THE NATURE AND DEVELOPMENT OF ENGINEERING EXPERTISE[1]

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Abstract

"Engineering is the application of science and mathematics to human problems." This is a view that pervades engineering education. Recent emphasis in the United States is "engineering is design." The thesis of this paper is that engineering as science as well as engineering as design are inadequate conceptions of engineering. The thesis is supported by comparing school and out-of-school knowledge. The nature of engineering is explored in terms of the activities of engineers and the goals of engineering education. Koen's definition of the engineering method "The engineering method is the use of heuristics to cause the best change in a poorly understood situation within the available resources" is introduced. The nature of expertise is examined. Alternatives to the "empty vessel" model are presented for the development of engineering expertise. The alternatives include cognitive apprenticeship, reflective practicum, cooperative learning and problem-based instruction.

Introduction

I have been involved in engineering, as a student and as a professional, for over twenty years. Frequently I have been troubled by the question, What is the engineering method? Is it applied science? Is it design? As a professor I have struggled with the question, What should my students learn and how should they learn it? These concerns prompted me to address the question, What is the nature of engineering expertise and how can it be developed effectively?

A study conducted by one of my colleagues (Johnson, 1982) provides valuable insight into the activities of engineers. My colleague was hired to collect protocol from engineering experts while they solved difficult problems. Working with a team of professors, he developed a set of difficult and interesting problems, which he took to chief engineers in large companies. In case after case the following scenario was repeated. The engineer would read the problem and say, "This is an interesting problem." My colleague would ask, "How would you solve it?" The engineer would say, "I'd check the engineers on the floor to see if any of them had solved it." In response, my colleague would say, "Suppose that didn't work." "I'd assign the problem to one of my engineers to check the literature to see if a solution was available in the literature." "Suppose that didn't work," retorted my colleague. "Well, then I'd call my friends in other companies to see if any of them had solved it." Again my colleague would say, "Suppose that didn't work." "Then I'd call some vendors to see if any of them had a solution." My colleague, growing impatient at not hearing a problem solution, would say, "Suppose that didn't work." At some stage in this interchange, the engineer would say, "Well, gee, I guess I'd have to solve it myself." To which my colleague would reply, "What percentage of the problems you encounter fall into this category?" Engineer after engineer replied, "About five percent"!

Are we preparing our students to solve five percent of the problems?

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I think the only responsible answer to this question is, "I should hope so, and in a fashion that is well-integrated with coursework which assures that they will be able to effectively 'solve' the other 95% of the problems they will face as professional engineers." Indeed, we must take great pains to see that our students are learning how to accomplish the 95% of their future tasks, as well as the 5%. There may be a tendency to think that this 95%, this asking questions and searching other sources for the solution, is either trivial or else unrelated to engineering education. In order to recognize a solution to a complex or difficult question certain knowledge and abilities are required. Such knowledge will often be, in part, specific to the field, and as such will have been acquired through specific education in the field. Such abilities may be more generalizable heuristics, but it should be expected that the continued development and utilization of them will have occurred throughout the educational experience, specifically, even through the undergraduate engineering curriculum itself. Refer to Koen (1985) and Latour (1987) for further discussion of the heuristics of engineers.

I have asked the question, What are your goals? of engineering faculties at numerous universities in the United States, France, England, and Norway. A wide variety of goals have been presented, including understanding mechanisms, discovering the truth, improving practice, helping students, solving problems, and developing students' problem-solving skills. The goals can be grouped into two broad categories: (1) the advancement of the state of the art and (2) the development of talent. The distribution of effort between these two goals varies considerably, from a strong emphasis on research (advancing the state of the art) to a strong emphasis on teaching (developing talent). The Director of the National Science Foundation in Washington, recently advocated these two goals (Block, 1987):

> The nation's science and engineering enterprise must have the financial resources to do two things: remain at the leading edge of discoveries and produce the technical personnel that the country needs.

In the remainder of this paper, the nature of engineering is examined along with the nature of expertise. School knowledge and out-of-school knowledge are compared. Recommendations for the development of expertise in engineering are presented and specific strategies for their implementation are suggested. These recommendations focus on means for getting students involved in learning through active learning strategies such as cooperative learning.

The Nature of Engineering

Engineering is popularly defined as applied science. Although this definition has been effectively disputed (DeSolla-Price, 1984; Koen, 1985; McKelvey, 1985; Roy, 1985; Smith, 1986), it still pervades the engineering curriculum. Roy (1985) states, for example, that thermodynamics (science) owes more to the steam engine (technology) than vice versa.

Another popular opinion is that engineering is design. The report from a recent National Science Foundation Workshop (Hancock, 1986) states:

> Design in a major sense is the essence of engineering; it begins with the identification of a need and ends with a product or system in the hands of a user. It is primarily concerned with synthesis rather than the analysis which is central to engineering science. Design, above all else, distinguishes engineering from science.

Equating engineering and design begs the question, What is design? Many definitions of design are available: design is an iterative decision-making process used to optimize the value of human resources, or design is a goal-directed, problem-solving activity. These definitions are convenient and I have used them myself in informal discussion. However, as Koen (1985) has aptly shown, these definitions are inadequate because they either raise the troublesome question of what is to constitute a goal, problem or need, or they commit the teleological fallacy.

Although numerous definitions of engineering persist, my preferred definition is one developed by Billy Koen (1985). According to Koen, "The engineering method is the use of heuristics to cause the best change in a poorly understood situation within the available resources." Heuristics in this case are defined as reasonable, plausible, but ultimately fallible approaches. They permit a solution or reduce the time to achieve a solution, but do not guarantee a solution. Details concerning the nature of engineering (as well as alternative definitions) are presented in Koen (1984, 1985, 1986, 1987).

The present curriculum in engineering reflects the engineering-as-applied- science definition. Schein (1973) has labeled this curriculum the "Normative professional curriculum." It resulted from the compromise worked out by the addition of practice-based disciplines to the modern research university, starting with the addition of a business school at the University of Chicago. The normative professional curriculum resulted from construing professional knowledge as the application of research to practice. This curriculum consists of three steps: (1) teaching the relevant basic science, (2) teaching the relevant applied science, and (3) giving the students a practicum in which to practice the application of that science to the problems of everyday life. This three-step sequence requires students to learn things early in their education that have no immediate use. Stice (1987) points out that engineering students are not likely to work very hard or very effectively at learning things for which they see no apparent use.

How much of a foundation in science and math is necessary? One year past high school? Two years? More? Can we teach engineering to students who have very little background in math or in science? Our experience has shown that providing students with interesting and meaningful problems whose formulation requires the learning of relevant theory helps build their skills and capture their interest. Schank (1987) recommends, for example, that reasoning, and not mathematics, be taught in school. He claims that the teaching of formulaic thinking can have disastrous effects. Much of formal education consists of the teaching of answers, and children brought up on formulaic thinking begin to believe there is an answer for every question. The mission of schools should be the development of students' reasoning and reflection skills, as illustrated by the following comment from Schank:

> When a person asks questions, of himself or of others, when he creates explanations, when he wonders about things and tries to figure out what is going on, that is when he learns best and thinks the most creatively.

Nickerson's 1986 book, Reflections on Reasoning, provides a fine example of the type of material that could be used in a reasoning-based curriculum. Nickerson raises questions about reasoning, invites the reader to reflect on the nature of reasoning, and suggests that reasoning has several facets. He views reasoning as a matter of both attitude and knowledge, and assumes that skill at reasoning is not likely to be acquired quickly or effortlessly. His discussion of reasoning is structured around three key concepts: belief, assertion, and argument.

Fundamental changes are now conceivable in the teaching of mathematics due, in part, to the tools that are becoming available. Personal computer programs and even powerful pocket calculators that can integrate, solve systems of equations, determine the roots of functions, and graph the functions are becoming readily available and increasingly affordable. These tools can free the student from the rote memorization of methods of mathematical manipulation, allowing more time for underlying concepts to be integrated with physical examples. Beneficial applications of new technologies are being explored by Corbitt & Fey (1984), Graham (1987), Steen (1987), Ralston (1987) and many others. In our courses we provide tools, including personal computers and software, and students teach each other under our close supervision (Starfield, England, Butala & Smith, 1984; Wassyng, Smith & Sharp, 1987).

The recent engineering-is-design trend has prompted engineering educators to focus on "capstone" design courses to address the problem of students' synthesis and design skills (that is, their procedural knowledge). Assuming that a single course will fulfill the design education requirement is very optimistic, especially since iteration and feedback are considered essential features of most meaningful learning. In order for students to benefit fully from "capstone" design courses they need preparation in design activities in addition to their preparation in applied science.

The Nature of Expertise

The nature of expertise has been described in terms of models of the learner, stages of skill acquisition, and the progression from novice to expert (Smith, 1987). A discussion of engineering expertise vis-a-vis engineering education must address the type of problems that engineers routinely solve, and contrast this with what is taught in engineering curricula (the study presented in the introduction concerning professional-engineering problem solving, for example). The nature of expertise is discussed here by comparing the types of mental activity required in school versus those required in post-educational professional activities.

School Knowledge versus Out-of-School Knowledge

Resnick (1987) described four broad contrasts between in-school and out-of-school mental activity. First she noted that individual cognition is stressed in school, while shared mental activity is stressed outside school. The standard form of school activity is individual. However, a great deal of activity outside of school is socially shared and distributed. Second, she discussed a distinction between reliance on tools outside of school versus a strong preference for pure thought in schools. Schools value thought that is independent of the physical and cognitive tools that are a vital and defining part of all practical activities. Outside of school most mental activities involve tools, and the very kind of cognitive skill that is needed depends on the type of tool that is available. Third, she noted the emphasis on symbol manipulation in school, compared with the need to function with physical objects and their properties in the post-school environment. Resnick commented that educational methodologies appear to be more and more removed from what they purportedly prepare students to do, even when consideration is limited to the way in which reasoning is taught. Fourth, Resnick reported that in school we aim for general and widely usable skills, while outside, people must develop situationally specific forms of competence. For example, expert radiologists interpret x-rays using processes quite different from those taught in medical textbooks, processes perhaps unteachable through texts.

In Educating the Reflective Practitioner Schon (1987) described school knowledge as a product. There exists a body of knowledge, the set of results of human research and experience, which is taught in schools with particular emphasis on those results from universities, research institutes and other formal research enterprises. And this body of knowledge constitutes the "product" conferred through formal education. This sort of school knowledge is formal and categorical; it is explicitly formulable in propositions that assign properties to objects, or explain in verbal or symbolic terms the relationship of objects and properties to one another. This knowledge is also assumed to be "molecular"; larger and larger aggregations of such knowledge can be built from smaller, more "basic" units of this knowledge. School knowledge is, finally, determinant. That is, correct answers exist and questions have correct answers. According to Schon it is the business of teachers to know the correct answers and to communicate them to students. It is the business of the students to "get" it, to absorb the set of correct answers, the product. It should be noted that the way knowledge is grouped in school is not the way in which it is grouped in the world.

Schon stresses that we must work to heal the splits between school and out-of-school knowledge. These splits include: school and life (many students believe that school has nothing to do with life), teaching and doing (what we do is not what we teach and vice versa), and research and practice (research is not applicable for the actual practice in which we engage).

The dominant model of the student in engineering education has been the "empty vessel." It is appropriate if one's goal is to confer school knowledge as explained by Schon, but it is inappropriate if one's goal is to develop independent, self-directed learners who can function proficiently with real-world problems. Kloss (1987) provides an interesting comparison of three pernicious metaphors for teaching: "college as factory," "college as laboratory," and "college as mental institution." He recommends new metaphors including "teacher as coach" and "teacher as player-coach." Alternatives to the "empty-vessel" (or "funnel-head") model of the teaching-learning process, including modeling out-of-school mental activity, cognitive apprenticeship, reflective practicum, active student involvement through cooperative learning and structured controversy, and problem-based instruction are presented in the next section.

The Development of Engineering Expertise

If the knowledge and skills taught in school have this much disparity with the knowledge and skills actually required by the professional engineer, the focus of attention in engineering education must be shifted. Four approaches that can assist in correcting this problem are (1) the modification of in-school activities to model out-of-school activities, (2) the cognitive apprenticeship, (3) the reflective practicum, and (4) active student involvement through cooperative learning.

Presentation of these four approaches below is followed by a discussion of their application at the University of Minnesota with respect to active learning, cooperative learning, and problem-based instruction.

Modeling of Out-of-School Activities

As described above, Resnick concludes that school learning is individualized, tool free, and decontextualized. She goes so far as to suggest that schools should rid themselves of educational methodologies that are not pertinent to the acquisition of skills required in the post-educational environment. Listed below are some features of successful programs for improving "higher thinking skills" (Resnick, 1987). These programs focused on school learning skills that share key features with out-of-school cognitive practice:

1. Socially-shared work organized around mutual accomplishment of tasks.
2. The shared features of apprenticeship. Making hidden processes overt and hence subject to

observation and commentary. Allowing skills to build up bit-by-bit, but allowing even the relatively unskilled to participate (perhaps by means of mutually shared tasks).

3. Instruction organized around particular bodies of knowledge and their interpretation such that the situational specificity is similar to that found in the post-school environment.

Cognitive Apprenticeship

Collins (1987) states that the differences between formal schooling and apprenticeship methods are many, but cites one as being the most important. He writes:

> Perhaps as a by-product of the specialization of learning in schools, skills and knowledge taught in schools have become abstracted from their uses in the world. In apprenticeship learning, on the other hand, target skills are not only continually in use by skilled practitioners, but are instrumental to the accomplishment of meaningful tasks.

Cognitive apprenticeship is characterized by several features. Tasks and problems are chosen to illustrate the power of certain techniques or methods, to give students practice in applying these methods in diverse settings, and to allow a slow increase in complexity so that component skills and models can be integrated. Apprenticeship methods are used in graduate education in most domains. Students learn how to solve problems that arise in the context of carrying out complex tasks, and to extend and make use of their textbook knowledge by undertaking significant projects guided by an expert in the field.

Collins summarizes three success models of cognitive apprenticeship: Palincsar and Brown's reciprocal teaching of reading, Scardamalia and Bereiter's procedural facilitation of writing, and Schoenfeld's method for teaching mathematical problem solving.

Reciprocal Teaching (Palincsar & Brown) involves students and teacher taking turns playing the role of teacher. The method utilizes modelling and centers on coaching students in four strategic skills: formulating questions based on the text, summarizing the text, making predictions about what will come next, and clarifying difficulties with the text.

In the Procedural Facilitation of Writing (Scardamalia & Bereiter) planning is broken down into five general processes, or goals: generating a new idea, improving an idea, elaborating on an idea, identifying goals, and putting ideas into a cohesive whole. Specific prompts are developed for each process, often in the form of "cue cards" which the teacher provides to the students.

Schoenfeld's approach to the teaching of mathematical problem solving to college students employs the elements of modelling, coaching, scaffolding, and fading in a variety of activities designed to highlight different aspects of the cognitive processes and knowledge structures required for expertise. He gives the class problems that lend themselves to the use of the heuristics he has introduced. He challenges students to find difficult problems, and at the beginning of each class offers to try to solve one of their problems. Schoenfeld advocates small-group problem solving because: (1) it gives the teacher a chance to coach students while they are engaged in semi-independent problem solving, (2) the necessity for group decision making in choosing among alternative solution methods provokes articulation through discussion and argumentation, (3) students get little opportunity in school to engage in collaborative efforts, (4) students are often insecure about their abilities, and (5) it emphasizes the differentiation and externalization of the roles and activities involved in solving complex problems.

Collins extracted effective teaching methods from the three effective learning environments described above. He stressed the point that a key goal in the design of teaching methods is to help students acquire and integrate cognitive and metacognitive strategies for using, managing, and discovering knowledge. Furthermore, he maintained that teaching methods should be designed to give students the opportunity to observe, engage in, and invent or discover expert strategies in context. The six teaching methods fall roughly into three groups: the first three (modeling, coaching, and scaffolding) are the core of cognitive apprenticeship, designed to help the students acquire an integrated set of cognitive and metacognitive skills through processes of observation and of guided and supported practice. The next two (articulation and reflection) are methods designed to help students both to focus their observations of expert problem solving and to gain conscious access to (and control of) their own problem-solving strategies. The final method (exploration) is aimed at encouraging learner autonomy not only in carrying out expert problem-solving processes, but also in defining or formulating the problems to be solved.

Cognitive apprenticeship with its emphasis on modeling, coaching, scaffolding and fading has the potential to make significant changes in the quality of undergraduate education.

Reflective Practicum

A "reflective practicum" is a practicum aimed at helping students acquire the kinds of artistry essential to competence in professional practice. "Reflection-in-action" is a key feature by which students learn design not by acquiring theoretical knowledge, but by interacting with their teacher-coaches in problem setting, framing and reframing of questions, experimentation, demonstration, imitation, testing of hypotheses, and frequent questioning and discussion. Schon (1983) describes reflection-in-action as follows:

> When someone reflects-in-action, he becomes a researcher in the practice context. He is not dependent on the categories of established theory and technique, but constructs a new theory of the unique case. His inquiry is not limited to a deliberation about means which depends on a prior agreement about ends. He does not keep means and ends separate, but defines them interactively as he frames a problematic situation. He does not separate thinking from doing, ratiocinating his way to a decision which he must later convert to action. Because his experimenting is a kind of action, implementation is built into his inquiry. Thus reflection-in-action can proceed, even in situations of uncertainty or uniqueness. . .

The main features of the reflective practicum are, according to Schon, (1) learning by doing, (2) coaching rather than teaching, and (3) creating a dialogue of reciprocal reflection-in-action between coach and student. The coach's task requires (1) substantive problem solving where attention is paid to the specific thing that is being worked on, (2) particularizing of the description and demonstration for the student at that time, and (3) the reduction of defensiveness, that is, doing 1 and 2 while building a relationship in which defensiveness is minimized.

When a teacher turns attention to giving reason (listening and reframing the problem, on-the-spot experimentation, and detection of consequences and implications), to listening to what students say, then the teacher exhibits a form of reflection-in-action. This formulation helps to describe teaching artistry. The approach involves getting in touch with what students are actually saying and doing, allowing oneself to be surprised, and then responding to the students. In Educating the Reflective Practioner Schon (1987) elaborates on his approach to the development of professional practice skills:

> Designing, both in its narrower architectural sense and in the broader sense in which all profession practice is designlike, must be learned by doing. However much students may learn about designing from lectures or readings, there is a substantial component of design competence--indeed, the heart of it--that they cannot learn in this way. A designlike practice is learnable but is not teachable by classroom methods. And when students are helped to learn design, the interventions most useful to them are more like coaching than teaching--as in a reflective practicum. (p. 157)

Active Learning Strategies

Active student involvement is essential to the development of students' talents. A powerful method for getting students involved is cooperative learning, developed by David and Roger Johnson at the University of Minnesota. The Johnson's cooperative learning strategies are conceptual in nature and must be adapted to each professor's subject, students, aims and personality.

In a cooperatively structured lesson, students are placed in small groups and given group assignments to complete while the instructor insures that members of each group actively discuss the lesson, master the assigned material, and receive rewards on the basis of how the group product compares with a preset criterion of excellence. Cooperative learning thus creates a situation in which students are responsible not only for their own learning but also for the learning of the other members of their group.

Cooperative learning involves much more than simply having students share of discuss material with other students, although this communication is important. The real crux of cooperative learning is that the group shares a goal, such as producing a final report or achieving a high group average on a test. The effectiveness of a group carrying out its goal is determined by the presence or absence of five essential elements of cooperative learning (Johnson, Johnson, and Holubec, 1986).

First, cooperative learning requires that group members develop positive interdependence. Students must feel that they need each other to complete the group's task, that they "sink or swim" together. Some ways to create this feeling are through establishing **mutual goals** (students must learn the material and make certain all group members learn the material), **joint rewards** (if all group members achieve above a certain percentage on the test, each will receive bonus points), **shared materials and information** (one paper for each group or each member receives only part of the information needed to do the assignment), and **assigned roles** (recorder, reader, summarizer, encourager of participation, elaborator).

Second, cooperative learning requires face-to-face interaction among students. No magic exists in positive interdependence in and of itself. Beneficial educational outcomes are due to the interaction patterns and verbal exchanges that take place among students in carefully structured cooperative learning groups. Oral summarizing, giving and receiving explanations, and elaborating (relating what is being learned to previous learning) are important types of verbal interchanges.

Third, cooperative learning requires individual accountability and personal responsibility for mastering the assigned material. Cooperative learning groups are not successful until every member has learned the material or has helped with and understood the assignment. Thus, it is important to frequently stress and assess individual learning so that group members can appropriately support and help each other. Some ways of structuring individual accountability are by giving each group member an individual exam or by randomly selecting one member to give an answer for the entire group.

Fourth, cooperative learning requires that students use interpersonal and small-group skills appropriately. Placing socially unskilled students in a learning group and telling them to cooperate will not produce the desired effects. Students do not generally come to college with the skills they need to collaborate effectively with others. So we need to help students learn the appropriate communication, leadership, trust, decision making and conflict management skills and provide motivation to use these skills in order for groups to function effectively.

Finally, students must be given guidance in analyzing how well their learning groups are functioning. Group processing means giving students the time and procedures to analyze how well their groups are functioning and how well they are using the necessary collaborative skills. This processing helps all group members achieve while maintaining effective working relationships among members. Feedback from the teacher and student observers on how well they observed the groups working may help the processing effectiveness.

There are three major ways of incorporating cooperative learning in the college classroom: **informal work groups**, which are informal and less structured; **formal work groups**, which are more structured and stay together until the task is done; and **base groups**, which are long-term groups whose role is primarily one of peer support and long-term accountability (Johnson, Johnson & Smith, 1988).
Informal work groups can be used in a variety of ways at any time. Three ways they can be used in a lecture class are: (1) to focus the students prior to the lecture, (2) to break up the lecture and provide the students a chance to review and check for understanding, and (3) to summarize the main points at the end of the lecture. Each of these three uses of informal groups can be initiated by asking the student to turn to the person next to them and discuss the question.

The longer term formal work group is put together to do a specific job such as review homework, work through a problem together, review for a test, perform a lab experiment and write a report, or conduct a design project.

Formal work groups are used in all my engineering classes. Students are given a problem to formulate and solve or material to be mastered. Students then work in small cooperative groups to formulate and solve the problem or frame a concept. They prepare a report (either on paper or on overhead transparency) describing how the problem was formulated and solved or how the concept was represented and how it relates to other concepts. Later, a representative from each group is randomly selected to present the group's solution, representation or summary. The representations or the approaches used by the various groups to solve the problem are compared and discussed by the whole class. Finally, each group is provided time for processing its effectiveness.

Another application of formal work groups is my use of structured controversy in environmental issues seminars. These seminars focus on content acquisition and on helping students develop collaborative skills (through cooperative group learning), constructive conflict management skills (through structured controversy discussion), and perspective-taking skills (through presentation and discussion of different perspectives on each issue. In a structured controversy students are assigned a position on an issue which they prepare, present and defend. The goal is to understand the best arguments on all sides of the issue, but the students are stimulated to prepare better arguments when they are confronted with a compelling argument from the other side. The structured controversy technique is described in Johnson, Johnson and Smith (1986), Smith (1984).

Base groups are long term groups with stable membership whose primary responsibility is to provide support, encouragement, and assistance in completing assignments. Base groups not only tend to improve attendance, they also are given the task of letting group members know what when on in class when they miss a session. The larger the class and the more complex the subject matter, the more important it is to have base groups.

Details of the informal, formal and base groups as well as additional information on cooperative learning are available in Johnson and Johnson (1987), Johnson, Johnson and Holubec (1986), Smith (1985), and Smith, Johnson and Johnson (1981, 1988).

Cooperative learning procedures have several important contributions to make to college education. The use of cooperative learning groups approximates more closely the activity of real-world employment and problem solving; allows students to tackle larger, more complicated, and often more interesting problems without feeling overwhelmed; allows students to serve as resources fore each other, hence taking some of the pressure off instructors and teaching assistants; and allow students to expend more effort on sharing ideas and on producing high quality products, and less on beating other students on performance measures.

Knowledge and skill are of little use if a student cannot apply them in cooperative interaction with other people. It does not good to train an engineer who does not have the competencies needed to apply knowledge and technical skills in cooperative relationships on the job, in the family and community, and with friends. The most logical way to emphasize cooperative competencies as learning outcomes is to structure the majority of academic learning situations cooperatively.

Directions at the University of Minnesota

In the Department of Civil and Mineral Engineering at the University of Minnesota we are focusing on instructional methods. Student-centered active learning provides a means for getting students to feel meaningfully involved. Cooperative learning groups provide a structure for group activity that works and that students enjoy. Structured controversy adds needed zest. Students constructing knowledge bases (such as concept maps and production systems) strengthen their understanding. Building expert systems provides students with a concrete means to experience the power of these techniques.

Our approach emphasizes modeling to devise stepping-stone design courses. Modeling is an activity of constructing representations (mathematical, computer, or otherwise) of problems. A course emphasizing the techniques of modeling resembles problem-based learning in its emphasis on problems, but differs in that the student is not expected to know and supply answers, but rather to explore the problems, discover methodologies, and formulate answers. Students manipulate the model, which in turn contributes to their understanding of the phenomena being modeled. They learn by building, revising, and discussing their models with each other. We select the material and methods to be presented to students by subjecting it to the Voller (1986) test: "Have you found it useful in your professional work?"

An example of our activity in using a modeling approach is our Honors course entitled Formulation, Modeling and Analysis of Engineering Problems. This course focuses on getting first-year students meaningfully involved in active learning with engineering problems. We provide tools, including personal computers and software, and students teach each other under faculty supervision.

Our work with cooperative learning groups has shown that these procedures can be effectively applied to the education of engineering students. Students learned to work with each other more effectively; managed larger, more complex problems readily; reported that they liked the cooperative learning experience; and took the initiative for their own learning beyond the limits of the assignment.

Research Needed

Extensive research is required to devise effective and efficient means of developing students' expertise in engineering. Some of this research includes the following:

1. Establish effective means for implementing student-centered active- learning methods, such as cooperative learning, in engineering education.

2. Determine the forms of tutoring and coaching that will create the beneficial conditions of apprenticeship. Examine the ways people actually do their work rather than assume that it follows a given rational or symbolic pattern of behavior.

3. Study how skills are learned in natural work settings. Studies are needed not just of experts, but of people in the process of becoming experts.

4. Determine improved uses of tools and technology, such as computers.

Conclusions

Traditional instruction in engineering is content-based and follows the normative professional curriculum: teach the relevant basic science, teach the relevant applied science, and allow for a practicum to connect the science to actual practice. As a result, attention is focused on students' mastery of declarative subject matter within narrow domains. This content theory of knowledge is inadequate for preparing students for professional practice in engineering (and in other disciplines, such as medicine and law, as well). Procedural knowledge or "how-to-do-it" knowledge is essential in engineering.

Impetus for change is coming from several research fronts: professional expertise (Schon), school versus out-of-school knowledge and activity (Resnick), cognitive apprenticeship (Collins), active learning (Smith, Johnson & Johnson) and the role of calculators, computers, and related technology (Steen, Ralston). As an example of the momentum being generated by this push to revitalize professional curricula, Harvard medical school recently implemented a problem-based curriculum similar to the one introduced at McMaster in 1968 (Abrahamson, 1987). In the McMaster model, students meet in small "tutorials" and consider problems that they cannot solve without acquiring, and thus learning, new information and skills.

My most important objective is to develop students' motivation and skills for continued learning, problem solving and application of course material after the course is over. The general models of instruction proposed would assist in providing direction for getting students meaningfully involved in learning and focus attention on active learning to help prepare self-directed, autonomous learners. The approach is consistent with the current state-of-the-art in college-level teaching. McKeachie, et. al., summarized the research on instruction as follows in the recent NCRIPTAL report Teaching and Learning in the College Classroom (1986):

> The best answer to the question, 'What is the most effective method of teaching?,' is that it depends on the goal, the student, the content, and the teacher. But the next best answer is, 'Students teaching other students.' There is a wealth of evidence that peer teaching is extremely effective for a wide range of goals, content, and students of different levels and personalities. (p. 63)

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