenges that must be overcome if such curriculum transformation is to be successful.

TRANSFORMING ENGINEERING CURRICULA: OPPORTUNITIES AND CHALLENGES

The literature on course and curriculum design recommends aligning learning objectives, learning experiences, and student assessments; see for example, Biggs (2003), Wiggins and McTighe (2005), Diamond (2008), and Posner and Rudnitsky (2006). This approach is fundamentally different from that of choosing lecture topics, identifying suitable tutorial problems, and writing exams. A focus on learning activities provides opportunities for many other kinds of learning experiences, including traditional problem solving classes (tutorials), project-based learning, work placements, design tasks, laboratory work, and so on, that are consistent with the characteristics of effective learning experiences. Shuell (1986) wrote:

> If students are to learn desired outcomes in a reasonably effective manner, then the teacher's fundamental task is to get students to engage in learning activities that are likely to result in their achieving these outcomes, … it is helpful to remember that what the student does is actually more important in determining what is learned than what the teacher does. (p. 429)

In curriculum design, decisions should be made on how best to arrange the sequence of learning experiences so that the students are encouraged to make linkages and connections across courses to build rich, interconnected knowledge. As a curriculum is designed, consideration should be given to establishing sequences of learning experiences that drive the development of increasing levels of competence in key skills such as analysis and design. In these sequences, students should meet ever greater challenges that promote higher levels of achievement. The "spiral curriculum" offers one model of how to achieve such sequencing (see e.g., Dixon, Clark, DiBiasio, 2000).

In *Educating Engineers: Designing for the Future of the Field*, Sheppard et al. (2009) discuss another important decision in curriculum design, selecting the optimal balance of learning experiences aimed at developing knowledge and skills, including professional skills, with learning experiences that require integrated application of the knowledge and skills. Based on a study of engineering programs at a number of institutions in the U.S., Sheppard et al. concluded that current curricula are heavily weighted toward analysis at the expense of effort aimed at developing design, experimentation, and professional skills. They offer a model for the transformation of engineering education that is consistent with the characteristics of effective learning experiences: "The ideal learning trajectory is a spiral, with all components revisited at increasing levels of sophistication and interconnection. In this model the traditional analysis, laboratory, and design components would be deeply interrelated…" (Sheppard et al., 2009, p. 191).

Achieving a transformation of engineering education in a manner consistent with the characteristics of effective learning experiences presents many challenges. Sheppard et al. (2009) note that teaching to develop deep understanding of concepts, and the ability to apply them, is a major challenge for engineering educators. The work of Nelson Laird, Shoup, Kuh, and Schwarz (2008) on learning in different academic disciplines demonstrates that common teaching practices in undergraduate engineering programs often discourage the use of the very approaches to learning needed to construct deep understanding.

Using data from 517 U.S. colleges and universities gathered as part of the National Survey of Student Engagement (NSSE), Nelson Laird et al. (2008) investigated the effect of discipline on students' use of deep learning approaches as well as on the achievement of three learning outcomes: student self-reported gains in personal and intellectual development, satisfaction with college, and self-reported grades. They also investigated the teaching approaches that faculty reported using across a range of disciplines. The data included survey responses from 80,000 college seniors and 10,000 faculty members (Kuh, 2003).

The investigators selected three sets of items from the NSSE as a measure of deep learning approaches: (1) higher order learning, analyzing basics elements of an idea or theory, synthesize information into new more complex forms, applied theories/concepts to practical or new problems; (2) integrative learning, worked on paper or project that required integration of ideas from various sources, including diverse ideas, put together ideas from different courses, discussed readings/classes with faculty outside of class, discussed readings/classes with others outside of class; and (3) reflective learning, evaluated strengths and weaknesses of own views, tried to understand another person's perspective by imagining how an issue looks from another's point of view, learned something that changed the way you understand an issue or concept.

When combined, these three sets of items form a scale with a reliability coefficient of 0.72. A complementary set of items from the faculty version of the NSSE provided information on the extent to which faculty emphasize higher order and integrative learning in their courses, and the importance they place on reflective learning in the courses they teach.

The findings are discussed using Biglan classification, which categorizes academic disciplines on three dimensions: whether they are pure or applied fields, whether they deal with life or non-life topics, and whether they are hard or soft (whether they exhibit a high or low degree of consensus about the knowledge and methods in the field) (Nelson Laird et al., 2008 p. 472). Most engineering fields fall within the hard, applied, non-life categories. The two findings most relevant to engineering are: that a positive correlation was found between the frequency of use of deep approaches to learning and the levels of student self-reported intellectual and personal development, consistent with studies of deep approaches to learning, and that the hard-soft distinction was the strongest predictor of differences across disciplines for both senior students and faculty members. For students in hard fields, the average level of use of deep learning approaches was nearly one-quarter of a standard deviation lower than for students in soft fields. For faculty, the difference was much more substantial. The average score for emphasis on deep learning by faculty in the hard fields was nearly three-quarters of a standard deviation below the average for faculty in soft fields.

The latter finding suggests that engineering instructors are less likely to design courses that engage students in deep approaches to learning than instructors in "soft" fields. This finding suggests that introduction of greater numbers of effective learning experiences will run counter to the preferences of many engineering instructors. The relationship between students' use of deep learning approaches and their self-assessment of intellectual growth indicate that engineering students are not as likely to feel they are developing intellectually and personally as their peers in non-technical fields.

Brint, Cantwell, and Hanneman (2007) offer a different perspective on engagement in engineering and science. Their work is based on data collected in 2006 from more than 6,200 students at eight large campuses of research universities in the University of

California system using the University of California's Undergraduate Expectations Survey (UCES). Students in the UC system come from the top eighth of high school students statewide and thus represent a relatively high-achieving group of students. Only the responses from upper division students were used to allow for an analysis of the effects of academic discipline on engagement.

This analysis identified two cultures of engagement with different educational values and norms:

> The humanities/social sciences (HUMSOC) culture of engagement prizes participation, interaction, and interest in ideas. It is closely related to the NSSE scale measuring active/collaborative learning. By contrast, the natural sciences/engineering (SCIENG) culture of engagement prizes quantitative skills and collective work on problem-solving as a means to obtain high-paying jobs after graduation. It is not closely related to any of the NSSE benchmarks. (Brint et al., 2007, p. 387)

The scale items that correlated most highly with engagement in the Humanities and Social Science culture, were (in order of decreasing factor loadings): asked an insightful question in class, brought up ideas or concepts from different courses, contributed to class discussion, talked with faculty about course materials, did more work than required because the course was so interesting, and communicated with faculty member by e-mail or in person. Brint et al. (2007) describe this culture as one of "individual assertion, classroom participation, and interest in ideas" (p. 390).

For the Sciences and Engineering culture, the most highly correlated scale items were (in order of decreasing loadings): developed quantitative skills, helped classmate understand material better, worked with group of students outside of class, reason for major: leads to high paying job, looked for courses in major that explain and solve problems, and developed computer skills. None of the survey items related to student-faculty interactions, participation or interest in ideas were loaded on the SCIENG factor. The SCIENG culture is described as one "based on working toward quantitative competencies through individual study and collaborative effort."

This study indicates that there are fundamental differences in expectations for engagement by students in engineering compared to majors in humanities and social sciences. These expectations may represent a hurdle to increasing demands for use of deep learning approaches, which may not be what engineering students expect and/or want. In the work to integrate philosophy into a thermodynamics course, Riley and Claris (2006) had some students who expressed the view that the integration was not what they wanted from a thermodynamics course. Clearly, implementation of deep learning experiences may lead to student dissatisfaction and resistance.

Several other recent analyses of national data demonstrate that academic cultures reinforce and reward different patterns of abilities, interests, and values while simultaneously discouraging others (Smart, Feldman, & Ethington, 2000). Moreover, research on engineering faculty and students provides evidence of differences among students and faculty in different fields of study (Lattuca, Lambert, & Terenzini, 2008; Lattuca, Terenzini, Harper & Yin, 2010). Of particular interest is the finding that there are sometimes large variations in the curricular emphases engineering faculty in different fields placed on professional and social contexts in their courses and their use of active learning pedagogies in their classrooms (Lattuca et al., 2010).

In addition to the challenges presented by the academic culture of engineering, other barriers must be overcome if we are to integrate greater numbers of effective learning experiences across our curricula. A potentially major barrier is the tension between the large amounts of content that can be covered within engineering courses and the amount of time that use of deep learning approaches requires. Many faculty members feel pressure to cover large amounts of content. Adopting teaching practices and assignments that require deep approaches to learning will potentially reduce the amount of material that can be covered while actually increasing the amount of material that is learned and retained by the students.

Another potential barrier lies in the need for special facilities for some types of effective learning experiences such as problem-based learning. This need for special facilities can be a major hurdle because creating sufficient numbers of spaces where students can meet to engage in the learning required by PBL requires financial resources.

A key process for any successful transformation in engineering education is supporting the faculty as they learn about and prepare to use teaching and learning methods that are unfamiliar to them. The paper by Felder, Brent, and Prince (2011) in this issue is dedicated to the topic of engineering instructional development. Among the topics covered in the article are options for instructional development program content and organization and recommendations to improve the quality and effectiveness of such programs.

In spite of substantial barriers, engineering programs around the globe are finding ways to integrate effective learning experiences throughout their curricula. As noted earlier, a number of engineering programs in Australia have rebuilt their curricula around PBL (Brodie, 2007). At Rowan University in the U.S., engineering students have "engineering clinics" each semester in which students engage in design projects to develop their technical and professional skills (Kadlowec et al., 2007). At Olin University, also in the U.S., engineering curricula focus on interdisciplinary projects and coursework, and have design integrated across all four years of study (Somerville et al., 2005).

Summary and Recommendations

In this article, we have defined effective learning experiences as those that support the development of expert professional practice. Drawing from the literature on development of expertise, students' approaches to learning, students' responses to instructional practices, and the role of motivation in learning, we formulated a set of instructional practices (Table 1) that are most likely to elicit learning that supports the development of expert professional practice. We described examples of course-level teaching methods in engineering, science, and mathematics education that are consistent with these instructional practices. We found, however, that the assessment of how successful the methods were in achieving desired outcomes varied significantly, especially for the examples from engineering.

Assessment of the peer instruction method in physics involved the development of an assessment tool, the Force Concept Inventory, which assesses whether students are acquiring the conceptual knowledge that is the goal of the instructional method. Such exemplary assessment is now just beginning in engineering education with the development of concept inventories in a number of domains (Reed-Rhoads & Imbrie, 2008). The use of model eliciting activities, MEAs, in the introductory engineering class at Purdue is an outstanding example of the use of formative assessment to develop an instructional method of great complexity. However, that effort has not yet produced evidence on the effectiveness of the MEAs in achieving the desired learning outcomes. Finally the assessment of the use of inquiry-based learning in an environmental engineering class focuses only on its impact on students' attitudes and beliefs about the effectiveness of the method. This assessment addresses important questions related to student motivation, but it is not sufficient to establish that learning outcomes are being achieved.

Clearly, we in engineering education are not as far along in implementing and assessing various types of effective learning experiences as our colleagues in mathematics and science education. Therefore, we have a great opportunity to learn from their work and to adapt their methods to studies within engineering education. During the process of adaption, we will have opportunities to do in-depth assessment of effectiveness of different learning experiences and to conduct research on engineering student learning. (Two other papers in this issue, "Situated Learning: Bridging Engineering Education Research and the Learning Sciences" by Johri and Olds (2011), and "Emerging Methodologies in Engineering Education Research" by Case and Light (2011) provide important insights into the process of assessing learning experiences in engineering education.)

When we sought examples of engineering programs where effective learning experiences were systematically integrated across an entire curriculum, we found a few, which we discussed at the end of the previous section. Those programs that have achieved curriculum-level integration of effective learning experiences did so in spite of substantial barriers that can discourage such integration. We believe that the use of a systematic curriculum design process can assist in overcoming such barriers and greatly increase the chances of successful curriculum-level integration of effective learning experiences. New engineering programs that are arising in nations around the world have a unique opportunity to apply such a process to build their curricula around effective learning experiences and to evaluate the effectiveness of a curriculum-level design process.

The literature summarized in this paper also raises important research issues related to the development and implementation of effective learning experiences in engineering education. The studies by Brint et al. (2007) and Nelson Laird et al. (2008) suggest that the academic culture in engineering may discourage the development and implementation of experiences that promote the use of deep approaches to learning. If this is an accurate assessment, research is needed to determine the effects of the academic culture of engineering on our students' learning as well as its impact on which students choose to enter and remain in the engineering.

Further study is also needed to understand why the majority of enhancements in undergraduate engineering education are made at the course level and why so few have been undertaken at the curriculum level, where the potential to effect changes that improve learning is great. A related question is why, when compelling evidence exists for the effectiveness of methods such as peer learning and inquiry-based learning in science education, have such methods not seen greater adoption in engineering? Research is providing some clues to the barriers- as well as the facilitators-of curricular and instructional changes. We believe, however, that further research is needed to understand how best to promote the integration of effective learning experiences throughout the undergraduate engineering curricula.

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