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THE NEW-CENTURY ENGINEER

ENGINEERING PRACTICE IS, in its essence, problem solving. There are, of course, many ways to describe this work. The U.S. Department of Labor describes engineering as the application of "the theory and principles of science and mathematics to research and develop economical solutions to technical problems . . . the link between perceived social needs and commercial applications" (U.S. Department of Labor, and Bureau of Labor Statistics, 2007). The outcome is often fabrication specifications, the creation and production of a physical artifact, changed personal or public knowledge, new technologies, or a changed state of the human condition.

ABET describes engineering practice as "a decision-making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective" (ABET, 2007, p. 2). The problems that engineers respond to are typically ill-defined and underdefined; that is (1) there are usually many acceptable solutions to a design problem, and (2) solutions for design problems cannot normally be found by routinely applying a mathematical formula in a structured way (Dym and others, 2005; Dym and Little, 2008). A former official of the National Science Foundation observed, "In essence, engineering is the process of integrating knowledge to some purpose. It is a societal activity focused on connecting pieces of knowledge and technology to synthesize new products, systems, and services of high quality with respect for [for example] environmental fragility" (Bordogna, 1992, p. 1).

However, as the enormous changes in technology that engineering has brought about are precipitating profound changes in society and daily life, they are precipitating similarly profound changes in engineering practice. The most central of these is a change from a *linear conception* of problem analysis and problem solving that presupposed a more stable organizational and physical environment to a *network*, *web*, *or systems understanding* of engineering work. The new environment for engineering is forcing the formulation of problems and interactive design of solutions to the center of professional activity. This represents a significant change in focus, away from problems in which "the number of variables was severely constrained, and problems could be reduced to quantitative dimensions" and solved by the use of knowledge and techniques common to all involved, and toward "complex systems" that are "so heterogeneous that interdisciplinary interactive groups sharing perspectives and information are needed to create and control them" (Hughes, 2004, p. 78).

New-Century Engineering: A New World of Problems and Problem Solving

Historically, the engineer's assumed perspective was outside the situation or problem—that of a disengaged problem solver who could confidently model the problem in objective, mathematical terms and then project a solution, framed largely in terms of efficiency and technical ingenuity, affecting a system uncontaminated by the frictions of human relationships or conflicting purposes. This concept of the professional as neutral problem solver, long central to engineering practice and education, is now outmoded, due in part to its own unintended consequences. For example, developing automobile technology and national policies with little regard for the social or ecological effects has proved to be a narrow-minded policy in the United States but one with potentially catastrophic ecological effects if continued in China.

Because engineers' work directly affects the world, engineers must be able and willing to think about their ethical responsibility for the consequences of their interventions in an increasingly interlinked world environment. Working with others, in this country and around the world, to understand and formulate problems, engineers are immersed in the environment and human relationships from which perception of a problem arises in the first place. Writing about this newer engineering sensibility, Rosalind Williams has described it as the viewpoint attendant upon living within a "hybrid world in which there is no clear boundary between autonomous, non-human nature and human-generated processes" (Williams, 2002, p. 31). The effects of engineering problem-solutions—their interventions into affairs—are being "fed back" to the engineers working, often in groups with other specialists or lay people, to define and solve problems within a common set of purposes.

The shift from an outside to an inside perspective can be understood as a shift from engineering for "them" to engineering for "us." Although this new point of view may be disarming, at the same time it holds the potential to inspire new thinking, for a shift from an outside to an inside perspective highlights the complex social, physical, and informational interconnections that enable modern technologies to function. As the globalizing economic system illustrates, division of labor produces great efficiencies by enabling each component of a complex interacting system to focus on maximizing the achievement of just one goal. However, the system as a whole is also likely to produce consequences not intended by the designers. These may "feed back" on both the system and its environment, sometimes in ways that threaten the continued efficiency of the system and the sustainability of its environment. Today's growing list of ecological problems, to say nothing of economic and social problems, have brought home in alarming ways the unintended consequences of many of our greatest technological triumphs.

Changing Knowledge

Professional practice depends on a specialized body of "engineering knowledge." As Vincenti offers, "Engineers spend their time dealing mostly with practical problems, and engineering knowledge both serves and grows out of this occupation" (Vincenti, 1990, p. 200). A distinctive feature of this specialized knowledge is that it includes what philosopher Gilbert Ryle called "knowing that" (Ryle, [1949] 2000). Shavelson and Huang add to Ryle's "knowing that" (that is, declarative knowledge), "knowing how" (that is, procedural knowledge), by suggesting that disciplines also rely on schematic knowledge, or "knowing why," and strategic knowledge, "knowing when certain knowledge applies, where it applies, and how it applies" (Shavelson and Huang, 2003, p. 14). 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 skills and facts to bear on a particular problem.

Another distinguishing feature of engineering knowledge is that it is not simply and totally a derivative of science. It is "an autonomous body of knowledge, identifiably different from scientific knowledge." (Vincenti, 1990, pp. 3–4). The idea of "technology as knowledge" (Layton, 1974) 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 model. In this newer view, technology, though it may *apply* science, is not the same as or entirely *applied* science" (Vincenti, 1990, p. 4).

Moreover, the knowledge engineers draw on is increasingly dynamic and complex. To successfully integrate process and knowledge, engineers must not only stay informed about new and emerging technologies but also be aware of knowledge and skills from other domains. As Table 1.1 suggests, engineers call on wide ranging knowledge, from theoretical tools to contextual knowledge. Taken to a high degree of detail, such a list could even include such things as marketing, finance, and sociology that are critical for particular engineering enterprises.

A Changing Process

Engineers are continuously balancing and negotiating tensions. For example, engineers must strike a balance between moving a project toward completion with incomplete knowledge or imposing delays to allow more complete knowledge to be gathered and employed. In *Designing Engineers*, based on ethnographic studies of three design projects, Bucciarelli makes the case that engineering is not an instrumental process: it is full of uncertainty and ambiguity. There is neither a routine solution nor a defined script for doing the work. For the software engineers in Perlow's 1997 ethnographic study *Finding Time*, 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.

Collaboration

Increasingly, engineering work is a highly collaborative process (Bucciarelli, 1996). There is just simply too much to know and to do. The scope, timeframes, and complexity of most projects require the effort of teams of engineers—experts in some aspects of engineering practice working in coordination with other experts.

Teamwork has inherent tensions. As Rubenstein observes, "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 . . . 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" (Rubinstein, 1975, pp. 1–2).

Table 1.1. Types of Knowledge Used by Engineers

Knowledge Type	Description
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.
Fundamental design concepts: operational principles and normal configurations	“Operational principle” describes “how [a device or technology’s] characteristic parts fulfill their special function in combination with an overall operation which achieves the purpose”—in essence, how the device or technology works. “Normal configurations” describes what is typically taken for the shape and arrangements for a particular class of devices (technologies).
Criteria and specifications	Technical criteria appropriate to a class of devices or technologies, including numerical performance criteria, such as impact performance criteria in the automotive sector or pressure vessel standards in the chemical industry.
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.
Practical considerations	Tacit knowledge, typically learned on the job, generally not codified. In addition, rules of thumb and heuristics (“design considerations,” Vincenti, 1990).
Process-facilitating strategies	Knowledge of tools and strategies for project management, leadership, teamwork, communications, and management.
Contextual and normative knowledge	Knowledge of values (personal, professional, cultural), norms (what is acceptable, expected behavior), contexts, and contextual factors that constitute the artifact’s ambience.

Sources: *Vincenti (1990), Koen (2003), and Kroes (1996).*

As the size of the engineering team expands and the members of the team become more diverse, these tensions become more complex. The members of the teams are, indeed, changing. From its nineteenth-century beginnings, American engineering has taken a course of upward mobility, providing a route for generations of ambitious, technically oriented young people to rise into the middle class, often going on to careers in industrial management. Engineering's status as an undergraduate professional degree continues to give the field an advantage in attracting upwardly mobile students—in contrast with medicine and law, both of which, in the United States, require costly graduate study—and since the 1960s, non-whites and women have entered the field. Although engineering lags behind other professional fields, including law and medicine, in its percentage of minority and women students and practitioners, it has seen an increased representation of these populations. For example, prior to 1970, women made up less than 1 percent of the students graduating annually with a bachelor's in engineering; they now make up over 20 percent of the graduating class. Similarly underrepresented groups now make up 12 percent of each graduating class. Still, these numbers fall short of their representation in the general population.

Collaboration is also a process that crosses time and cultures. Increasingly, engineering endeavors involve teams scattered across continents, working toward a common purpose. Corporations are moving aggressively, tapping into technical talent wherever they can find it, recognizing that synergized, distributed expertise can bring both needed engineering and cultural knowledge to a project, which holds the potential to build new markets.

The New-Century Engineer

What professional goals and values might guide the engineer in this new, networked context? As we suggest in Part Five, the codes of engineering ethics in the particular engineering specialties, when taken together, point to a set of overarching values and goals of the profession. All of the codes acknowledge the overall mission of the profession as contributing to human welfare. In line with this mission, they describe the overriding importance of public safety, health, and welfare, and protection of the environment in all that engineers do (Little, Hink, and Barney, 2008; National Academy of Engineering, 2004). They also stress the responsibility to be competent in one's work, to be careful not to misrepresent one's competencies, and to continue building one's competence through ongoing professional development.

Globalization of engineering work has added urgency and complexity to each of these goals. To enact them, the "new-century engineer," needs attributes that connect "engineering's past, present, and future" (National Academy of Engineering, 2004, p. 54; see also Downey and others, 2006; Shuman, Besterfield-Sacre, and McGourty, 2005; and Oberst and Jones, 2006). In *The Engineer of 2020*, the National Academy of Engineering (NAE) describes nine attributes that build on strengths inherited from the past while incorporating the qualities that are becoming critical in the changing world of engineering practice, with its more public and interactive aspects of designing and working with today's complex new technologies, for more complicated problems.

The first two attributes, "strong analytical skills" complemented by "practical ingenuity," are long-familiar goals of engineering education. Engineers must be able to employ "science, mathematics, and domains of discovery and design to a particular challenge and for a practical purpose" (NAE, 2004, p. 54). However, although engineers must be able to use science and mathematics in their thinking, this thinking is not oriented toward theory but to "discovery and design" for particular purposes in response to specific challenges. In other words, an engineer's analytical thinking is framed by and used in the service of practical ends. With "skill in planning, combining, and adapting," the engineer uses both science and "practical ingenuity" (p. 54).

The engineer also needs "creativity," described as the ability to respond to challenges by combining in new ways "a broader range of interdisciplinary knowledge and a greater focus on systemic constructs and outcomes" (p. 55). Engineering practice increasingly demands an approach to problems that resembles engineering design work. Attendant to creativity is a fourth attribute, which NAE calls "communication," a way to address the need for engineers to become more "accountable": because they will increasingly work as part of interdisciplinary teams, engineers must be able to explain their thinking to diverse audiences and partners as well as think with others in order to arrive at solutions to problems (p. 55).

A fifth attribute, "mastery of the principles of business and management," stresses the need for engineers to understand—and act in light of—"the interdependence between technology and the social and economic foundations of modern society" (p. 55). If they can do these things, then engineers will be able to exhibit "leadership" that acknowledges "the significance and importance of public service . . . well beyond the accepted roles of the past" (p. 56). Complementing leadership is a greater sense of "professionalism" and "high ethical standards." These attributes are connected to a quality that "cannot be described in a single word" but encompasses "dynamism, agility, resilience, and flexibility" (p. 56), character traits that need leadership, high ethical standards, and professionalism to give them balance and point. None of these attributes can be developed quickly. Hence the need for the final attribute: engineers must be "life-long learners" (p. 56).

We believe that Shulman's description of a professional encompasses the professional values described in the engineering codes and NAE's nine attributes: the new-century engineer provides a worthwhile service in the pursuit of important human and social ends, possesses fundamental knowledge and skill, develops the capacity to engage in complex forms of professional practice, makes judgments under conditions of uncertainty, learns from experience, and creates and participates in a responsible and effective professional community.

Preparing the New-Century Engineer

We are convinced of the direction and scope that the profession is now taking and thus the necessity of cultivating in aspiring engineers the knowledge, skills of practice, and understanding and commitment to enact these values and attributes in daily professional life. The task, then, is not only to identify the specific engineering knowledge, skills, and values that students need as they enter the profession but also to determine what kind of educational experience and what approximations of professional practice will best position students to continue to develop them. Because engineering schools initiate but do not complete the formation of their students as engineers, starting the process in such a way that the students' progress toward greater engineering competence can continue and be sustained is no small task.