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What is Engineering Practice?*

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In this paper we develop a description of engineering practice. This description is based on published research on engineering work and on interview data from the engineering faculty. It was undertaken as part of a larger study that is underway at the Carnegie Foundation for the Advancement of Teaching. The study is looking at the relationship between how engineering is taught and how it is practiced.

Keywords: engineering practice, engineering work, work practices, design, problem solving, analysis.

INTRODUCTION

PROFESSIONS, such as engineering, medicine, teaching, nursing, law and the clergy share a common set of tenets, namely that practitioners should [1]:

- provide worthwhile service in the pursuit of important human and social ends;
- possess fundamental knowledge and skills (especially an academic knowledge base and research);
- develop the capacity to engage in complex forms of professional practice;
- make judgments under conditions of uncertainty;
- learn from experience; and
- create and participate in a responsible and effective professional community.

The embodiment of these tenets varies from profession to profession, influenced by the profession's particular goals. In this paper we explore the form of these tenets in engineering practice. More specifically, we address the question, what is engineering practice? In this exploration, we aim to go beyond the concise definitions of engineering offered by, for example, the U.S. Department of Labor that, on its Website, describes engineering as the application of 'the theory and principles of science and mathematics to research and develop economical solutions to technical programs. [This work] is the link between perceived social needs and commercial applications' [2]. On the other hand, we wish to develop a less detailed and more generalized picture of the work than is offered by such scholars as Meehan [3], Florman [4], Bucciarelli [5], Perlow [6], Vincenti [7], Bailey and Gainsburg [8], and Rubinstein [9].

In addressing the question 'What is engineering practice?', we also need to consider whose point of view is expressed in the answer. Certainly one point of view is that of individuals and organizations engaged in engineering work and one could develop a picture of engineering work based on, for example surveys and interviews of practicing engineers. Another point of view is offered by researchers who observe the work of engineers, then synthesize these observations into patterns and more generalized understanding of the nature of engineering practice (e.g., [5, 6]). Still, another point of view is offered by those engaged in engineering education, namely engineering faculty and students. In this paper we consider the latter two perspectives by summarizing key components of engineering work described in the research literature, then comparing and contrasting these components with how engineering faculty and students talk about engineering practice.

In the next section we outline our underlying motivation for posing the question 'What is engineering practice?' and summarize our research methodology. This is followed by three sections that look, in turn, at:

1. engineering as problem solving, considering the systematic processes that engineers use to define and resolve problems;
2. engineering as knowledge, considering the specialized knowledge that enables, or if you will, fuels the process; and
3. engineering as the integration of process and knowledge.

In essence, in these three sections we develop a representation or model of engineering work. This model is offered with the caveat that any model is an attempt to mimic elements of 'the real thing'—it can never be the real thing, it can never be exact, but it is hopefully useful in accurately capturing relevant features and their relationships. In the final section of the paper we present implications of this model for engineering education.

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Background

Professional education ideally must reflect practice if it intends to prepare future practitioners. As society deals with political, social, economic, and technological changes; professional practice and professional education often are redefined and reformed to suit societal needs. Engineering is no exception. For the last two centuries, engineering as a practice has affected and has been affected by trends in politics, society, economics, and technology. Hence, the 'ingenious' engineer has always been influenced by the past, continues to shape the present, and will affect the future.

Engineering is not just about mechanizing or digitizing the world to make life less burdensome and nations more powerful. Engineering as a profession ought to improve the world for the common good. The professional education of engineers demands the acquisition of a body of specialized knowledge, problem-solving skills, and good judgment for the service of society. These three domains of engineering education are aimed at forming engineers who are intellectually trained, practically adept, and ethically responsible for their work. Every professional engineer, therefore, is called on not only to achieve a certain degree of intellectual and technical mastery, but also to acquire a practical wisdom that brings together the knowledge and skills in a way that best serves a particular purpose for the good of humanity.

One of the biggest challenges, of course, has always been to teach and learn the integration of knowledge, practical skills, and ethical judgment in a setting often removed from actual practice. Ideally, the educational processes in a university setting integrate these domains, and thereby serve as an apprenticeship to the profession. This apprenticeship should guide the novice towards the acquisition of cognitive and practical skills, and the development of a sense of professional and personal responsibility.

The Carnegie Foundation for the Advancement of Teaching is studying the current forms of this apprenticeship in engineering schools in the United States. More specifically, the Foundation aims to answer the central question: '*What are the pedagogies that make up engineering education, and how are they related to engineering practice?*'. In this paper we address 'What is engineering practice?'. The overall findings for the Foundation's study of engineering education will be presented as a book titled *Educating Engineers: Theory, Practice and Imagination*, to be published in late 2006.

The picture of engineering practice or, if you will, engineering work, described in this paper is based principally on research findings published in the literature (a researcher perspective), and themes that have emerged from interviews of engineering faculty, administrators and students (an academic perspective). More than 300 engineering educators and students at seven engineering schools across the U.S. were interviewed in the period December 2001–May 2002 about their teaching and learning practices, and their perspectives on engineering practice. The interviews were in-person in the form of semi-structured interviews and focus groups, and were digitally recorded and transcribed. The seven engineering schools included publics and privates ranging in size from 5 000–45 000 students, from a variety of Carnegie Classifications. The schools were selected based on published evidence that faculty were actively experimenting with their educational practices.

We believe that the resulting picture of engineering work (which includes identified congruencies and incongruencies between these two perspectives) is a reasonable and valid lens to hold up against educational practices. It represents what those who methodically study engineering work and those who design, implement and deliver engineering education think the profession is all about. Identified consistencies and mismatches between the literature's perspective and how engineering faculty go about delivering engineering education are potentially powerful leverage points with which to spur the academy to affect improvement of their programs.

An alternate and complementary picture of engineering work could be created based on perspectives expressed by those directly engaged in engineering practice. This would provide the opportunity to look at consistencies and mismatches between the picture of engineering practice articulated by the individuals practicing engineering and the individuals offering engineering education. Furthermore (and perhaps more importantly), it would allow for the identification of consistencies and mismatches between multiple perspectives of what engineering work is. In this paper, we take the modest step of laying out a picture of engineering work, as articulated in the research literature and by the academy.

ENGINEERING WORK AS PROBLEM SOLVING

Engineering work is focused on resolving an undesirable condition through the application of technologies. The technologies involved may be well established, nascent, or as-yet unimagined. Therefore, a central (if not *the* central) activity of engineering work is solving problems. Rubinstein, in his 1984 book entitled *Patterns of Problem Solving* offers that a problem is 'a question for which there is at the moment no answer . . . It may be solved by calculations, by consulting reference work, or by acting in a way which helps recall a previously learned answer'[9, p. 3].

Engineering work is about solving *problems*. Implicit in this statement is that the intention of engineering work is to affect change in the world by, for example, modifying processes or procedures or introducing new products, technologies or knowledge. These changes constitute the solution. Unlike scientists, engineers are tasked with being change agents.

The problem being undertaken by an engineer (or a team of engineers) may take the form of a need, real or perceived (e.g., 'We need a means of ensuring that this 100-year old building meets modern-day earthquake standards, while maintaining its distinct architectural features.'), or may be stated as a question (e.g., How did the World Trade Center collapse?' 'Will thermal cycling cause fatigue in the proposed solder joint configuration?'). Whether the problem is stated as a need or a question, its very postulation is motivated by a desire to increase actionable understanding and undertake action. Because there are constraints on the solution, both on the work activities themselves (e.g., amount of time, money), and on the solution (e.g., cost, weight) engineering work is constraint-based problem solving.

In one of the early chapters in Rubinstein's aforementioned book, he describes this process of constraint-based problem solving: 'We pose a problem by defining the desired goal in terms of the state description. We solve the problem by selecting a process that will produce the desired goal from the initial state. Here the transition from the initial state, through the process to the goal will tell us when we have succeeded. The total process, i.e., the solution, may be entirely new although parts of it may not be new' [9, p. 3]. He goes on to say that this total process 'is a matter of appropriate selection, selection of an ultimate solution, or selection of a process leading to a desired explicitly stated goal' [9, p. 7]. He warns us that there is no guarantee (or, for that matter, likelihood) that the solution is unique and no reason to assume a priori that the set of all constraints uniquely determines the outcome of problem solving. Often the constraints conflict with one another and these conflicts must be resolved somehow (often through trade-offs) before a solution can be found. 'In general, the idea that there exists exactly one technologically best solution for every [engineering] design problem is highly questionable' [10, p. 55].

In a later chapter, Rubinstein refines his description of problem solving for the particular case of engineering, outlining the three clusters of work activities involved:

1. **Problem or Current State Identification (Cluster A):** Work activities are focused on creating a description of the present state of what is (where we are). Included is defining what the real problem, question and/or need is. The problem may arise from, for example, legislative action, market demand, natural or political disasters, or a technological opportunity.
2. **Attribute and Constraint Definition (Cluster B):** Work activities are focused on creating a description of the desired attributes and goal of what ought to be—in other words, what is desired and how/where we want to be. Included are defining constraints, requirements and attributes of the new desired state, as well as global functional properties and costs.
3. **Means–End Development (Cluster C):** Work activities are focused on creating a description of the process to bridge the gap between what is and what is desired, namely, a prescription of what to do and how. In this stage, the means of moving from Problem Identification to a solution that meets constraints and embodies desired goals and attributes is derived. The activities use a means–end analysis, in which a step-by-step procedure examines a description of current status (starting from identified problem or current state) and compares it with the desired end result until a solution is obtained. At each step the degree of misfit between the current state and the desired goal is established.

The work activities associated with Problem Identification (A) and Attribute and Constraint Definition (B) are critical to setting the direction of an engineering project. Since many engineering problems start off by being under- or ill- defined, this direction-setting work is both critical and difficult. It is in these stages that the condition to be remedied or investigated is defined and scoped. The definitions that come out of Problem Identification (A) and Attribute and Constraint Definition (B) describe the problem to be solved and (ideally) a well posed set of requirements and constraints that any viable solution must meet.

In Means–End Development (C) the emphasis is on the process that leads to a desired goal from an initial state. In other words, it seeks to establish the pattern or form of solution as the problem solvers (the engineers) think aloud while proceeding toward the desired goal. Means–end development requires 'continual translation between the state and process descriptions of the same complex reality' [9, p. 3]. This translation involves generating candidate solutions and evaluating and implementing them. This generation–evaluation–implementing translation requires that engineers work with ideas (e.g., creative thoughts unencumbered by reality), evidence (discrete information that represents aspects of product performance) and models (physical or mathematical representations).

To be able to engage in Means–End Development work, engineers must be able to exercise creative and intuitive instincts, valuing willingness in self and others to act in the absence of complete knowledge and certainty. There must also be a willingness *to generate candidate solutions*, as a very good solution is more likely to emerge if more ideas are generated up front (in other words, if you don't become married to your ideas and gleefully defer judgment!). Means–End Development also involves *evaluating and implementing candidate solutions* for, at some point, the engineer must select from candidate solutions the best one for the current situation. Eris [11] refers to this as the convergent facet of means–end development [11].

It is tempting (and naïve) to interpret these three activity clusters as sequential; in other words, that completing Problem Identification (Cluster A) means having created a well-defined/crafted statement of a user need or existing problem, leading into Attribute and Constraint Definition (Cluster B), where a well-defined statement of solution requirements and constraints are articulated, leading (finally) to the creation of an artifact, device or product that solves the problem and meets the requirements/constraints. Reality is never this clean or sequential—often the real problem is unearthed while engaged in Cluster B activities, or Cluster B requirements are ambiguous and need to be reformulated while engaged in Cluster C activities. Also, this type of problem-solving is such that the deeper you get into the problem, the more you understand it, therefore the more precisely the desired requirements and constraints can be defined (this is particularly true of emerging technologies and radical design). What this translates into is that the work involved in Problem Identification, Attribute and Constraint Definition, and Means–End Development is inherently iterative and intertwined as is part of the very nature of engineering work.

Furthermore, engaging in engineering problem-solving often involves parsing and partitioning the problem by identifying sub-problems that can be worked on independently from one another. As part of solving an overall problem, A–B–C type activities are repeatedly undertaken to solve identified sub-problems.

The primary or overall problem and its associated sub-problems may be problems of design or problems of analysis, or any combination thereof. Both are central to engineering and involve A–B–C clusters of activities, as described above. A design problem is primarily aimed at developing or devising a process or strategy (C) that will generate or achieve a solution to the problem while realizing and acknowledging the current state (A). This process, which is just one among many possible processes, is examined based on the acceptability of the solution, which in turn is evaluated against the desired solution (B). The process is refined until the best possible process that transforms the current state to the desired state is achieved. The best possible process is generated through the synthesis and integration of knowledge resulting from the evaluation of the trial processes.

Design problem-solving can be described as:

1. A line after boxed "formula".
2. "Formula" needs to stand out more from text.
3. Have "formula" in italics to make it stand out more.

In contrast, solving analysis problems takes a different approach, as it is often a response to a design problem. Its main focus is to assess and evaluate a design solution, which has become the current state (A), by devising a model (C) that represents the solution and using the model to test the validity and acceptability of the solution in achieving the desired goal (B). Any failure or error resulting from the test is re-assessed and the model is adjusted. The model is again tested to check its predictability in achieving the desired goal. An ideal model is achieved if its predictable response is consistent with the desired goal. The ideal model then becomes a guide for developing and improving the design solution.

Analytic problem-solving can be described as:

1. Line after boxed "formula".
2. "Formula" needs to stand out more from text.
3. Have "formula" in italics.

We do not mean to imply that the actual clusters of activities associated with Problem Identification, Attribute and Constraint Definition, and Means–End Development are the same in design and analysis problem solving. *What is the same for both design and analysis problem solving is the overall pattern of starting from a current situation, aiming for a desired state, and working to connect the current with the desired.*

Comparison with faculty and student comments

Three themes regarding engineering as problem solving emerged from our interviews of engineering faculty and students that are consistent with the ideas about problem solving outlined above. These quotes from faculty and students are representative of ideas expressed in many interviews They are that:

1. Engineering is, at its core, problem solving.

   To me, being an engineer means being a problem-solver, somebody who is capable of analyzing a situation and finding, if not an optimum solution, a solution within a set of constraints. School#2 faculty.

   To be an engineer is to solve problems. And that's the one skill that's overall the most important in my mind. School#1 faculty.

2. A key component (if not the key component) of engineering problem solving is formulating the problem, including both technical and non-technical requirements and constraints, and being able to partition a problem into sub-problems.

   I would say that ability to formulate the problems to be solved is really the crucial aspect here. Once you've got the problem formulated correctly you're more than half way to solving it . . . But that action of posing it—what are your assumptions, what are you trying to do, what should you be trying to do?—that's the central aspect. School#7 faculty

   [Engineers] take problems and divide them into smaller problems and find solutions . . . This is an important skill. School#2 faculty

   You need to be able to break a problem down into pieces. Then you consider how to deal with the parts. School#3 faculty.

3. Other key components include being able to generate, evaluate and implement candidate solutions, as well as to understand that problem solving is intrinsically an iterative and integrative process.

> *In order to . . . figure out different ways of doing things you have to be able to come up with different ideas and try things out.* School#2 student

> *An engineer must have a strong analytical and physics, mathematical background which he will use to translate the designs into reality.* School#5 faculty

> Student A: *There are an infinite number of ways to solve a problem—it is just about finding the most efficient way. . . . I focus on the thought process. Even if I see a new problem, I have a thought process.*
>
> Student B: *You need to know how to prioritize the tasks. You need to be able to identify what is important and what is not, since there is not enough time. You need to be able to define what has to be done.* School#3 students

We did not hear faculty and students differentiate between design and analysis problem solving; instead they used the general term 'engineering problem solving' or simply 'problem solving.' On the other hand, we did hear them refer to 'design problems,' and 'analysis problems,' which does imply some distinction between these types of problems.

ENGINEERING WORK AS SPECIALIZED KNOWLEDGE

Engineers are able to engage in the problem solving described above because they have mastered a specialized body of knowledge. In *What Engineers Know and How They Know It*, Vincenti offers 'We can start with the obvious statement that engineering is a problem-solving activity. Engineers spend their time dealing mostly with practical problems, and engineering knowledge both serves and grows out of this occupation' [7, p. 200]. He goes on to say that 'What engineers do depends on what they know . . . [this is] the cognitive dimension of engineering.' A distinctive feature of this specialized knowledge is that it includes what the philosopher G. Ryle called 'knowing that' and 'knowing how' [12]. Shavelson and Huang add to Ryle's 'knowing how' and 'knowing that' distinctions (which they call declarative and procedural knowledge, respectively) by suggesting that disciplines also rely on schematic knowledge ('knowing why') and strategic knowledge ('knowing when certain knowledge applies, where it is applied, and how it applies') [13]. The knowledge that engineers must bring to bear in their work includes knowing how to perform tasks, knowing facts, and knowing when and how to bring appropriate tasks and facts to bear on a particular problem.

Another distinguishing feature of the knowledge on which engineering work is based is that this knowledge is dynamic. Our collective understanding of the world and how to affect it continues to change and is becoming more comprehensive, complex and complete. This means that to carry out their work successfully, engineers need to stay informed of new and emerging technologies. The U.S. Department of Labor Website [2] lists as one of four significant points on being an engineer that 'continuing education is critical to keep abreast of the latest technologies.' For example, a mechanical engineer graduate of 1980 would have had little exposure to finite-element analysis in his formal engineering education, but in 2004 this technology is becoming a standard tool with which to evaluate product performance. Practicing in 2004, he would be expected to know at least the tool's capabilities, if not how to use it. How might he go about learning it (short of going back for additional engineering degrees)? The multi-million dollar business of professional education and trade journals in the U.S. seems to indicate that at least some engineers and corporations are taking advantage of formal opportunities to stay up to date. In addition, many companies provide in-house, specialized training with the same intent. An engineer's ability to comprehend, critique, synthesize and adjust to this new knowledge is seen as essential to successful engineering.

Additionally, the knowledge that an engineer draws from is continually expanding and evolving because of the work itself. If engineers are reflective, alert and methodical as they carry out an engineering project, they are smarter at the end of the project. They add to their tacit and conceptual understanding of how a particular class of physical systems operates and of how work happens in the engineering setting where they are employed—this is knowledge that can be brought to bear on their next project. This knowledge can be thought of as an essential and highly desirable secondary product of the work. It can also be shared with other engineers formally, through publications (e.g., internal project reports, trade journals with a practice focus), and informally (e.g., through engineer-to-engineer mentoring, conference discussions). Thus, knowledge generated in carrying out their work is added to the engineering community's knowledge base.

A third distinctive feature of engineering knowledge is that it is not a derivative of science—it is 'an autonomous body of knowledge, identifiably different from scientific knowledge with which it acts' [7, pp. 3–4 and footnote 1]. The idea of 'technology as knowledge' (the title of an influential paper by Edwin Layton, one of the view's early champions) credits technology (and, by extension, engineering) with its own significant components of thought. 'This form of thought, though different in its specifics, resembles scientific thought in being creative and constructive; it is not simply routine and deductive as assumed in the applied-science

Table 1. Knowledge types used by engineers: The Typing is largely based on the work of Vincenti [7], Koen [14], and Kroes [10]

Knowledge type	Description
1. Theoretical tools: Math-based, and conceptual	Mathematical methods and structured knowledge, scientific, engineering and phenomenological theories, intellectual concepts. 'Engineering science' consists of specific combinations of math and science around particular engineering domains.
2. Fundamental design concepts: Operational principles and normal configurations	Operational principle describes 'how [a device's/technology's] characteristic parts fulfill their special function in combination to an overall operation which achieves the purpose'—in essence, how the device (technology) works. Normal configurations describes what is typically taken for the shape and arrangements for a particular class of devices (technologies).
3. Criteria and specifications	Technical criteria appropriate to a class of devices (technologies), including numerical performance criteria. (e.g., impact performance criteria in the automotive sector, pressure vessel standards in the chemical industry).
4. Quantitative data	Physical properties and quantities required in formulas and required to demonstrate device performance. Understanding of procedures and processes for generating such properties and quantities.
5. Practical considerations	Tacit knowledge (typically learned on the job) generally not codified. In addition, rules of thumb and heuristics (this category was called 'Design Considerations' by Vincenti [7]).
6. Process-facilitating strategies	Knowledge of tools and strategies for project management, leadership, teamwork, communications and management.
7. Contextual knowledge (NSPE, NAE, Kroes)	Knowledge of values (personal, professional, cultural). Knowledge of norms (what is acceptable behavior, what is expected behavior). Knowledge of contexts, and contextual factors that constitute the artifact's aesthetic.

model. In this newer view, technology, though it may apply science, is not the same as nor is it entirely applied science. . . . Treating science and technology as separate [but overlapping] spheres of knowledge, but man-made, appears to fit the historical record better than treating science as revealed knowledge and technology as a collection of artifacts once constructed by trial and error but now constructed by applying science' [7, pp. 3–4].

Types of knowledge that engineers bring to bear in their work are wide-ranging. Table 1, based largely on the work on Vincenti, illustrates types of knowledge into which engineers tap. The list is intended to be generally representative of engineering knowledge. Notice that the items range widely—from 'Theoretical Tools' to 'Contextual Knowledge.' Even with this spectrum of knowledge types, types of knowledge that are critical for particular engineering enterprises have been omitted (e.g., marketing, sociology), but their omission should not diminish the general utility of Table 1.

It might be tempting to label the list in Table 1 as 'the Body of Knowledge' for engineering work. This label is problematic for several reasons. First, not all knowledge types will be needed for every engineering project, and some projects require knowledge-expertise not encompassed in the table (e.g., specialized business practices). Therefore, the table is both too big and too small—and as such is not up to the task of representing the body of knowledge for all of engineering. Secondly, not all practicing engineers need be expert in every knowledge type to be successful. Even within a knowledge type, the particulars would vary by engineering discipline (e.g., electrical engineering, mechanical engineering, environmental engineering), by industry sector (e.g., information technology, transportation, agriculture, health services), and by years of experience. Therefore, the table is probably too broad to represent a single engineer's body of knowledge. In summary, engineering knowledge is:

- knowledge that can be 'put into play' (knowing how, that, why and when);
- knowledge that is continually changing (expanding, evolving);
- knowledge that ranges from science-based to contextual, from tacit to procedural.

Vincenti cautions that 'Any detailed analysis of engineering knowledge runs the risk of seeming to divorce such knowledge from engineering practice . . . the inseparability of knowledge and its practical application is in fact a distinguishing characteristic of engineering' [7, p. 207]. Heeding this warning, in the next section we consider how this knowledge is integrated with problem solving as the practice of engineering.

COMPARISON WITH FACULTY AND STUDENT COMMENTS

Three themes regarding the specialized knowledge used by engineers emerged from our interviews of engineering faculty and students that are generally consistent with the ideas outlined above. They are that:

1. A core component of the specialized knowledge is what is referred to by many faculty as 'the fundamentals,' which often includes mathematics and concepts from the natural sciences. Many faculty would label this as the core component:

> *Engineers definitely need a very solid foundation in the fundamentals, which very often also includes a good background in mathematics. A lot of these tools are needed before you can actually let your creativity work and begin designing things, begin inventing the things. So I think this is very important.* School #7, faculty

> *The ability to adjust to the new information and the new technologies that become available [is essential for an engineer]. And that comes from solid and fundamental knowledge, which allows you to adapt to new situations. If you know what is the latest fad and what is the latest thing in fashion– that is not necessarily helpful. It's fundamental knowledge and the ability to think, and combining that with common sense: that is important.* School #7, faculty

2. Lifelong learning, which includes acquiring new knowledge and skills, is key for continued professional success:

> *Lifelong learning has to be part of it. What they've been exposed to while they're in school is the basis on which they're going to build . . . I have not taught a course in the last 25 years that I had as a student. Technology changes. So, be aware of it, accept it, and understand that if you want to function as an engineer, it's a case of lifelong learning. There is no substitute to that.'* School #1, faculty.

> *'We try to stress life-long learning. What they learn here won't get them very far unless they continue to learn.'* School #4, faculty

> *'[Engineers need] the ability to self-educate, to meet new problems you have not seen before. When you get out you will see problems you have not seen in the classroom. You need to be able to train yourself or you will be in trouble.'* School #3, faculty

Many faculty add that key to being able to engage in lifelong learning is a solid grounding in the fundamentals:

> *I think to be a successful professional engineer you have to have strong base of knowledge and be able to adapt to the changing world. . . . Analog design or electronics or circuits or electrical computer engineering is not going to look the same in thirty years. . . . So the successful professional engineers are going to be the ones that are always evolving with the technology, and always changing. I think that by the way we try to really instill the fundamentals, I think that's really important for [students] to become strong professional engineers.* School #2, faculty

> *We hear students say that engineering has a half-life of a year and a half, and we ask them, 'What do you mean by that—does Newton's Laws change? Does the First Law of Thermodynamics change?' . . . So, what are we doing with these engineering folk? We start by giving them fundamentals . . . So when they go out, they are wary of quick solutions and slick devices and they're ready to sit down and think.'* School #1, faculty

3. Types of knowledge that engineers bring to bear in their work are wide-ranging, including understanding of culture, context, and ethics:

> *More and more I see less and less of the technical skills and more of the human skills– basically, more of the societal skills. Why? The human factor, the cultural understanding, that come together more and more important . . . '* School #5, faculty

and various forms of communications, including good written, oral, and interpersonal communication:

> *It's just a fact of life that in the modern world good engineering work that is un-communicated has the same value as engineering work that was never done. . . . They have to learn to work professionally with people that are not of their own choosing, and of not necessarily of the same ability level, and whom they may or may not ever work with again'.* School #7, faculty

> *I think engineers need to have excellent oral and written communication skills, because if you want to invent a new widget that will save society, if you can't communicate those ideas to society then it's useless to society. So I think Engineers need to know how to tell a non-technical audience the importance of their technical contribution.'* School #3, faculty

> *The top ranked skill for engineers is the ability to communicate well. Close to that, the ability to work on a team and be effective on a team.'* School #7, faculty

We did not hear faculty and students explicitly mention knowledge-types (2) fundamental design concepts, (3) criteria and specifications, (4) quantitative data, (5) practical considerations when talking about the knowledge and skills central to engineering practice.

THE PRACTICE OF ENGINEERING: INTEGRATING PROCESS AND KNOWLEDGE

Engineering practice is not simply a problem-solving process and specialized knowledge. It is the complex, thoughtful and intentional integration of these towards some meaningful end. For example, in generating candidate solutions (as part of the Means–End cluster of activities), engineers search past experiences related to similar situations to find knowledge that has proved useful. They also incorporate novel features to the current problem, even to the extent that these features depart from what has worked in the past.

As another example of engineering work involving connecting process and knowledge, consider how engineers go about evaluating and implementing candidate solutions. Evaluating involves analyzing the candidate solutions using a variety of knowledge types, often in the form of codified tools to predict performance. These predictions are then compared with requirements and constraints to select a final and best solution. Among the tools that engineers use to select from and refine candidate solutions are analytical and physical models that are based on heuristics, science, mathematics and rules of thumb. Engineers must know what analytic and physical tools are available to them, and must decide which are appropriate given time and money constraints, and accuracy requirements. Technical know-how (codified knowledge) and tacit knowledge, in addition to judgment based on experience and skepticism are all required.

It is important to note that the integration of process and knowledge happens within the mind of a single engineer and between engineers. Very little engineering work is solitary, and it is increasingly being recognized as a social process [5]. The reality is that few engineers are expert in all aspects of the engineering problem solving process and in all knowledge types, and many (if not most) engineering problems have timeframes and complexity that require teams of engineers to work on them. The vast majority of practicing engineers become expert in aspects of engineering practice, and then by working in a coordinated manner with experts in other aspects, the project moves forward. For example, a design engineer may be particularly knowledgeable about processes related to generating candidate solutions (C: Means–End generation) and draws from her knowledge of Fundamental Design concepts (2) and Criteria and Specifications (3). She may then interact with an engineering analyst who is expert in using models to analyze candidate solutions to predict performance. Finally, both of their particular roles (design engineer and analyst) may be orchestrated by an engineering project manager, who is expert in the overall process and its implementation in a particular company. This example illustrates that individual engineers may be expert in a part of practice and that engineering work is commonly team-based—there is just simply too much to know and to do for the engineering of modern engineering artifacts to be a solitary act.

The integration of process and knowledge creates tensions that must be continuously balanced and negotiated. For example, engineering work requires a balance between moving a particular project towards completion with incomplete knowledge and imposing delays to allow more complete knowledge to be gathered and integrated into the process. In *Designing Engineers* [5], based on ethnographic studies of three disparate engineering design projects, a case is made that engineering is not an instrumental process and that it is full of uncertainty and ambiguity. There is generally not a routine solution or a totally defined script for how to go about the work. For the software engineers in Perlow's ethnographic study *Finding time, stopping the frenzy* [6] this manifested itself in the engineers feeling that they were perpetually in crisis mode, as they dealt with competing demands, frequent interruptions and shifting deadlines.

Another tension is created as the result of the disparate and perhaps conflicting knowledge-types that engineers must integrate into the work (e.g., quantitative data and qualitative data, science based and contextually based). Even within a knowledge-type there may be conflicts. Rubenstein poignantly illustrates this in considering value systems (which is an example of contextual knowledge): 'the same problem, two different value systems; therefore two different criteria, different decisions, and different solutions. This is the problem of problems, the subjective element of problem solving and decision making. Man's value system, his priorities, guide his behavior as manifested in problem solving and decision making. Two people, using the same rational tools of problem solving, may arrive at different solutions because they operate from different frames of values and, therefore, their behavior is different' [9, pp. 1–2].

Understanding of engineering work's complex mix of formal, contextual, social, tacit and explicit knowledge has grown considerably of the last 15 years as sociologists undertake studies of not only the social aspects of the work (e.g., with whom engineers interact, for what purposes, in what contexts) but also the substantive aspects of the work. In [15] Barley reviews some recent studies of this type. He also notes that a real challenge in this type of research is that to 'conduct fieldwork on technical practices requires researchers to have at least rudimentary knowledge of the scientific and technical disciplines in which the practice is rooted. It is for this reason that many of those who have studied technical practice have either been trained engineers and technicians or have worked in technical forms or engineering schools.'

Comparison with faculty and student comments:

Four themes regarding engineering practice emerged from our interviews of engineering faculty and students that are consistent with the ideas about engineering practice outlined above. They are that:

1. Engineering practice involves the integration of process and knowledge to some end:

    What an engineer needs are to be able to identify gaps in that existing knowledge, to be able to know where to go to fill in those gaps, and to be able to apply that synthesized knowledge to a particular problem and provide a solution. In the broadest sense, that's what an engineer does.' School #4, faculty

2. Engineers need to design products keeping in mind potential benefits to humanity and the environment:

    An engineer uses his/her skills to benefit mankind. There are lots of ethical decisions involved, including how close to cut the factor of safety and using this steel beam that costs less versus another one that costs more. School #3, student

    An engineer must be able to think inside and outside of the box. And must think beyond now and about the future and everyone around you. Sustainability is important. An engineer must address broad concerns. School #7, student

    You need to be able to consider social, political and economic constraints. You need to look at alternate solutions and their relation to cost and environment. School #3, student

    I think that to be a professional engineer, you need to not only know the technical problem solving but you also have to be aware of the larger context in which you are doing it. . . . You need to take a lot of stuff into account. You can't divorce the engineering problem with the social context. . . . They can't ignore the ethics of doing it. School #4, faculty

3. Engineering practice is a social activity, involving teams working in concert towards a

common goal. As a result of this, the work involves a variety of forms of communication, from written to oral, and from formal to informal:

> *Listen to the industry, every time that you talk to people, lecturers come here and talk: 'teamwork, teamwork, teamwork.' Look at all the designs, which are being done. If you are not able to work in a team–these are all inter-disciplinary teams. And when you are designing an appliance, or washer-dryer. There are people on electrical, mechanical, and you name it and they have to sit down together and work on this project.* School #5, faculty

4. Engineering work engages engineers as individuals, as members of project teams, and employees of corporations, and as members of the broader professional and societal communities:

> *What it means to be a professional engineer includes at least two things in my mind. One, to recognize that they are members of a community, that they just can't act alone . . . There are boundary conditions on making money, and that as a professional you don't just do everything that you're asked to do, you're not just a hired gun. The second thing is that you're not just a lone hired gun, that you have a responsibility not just to the professional society, but also to society as a whole. And that the professional society as a whole has an obligation to society as a whole.* School #3, faculty

What we did not hear faculty and students comment on was the fast-paced, multifaceted and fragmented nature of engineering work, as exemplified by Perlow's [6] and Bucciarelli's [7] ethnographic studies of engineering work.

THE QUESTIONS WE ARE ASKING ABOUT TODAY'S EDUCATION OF ENGINEERS

The description of engineering work laid out in the previous sections allows us to elaborate further on the core question that the Carnegie study aims to address, namely, '*What are the pedagogies that make-up engineering education, and how are they related to engineering practice?*'. We refine and expand this central question into a family of questions on how engineering is taught and learned:

- What types of knowledge are taught (and who decides what types)? In what ways are they taught? What ways are the various types best learned? What pedagogies encourage learning that is about both the 'what' and 'how'? What pedagogies encourage and enable learners to continue to expand and update their knowledge?
- In what ways is engineering problem-solving taught? What methods are used to teach analytic problem solving? What methods are used for teaching design problem solving? For problem-solving that integrates design and analysis?
- What types of educational experiences challenge student to integrate specialized knowledge and problem-solving? In other words, what pedagogies have students engage in engineering practice? Which are best?
- In what ways are students challenged to integrate contextual information and knowledge into problem-solving? How are students taught to act with professionalism? How might things be improved?
- What is the relationship between engineering practice and education? What should this relationship be in the future? Who should be involved in defining and maintaining this relationship? How does history influence this relationship?
- Are the educational practices we observed up to the task of educating future professionals?

In the forthcoming *Educating Engineers*, we address the questions listed above and consider how effective an apprenticeship for practice current programs are. We consider part of the apprenticeship to be aimed at the development of the student's analytic reasoning in the use of engineering principles or ideas to solve engineering problems. Another part focuses on the development of technical and creative skills that are taught within practical contexts. A final part introduces students to the various roles and responsibilities of a professional engineer, and provides the social and ethical perspective for their work.

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