the field to consider how the entry-level degree for professionals might better align with current and future needs.

A Tool for Change

We offer this book to engineering faculty and administrators, national leaders in the engineering profession, and higher education leaders as a catalyst for reflection and assessment of engineering education. We hope that it causes the reader to explore a core question: *What are today's educational practices and how well do they support the development of tomorrow's engineer?*

This questioning may happen at the individual level. For example, faculty members creating and teaching analysis or design courses may be drawn to the particular sections of the report that describe their areas of the undergraduate engineering program. We hope that individual faculty members will consider their courses in the context of the entire program. We imagine that this question might also drive department- or program-wide affinity or working groups as they review programs, discuss pedagogy and assessment, or consider curriculum changes. Similarly, we imagine that professional societies, as well as accreditation and funding agencies, might undertake a similar process using this book as the basis for study and recommendations.

Ultimately, however, our goal is more ambitious than prompting reflection or incremental improvement. Our goal is action, for we believe that incremental improvement will lead only to a more optimized linear model of education that will, if not at the moment of its redesign, quickly thereafter become once again "overstuffed." To accomplish this task, we need to undertake what Vincenti (1990) termed "radical" design and develop a new approach to undergraduate engineering education, the core of which is professional engineering practice, not historical tradition. Both the learning sciences and our sister profession, medicine, offer much to draw from. This redesign, as one of its requirements, should have continuous revitalization and rejuvenation.

Thus, through this book, we extend a challenge to the engineering community: Reflect, assess, debate, design, and prototype a truly networked engineering education, one that engages both student and teacher in learning in context. Engage as colleagues and make the redesign of engineering education a national undertaking for the next five years. Redesign engineering education to prepare the new-century engineers that today's problems demand.

PART ONE

PREPARING THE NEW-CENTURY ENGINEER

PROFESSIONALS, EXPLAINS LEE SHULMAN, provide a worthwhile service in the pursuit of important human and social ends; possess fundamental knowledge and skill; 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 responsible and effective professional communities (Shulman, 1998).

Engineers, as do other professionals such as physicians, nurses, lawyers, and clergy, work within ever-increasing complexity and changing conditions. As the external environments for engineering practice have changed, so too has the substance of the work—the problems engineers address and the knowledge they draw on to do so. At the same time, their relations to work and the workplace as well as to their colleagues are also changing dramatically.

Although engineering schools aim to prepare students for the profession, they are heavily influenced by academic traditions that do not always support the profession's needs. From the time that the formal training of engineers in the United States was first patterned after the French model—a curriculum of basic sciences, technical subjects, and humanities, with theory taught before application—through the middle of the twentieth century, engineering education struggled

to establish its place in the academy and earn the recognition of practitioners, both responding to and being shaped by the values of the academy. The solution has always been to add more rather than to consider the overall design. Thus a jam-packed curriculum focused on technical knowledge is the means for preparing students for a profession that demands a complex mix of formal, contextual, social, tacit, and explicit knowledge.

The case of engineering education, however, is not unique. The Carnegie Foundation's studies of the education of lawyers, clergy, physicians, and nurses have also found that professional education has been dealing with the challenge of integrating knowledge and practice in a way that more fully prepares students to enter the profession.

The foundation's reports recommend that professional schools, because they are responsible for the preparation of practitioners, should aim for an increasingly integrated approach to the formation of students' analytical reasoning, practical skills, and professional judgment. Although some engineering schools have introduced programs, teaching methods, or curricular structures that attempt to integrate these professional goals, none offers a comprehensively networked approach.

In this first part, we look first at the profound changes in the profession of engineering. Then, to begin our consideration of how U.S. engineering education aligns to current and future needs, we describe the current linear components model that we found so prevalent and the nascent networked components approach that integrates knowledge and practice.

1

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.

2

TECHNICAL KNOWLEDGE AND LINEAR COMPONENTS

ALTHOUGH THE 1,740 UNDERGRADUATE engineering programs in the United States vary in their emphases and serve diverse student populations, they are remarkably consistent in their goal: U.S. engineering education is primarily focused on the acquisition of technical knowledge. Indeed, over its two-hundred-year history, the formal education of engineers has consistently emphasized the study of concepts and ideas grounded in mathematics and the physical sciences; offered practice of skills, strategies, procedures, and techniques seen as central to engineering practice; and called for development of understanding of professional and cultural ethics and standards.

U.S. undergraduate engineering programs also share a remarkably homogeneous curriculum and pedagogy. Our reading of ABET self-study reports; interviews with faculty, administrators, and students; classroom observations; and reading of the history of engineering and engineering education all pointed directly to four building blocks—or, as we call them, linear components—that make up engineering education. Each block has its own cluster of courses that have distinct, although not necessarily explicit, learning goals and a particular approach to pedagogy and assessment.

The Four Linear Components

The largest block of the engineering curriculum is made up of the mathematics, science, and a body of knowledge called "engineering science," often referred to as the "fundamentals" or, as faculty told us, the major part of the knowledge that every engineer ought to master. These courses

make up the greatest number of credits or units in the program, and the course sequences, some of which are layered four and five courses deep, suggest to students not only that theory precedes practice, but that one needs to move from theory to practice in a particular sequence.

Students begin with mathematics and physics, chemistry, or increasingly, biology courses, taught theoretically and by faculty outside the engineering program. In their sophomore year, students continue math and science courses while beginning the engineering science sequence; they also identify a concentration. The engineering science courses may reintroduce concepts and skills the students encountered in science and mathematics courses, this time with a focus on their uses in engineering. Emphasizing deductive reasoning, faculty present students with methods for solving problems, along with paradigmatic examples of problems and solutions, making extensive use of blackboard or Microsoft PowerPoint. Students learn as individuals, largely by applying formulas and rules to the solution of structured, "right-answer" problems, whether in class, as homework, or on exams.

By their junior year, the students will have completed the mathematics and science requirements, and they start taking the technical, or "analysis," courses particular to their field of engineering. These technical courses introduce new concepts and skills derived from and aligned with those the students encountered in the engineering science courses. Using these second-generation principles, students evaluate such engineering elements as gears, bearings, circuits, transistors, and other key technologies of their particular fields.

The upper-level courses also employ lecture and right-answer problems for homework and exams, and the labs connected to the courses are used largely for demonstrating the concepts, although students may be asked to develop systems. At their very best, technical courses ask students to solve open-ended analysis problems and tackle design exercises. The engineering faculty responsible for teaching the engineering science and technical courses often do not have much freedom in defining content, as most of these courses are prerequisites or requirements, and course material has been established by the curriculum committee and the field.

Seniors continue taking technical courses, some of which broaden the range of engineering elements they are exposed to or deepen their experience with those elements they already know. The senior year generally concludes with a design experience, in which the instructor, who might be an adjunct faculty member from the field, acts as a coach or guide, and students are challenged to develop entirely new skills.

From Theory to Practice

Lab courses are usually either appendages to theory courses or extend the teaching of formal concepts begun in theory courses. In the lab, students see theory in action, learn to prototype, and try to debug ideas. Here, however, the setting and teaching are quite different from those in theory courses. Faculty or graduate assistants explain procedures and then coach students, who generally work with lab partners.

Thus students generally experience problem solving as a linear, two-step process that involves first acquiring a body of technical knowledge and then generating models and analyzing engineering systems. The tradition of putting theory before practice reflects the notion that "engineers needed grounding in these 'fundamentals' to have command of basic principles that could be applied to a variety of technical problems" (Williams, 2002, p. 40).

Practicing Design

Design is a relatively recent addition to engineering education, and the central focus is teaching students to define needs, generate many possible solutions, and move toward an optimum solution. Although some programs offer first-year design experiences, design is generally reserved for the senior year. The design projects of the final year are often unstructured problems that demand imagination and teamwork. The projects may either simulate engineering practice or present graduated experiences of it, and assessment often focuses on communication and teamwork. It may appear to students as both a welcome introduction to the "real world" but also an anomaly in their experience of a deductive model of science applied.

From Student to Professional

ABET accreditation requirements now specify that students can take up to 36 percent of their total 120 to 130 undergraduate credit requirements outside of technical studies, in the humanities, business, and social sciences. Explicit inclusion of the humanities and what we now call the social sciences in the undergraduate engineering program dates to the early nineteenth century. The purpose behind the long-standing expectation is lofty: "The fields of humanities and social sciences from which some courses must be selected include history, economics, and government, wherein knowledge is essential to competence as a citizen; and literature, sociology, philosophy, psychology, and the fine arts, which afford means for

broadening the engineer's intellectual outlook" (Grinter, [1955] 1994, p. 82; see also Mann, 1918; Society for the Promotion of Engineering Education, 1930; Bucciarelli and Kuhn, 1997). The assumption is that exposure to the humanities and social sciences will contribute to the students' "development of both a personal philosophy which will insure satisfaction in the pursuit of a productive life and a sense of moral and ethical values consistent with the career of a professional engineer" (Grinter, [1955] 1994, p. 76).

Although they are required, the humanities and social science courses, including ethics, are not treated as integral to the business of becoming an engineer. With the exception of the ethics modules in some capstone design courses, liberal arts requirements remain appendages rather than central elements of what is required to learn to be an engineer. Students generally choose courses rather haphazardly from a list of those that meet distribution requirements, and the learning in those courses is seldom integrated with their development as engineers. Too often, these courses are seen simply as hurdles to be cleared, standing in the way of rather than informing the process of learning to be an engineer. The courses and their content remain largely disconnected from the technical education program, and it is largely up to the student to bring them together, if they are brought together at all.

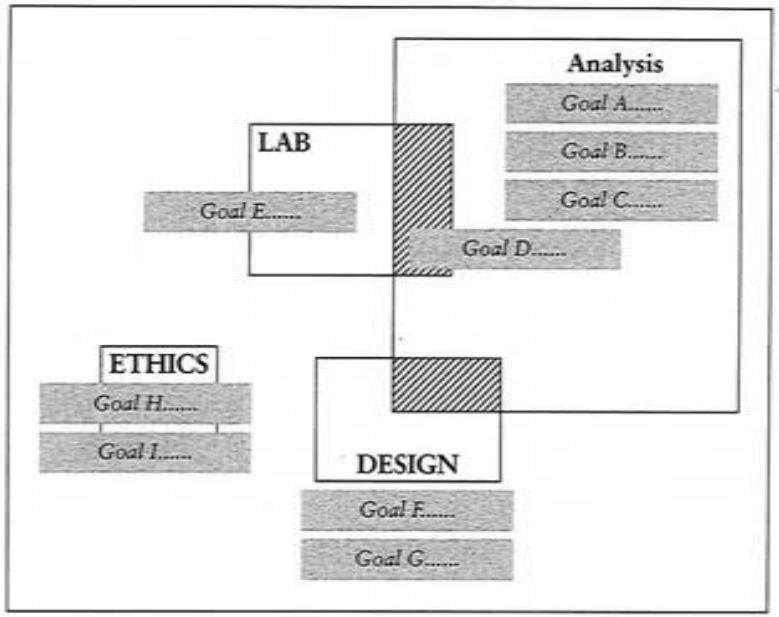
We might then more accurately say that engineering students have curricular experiences that may or may not expose them to the societal implications of engineering work. The ethical standards, social roles, and responsibilities of the profession, often framed around avoiding wrongdoing, are treated as ancillary elements of engineering work. Students are rarely afforded multiple opportunities to actively struggle through ethics problems in classroom discussions and assignments that would help them connect the ideas, principles, processes, and habits of mind of engineering.

As it stands now, the liberal arts component of most engineering programs does not realize its potential to inform practice in these rich and compelling ways. This means it is unlikely that the goal, expressed as important by both faculty and employers (Lattuca, Terenzini, and Volkwein, 2006), of students learning to consider the implications of engineering in global and social context can be adequately achieved.

Four Unbalanced Blocks

Figure 2.1 presents a visual rendering of engineering education, depicting what we have observed about of the historical "linear components":

Figure 2.1. Linear Components Model



how undersized design and laboratory are, relative to the multiple roles they play a student's development, including being the best proxy for a clinical experience, and how distant and small are considerations of professionalism—ethics, social responsibility, integrity, lifelong learning. Moreover, where the boxes connect, the relationship is unidirectional—hence "linear" components.

The linear components represent a result rather than a plan. Over the history of engineering education, the remarkable expansion of scientific knowledge and the increasing professional prestige associated with it encouraged engineering educators to respond by adding science-based courses to the already extended and overloaded curriculum, thus further reducing the provision for laboratory, social science, and the humanities. Today's curriculum is as "congested beyond endurance" as Mann found it in 1918 (p. 25), if not more so.

The packed curriculum results in practical problems. The conceptual difficulties and pace at which the material is presented, in addition to the manner of its presentation, contribute to attrition (Seymour and Hewitt, 1997). Critics have noted that the workload of science and math courses can be so overwhelming that students end up losing interest in

the profession for which they are being prepared. Furthermore, the curriculum is such that it is almost essential that students be committed to engineering from the day they matriculate: "discovering engineering" at some point during—or after—undergraduate studies and being able to shift into the field is very uncommon.

Engineering has the highest persistence rate of any undergraduate major: 57 percent of students who matriculate in engineering remain there. The next highest is business at 55 percent, followed by sciences and mathematics at 44 percent and computer science at 38 percent (Ohland and others, 2008). However, engineering has the lowest percentage of students migrating into the field: only 7 percent of students who major in engineering did not matriculate in engineering, whereas for all other fields the comparable number ranges from 35 to 59 percent (Ohland and others, 2008). Though women and underrepresented minority students generally persist in engineering at the same rates as majority students, their overall absence from the engineering student body, relative to their presence in the general population, remains striking.

However, we believe that the reasons for trying to effect change in engineering education go beyond the need to address even such important problems as these. The historical model of engineering education treats learning as a deductive sequence, in linear fashion, suggesting a form of mechanical causation in which each component propels the next in line. Proficiency in "engineering science" counts most, and the proper progression is always from scientific theory to engineering practice. The implied theory of knowledge is that engineering is in the main deductive.

Our field observations of engineering programs, described in detail in Parts Two through Five of this volume, suggest that this impression is strongly reinforced by the deductive strategy used in teaching the core subjects of engineering science. Formal knowledge overshadows practical experience, even experiments under laboratory conditions, and suggests that the engineering student, if not the engineer, is an individual competing with other similar but mutually disinterested individuals for achievement. The strength of the pedagogy is such that it competes with the goals of team-based learning, including capstone design experiences.

It is, of course, possible to maximize the potential for learning in the linear curriculum. We saw, and describe here, many innovative approaches to teaching in the traditional curriculum. However, the pieces remain blocks, and though we might rearrange them or change their size, they remain blocks, with all the attendant limitations on the structures that can be built with them.

Aligning Preparation to Professional Practice

The innovations we observed suggest that it is possible to network the components in such a way that engineering education would be better aligned to the profession. Less concentrated on engineering science and analysis courses, a networked approach would integrate theory, laboratory, and design experiences at each phase of the program in a spiral configuration of developing professional competence.

For example, in some programs that we observed, the starting point for students is an overview of the profession as well as some experience of design activity, even when students have hardly any real scientific knowledge to guide and complement that activity. The idea behind this approach is that efforts at design and questions about the nature and scope of engineering are valuable, even or especially at this stage of learning. In experiencing a simplified approximation to engineering practice, the novice nonetheless gets a sense of the breadth of engineering's dimensions.

These first encounters with the field as a whole can be important motivators to learning. They enable the student to grasp firsthand the value of acquiring difficult knowledge and skills that engineering work entails. The students' experiences with design and other dimensions of professional practice are often continued in different contexts through the subsequent years of the program.

Students entering a networked curriculum would encounter engineering from the first as a clearly professional and inventive field. Developing and maintaining competence in professional practice would be understood as a spiral process that builds and draws on various kinds of knowledge and skill, importantly including deduction and scientific analysis, but understanding and commitment as well. With professional practice as a center, students would encounter engineering as a field that requires working closely and effectively with others not only to solve problems but to formulate them as well.

We believe that the widening difference between the new demands on the profession and the inherited model of engineering education has created the conditions for a transformation. A shift from the linear components of the historical curriculum to a networked approach would align with both professional practice and new understanding about learning, teaching, and the development of professionals.

3

A HISTORICAL CURRICULUM IN A NEW ERA

MUCH OF UNDERGRADUATE ENGINEERING EDUCATION has remained the same since Jefferson's 1802 legislation establishing West Point although the emphasis given to the various components of the curriculum has shifted over time, to keep pace with burgeoning scientific and technological knowledge and to increase the status of the discipline. As the history of engineering education indicates, today's model represents the accumulation of a number of design decisions, though memory of these has tended to fade over time, making the present form of engineering education seem, misleadingly, far more inevitable than it actually was.

A Technical Orientation

Early engineering schools prepared students for work that was understood to encompass a wide range of "industrial, commercial and public activity" (Society for the Promotion of Engineering Education, 1930, p. 129). Courses like "Topographical and Hydrographical Surveying," "Machine and Freehand Drawing," and "Masonry and Carpentry" addressed the demand for agriculture and mechanics. As industry expanded, the professional or practical courses quickly shifted their focus to manufacturing concerns. In shop courses, students learned to operate machine tools; in graphics courses, they learned to communicate product geometries as drawings.

Hence, in the early years, scientific knowledge and industrial practice were the focus of these technical schools, whose aim was to train men who could use the rapidly growing scientific knowledge to address the needs of a growing economy and to improve production. However, because

of its practical orientation, engineering education was seen as a threat to traditions of higher learning that valued Greek, Latin, history, philosophy, and theology (Mann, 1918; Society for the Promotion of Engineering Education, 1930; Grayson, 1993). This perceived threat led to pressures from both the academy and industry. Engineering struggled to earn academic credibility and professional recognition. In an effort to "professionalize" engineering, educators began putting stronger emphasis on science and math and promoting a scientific approach to the practice (Coxe, 1894; Mann, 1918), such that science and math, with "humanistic" studies, became significant components of the curriculum and helped engineering schools achieve academic respectability.

Theory Versus Practice

From the mid-1800s to the end of World War I, engineering curricula swung back and forth between heavy practical training on the one hand and pure science on the other. What started as a curriculum focused on design and fieldwork, which became the pattern of civil engineering and later mechanical engineering, eventually began focusing on scientific method and experiment (Grayson, 1993).

At the same time, engineering education struggled with the growing tension between advocates of broader education and those who promoted practical training for immediate employment. However, in the early 1900s, as the nation experienced a surge in economic growth and inventions, engineering education began focusing on the sciences to meet productivity demands. With the growth of electrical engineering, laboratory instruction began increasing in popularity, thus overshadowing the once-dominant shop work.

Joining the Academy

By the turn of the twentieth century, as a new university-based way of training engineers gained ascendancy, engineering became an academic field along with other professions that were entering the university in search of legitimacy through association with scientific research. This new emphasis developed at the height of the second industrial revolution, as new technologies based on advances in internal combustion, chemistry, and electricity spawned huge new industries and set mechanical and electrical engineering on an upward swing in numbers and influence.

Thus the bachelor's degree became the sought-after credential for entry into engineering practice. Civil, mechanical, and electrical engineers

typically began their training firmly within the larger structure of American higher education. By this time, the undergraduate curriculum combined a strong core of mathematical and scientific courses with a substantial requirement of courses in the humanities and other liberal arts. "The basic process of engineering education should be an undergraduate curriculum of coherent and integral structure, directed to the grounding of the student in the principles and methods of engineering and to those elements of liberal culture which serve to fit the engineer for a worthy place in human society and to enrich his personal life" (Society for the Promotion of Engineering Education, 1930, p. 84). Significantly, it also emphasized practical experience in laboratories and shops, including design experience.

The undergraduate curriculum developed through close working relationships among the engineering schools, professional associations, and American industry. Indeed, for the past hundred years, corporations and corporate philanthropy have sought to spur and support development and coordination in engineering schools and the preparation and training of engineering faculty.

Into an Era of Engineering Science

Since the cold war's intense military competition with the Soviet Union and rivalry in space exploration, U.S. undergraduate engineering education has emphasized engineering science and research. The massive national effort to intensify studies in science and technology brought the education of engineers, like the training of physicians, to the forefront as a major concern of the national government. Just as medical education has been importantly stimulated and shaped by the National Institutes of Health and the National Institute of Medicine, so the National Science Foundation (NSF) and the NAE, drawing on distinguished engineering talent, have given impetus to better preparation of engineers. For engineering education, the result has been a displacement of practical experience and design to the margins of a more scientific, less "practical" engineering curriculum. As we describe in greater detail in Part Six, the result for medical education has been an overhauled approach, with greater integration, that focuses on the entirety of professional practice.

When the NSF was established in 1950 as an independent government agency, as part of the national strategy to address the nation's defense and welfare needs through scientific and technological research, engineering schools began recruiting academic researchers rather than practicing engineers. The NSF awarded funds through competitive grants, and the schools needed faculty members with strong mathematical and scientific research capabilities if the programs were to compete successfully for these important grants.

Thus, in the decade between 1950 and 1960, engineering education experienced a true paradigm shift, from an applied, practical focus to a mathematical, engineering science focus (Grayson, 1993; Pister, 1993). The growing research culture continued to thrive with the creation in 1964 of the NAE—a private, nonprofit organization—to advise the government and conduct its own studies on matters concerning the economic and social implications of engineering and technology.

At the same time, productivity and efficiency became the central forces of industrial growth, and by the late 1970s pressure for innovation forced the engineering curricula to give special attention to design and methods used to teach engineering design that go beyond "the routine." Throughout the 1980s and into the 1990s, university-industry interaction intensified through corporate research and development projects, industrial contracts, and entrepreneurial initiatives. The increasing collaboration with industrial partners and the changing demands of engineering work emphasized the need for educating engineers not only in engineering science, mathematics, and other discipline-specific tools but also in nontechnical skills such as teamwork, communication, negotiation, and integration necessary to operate in a complex and ambiguous environment (Bucciarelli and Kuhn, 1997; Prados, Peterson, and Lattuca, 2005). In these decades, increased pressure to include more technology in the curriculum, particularly computer-related technology, squeezed the already packed curricula to the point that the freshman design courses were eliminated or scaled back significantly at most schools (Evans, McNeill, and Beakley, 1990).

Now, as the U.S. economy has become more enmeshed with the rest of the world, voices expressing worries about the competitiveness of American technological workers—and engineers in particular—are becoming louder and more insistent. In this context, questions about the value added by U.S.-trained engineers have come to the fore, as government, industry, and the academy seek to define an American comparative advantage in relation to the engineering workforces of rising industrial powers such as China and India. Behind all this lie the new technologies of the microprocessor and integrated circuitry—the sources of today's information, or what could be called the third industrial revolution. These events have outpaced the educational processes built around the post-war engineering science model.

Chronic Issues

Since the Mann report of 1918, engineering education has received criticism about the curriculum and pedagogy, to the point where these have become a set of chronic challenges or issues. Again and again, engineering education has been faulted for trying to teach too much, believing that a comprehensive background in mathematics and sciences is a prerequisite to the learning of practice.

For example, just as the Mann report noted the overcrowded curriculum and inadequate assessment as well as a need for integration of theory and practice and better retention, so Duderstadt refers to the curriculum as an "obstacle course" (Duderstadt, 2008, p. 34), commenting that "the science-dominated engineering curriculum has also led to an overdependence on the pedagogical methods used in science courses—large lecture courses, rigidly defined problem assignments, highly structured laboratory courses—all of questionable utility for teaching the most important technical skills of engineering: the integration of knowledge, synthesis, design, and innovation" (Duderstadt, 2008, p. 33).

Similarly, Duderstadt's observation that "As the knowledge base in most engineering fields continues to increase exponentially, the engineering curriculum has become bloated with technical material, much of it obsolete by the time our students graduate" echoes the so-called Wickenden report: "Our primary concern should not be with content, but with mastery of the methods of learning and we believe a cumulative effort to be of greater worth than ever widening spread" (Society for the Promotion of Engineering Education, 1930, p. 147). In 1955, the "Grinter report" called for more integration of laboratory and design, as well as the humanities, observing, "Engineering Education must contribute to the development of men who can face new and difficult engineering situations with imagination and competence. Meeting such situations invariably involves both professional and social responsibilities" (Grinter, [1955] 1994, p. 74).

In the early 1990s, Karl Pister commented, "We have taken a great deal for granted in designing curricula and we badly need to revisit both the input and output ends of the process" (Pister, 1993, p. 66) and suggested in the 1995 report that he chaired, that as "there is no simple, universal prescription for dealing with complexity and constant change ... To meet the challenges that the nation faces, each engineering college or school should enter a period of experimentation, monitored by self-assessment and feedback from industry" (National Research Council's Board on Engineering Education, 1995, p. 2). More so now than ever, we believe that the time has come for engineering education to make profound changes so that education for the profession is just that—aligned for new demands on the profession. Although doing so may not eliminate all of the challenges inherent in preparing engineers, we believe that a new approach can reduce or eliminate many of the chronic issues.

Beyond the Blocks

Research on how people learn offers a way to rethink engineering education that addresses engineering's chronic issues and offers a way of thinking consistent with new-century professional practice. The fundamental discovery made in the recent research into learning, which has explored how experts in any domain actually think and act, is that all forms of competence, in both thinking and skillful performance, develop through a process of guided experience that in some ways resembles the traditional entry into professional life via apprenticeship. Some theorists have even called the process of guiding novices toward expertise a *cognitive apprenticeship*, describing the specific processes of thinking that enable beginners to make progress in learning. Careful descriptions of the development of experts—ranging from athletes to scientists to chess players and musicians—reveal that high-performing individuals share a set of features that seem common to expertise.

What Experts Know

The first of the features of expertise is the ability to know a great deal and, most crucially, to have that knowledge readily available in ways relevant to the activities of their practice. In their particular domains of activity, experts have mastered well-rehearsed procedures for handling knowledge based on experience. This observation holds whether the field is chess or musical performance or the practice of medicine. Experts' superior ability to relate their knowledge to problems stands out when compared with that of novices in a field.

Confronted with complex problems, experts can assess the complexity in ways that enable them to bring their knowledge and experience to bear quickly and efficiently. Novices, by contrast, although able to solve problems that have been carefully structured in advance—such as the problem sets provided by mathematics and science textbooks—are often at sea when confronted by open-ended or poorly structured situations.

Experts can also read situations. They quickly size up what is salient, asking which facets of a complex situation are important for solving a challenge. They often do this without stopping to think, judging situations

holistically. This is what makes expertise appear so mysterious, even magical, to the beginner. Beginners develop expertise gradually by employing feedback from competent coaches to improve their performance. However, as practitioners become more competent, moving into greater degrees of expertise, their knowledge and skill become tacit, second nature. They have less need to painstakingly think through problems and can instead use their growing experience to approach solutions efficiently and confidently (Bransford, Brown, and Cocking, 2000).

From Novice to Competent Practitioner

What might the learning sciences contribute to engineering education? First, it is important to grasp that students are on a trajectory from novice to competent performance as practitioners. That is, students must learn to move from solving highly structured problems involving formal concepts, as in their theoretical courses, toward building ability to both formulate and solve less structured, more uncertain kinds of problems. In one sense, this describes a linear progression.

The surprising insight from learning theory, however, is that the most efficient way to facilitate this transition is not a simple one-way movement, starting from structured "theory" courses and ending with unstructured design. In a professional practice like engineering, competence is manifest in the ability to read complex and ambiguous contexts and to carve out from them the important and productive problems that can then be addressed with precision through structured problem-solving techniques. Developing this capacity requires not a once-and-for-all movement from theory to application, but a continuing back-and-forth between general theoretical principles and the particularities of the problem situation as the student builds more sophisticated skills through experience.

UNDERSTANDING COGNITIVE DEVELOPMENT Engineering education differs from most other professional education in an important way: the students are primarily eighteen to twenty-two years old. Engineering students are thus still in a formative phase of cognitive development. The learning and developmental sciences can help engineering educators understand cognitive development and thus better approach teaching for the goals of knowledge in the discipline, skills of practice, and understanding and commitment.

In their extensive work on college students' cognitive development, Patricia King and Karen Kitchener have described the development of what they call *reflective judgment*: the judgments individuals make about ill-structured problems for which there are multiple possible solutions (see, for example, King and Kitchener, 1994). As individuals develop mature reflective judgment, their epistemological assumptions and their ability to evaluate knowledge claims and evidence and to justify their claims and beliefs change. This progression, which King and Kitchener categorize into seven stages, clusters into three levels: *prereflective thinking*, *quasi-reflective thinking*, and *reflective thinking*.

- At the lowest level, prereflective thinking, individuals imagine knowledge to be certain and absolute, though they are aware that not everyone has knowledge in any given area and sometimes the truth about an issue is not yet known even to authorities. At this level, they acquire knowledge from authorities or from direct personal experience.
- At the next level, quasi-reflective thinking, individuals recognize that some problems are ill structured and inevitably include elements of uncertainty. Pascarella and Terenzini explain: "Knowledge claims come to be seen as requiring justification and evidence ... Reasoning and evidence are offered in support of beliefs, [and] the individual begins to realize that others' views may be more strongly reasoned and supported" than one's own so if one is to convince another, one has to provide a stronger justification. "[K]nowledge [about unstructured problems] is considered subjective, context specific, shaped by the individual's perceptions and interpretations of the evidence and criteria for judging ... In accepting knowledge as contextual, the individual recognizes the legitimacy of other views and conclusions" (Pascarella and Terenzini, 2005, p. 37).
- At the highest level, reflective thinking, individuals "recognize that knowledge is never a given but rather the outcome of inquiry, synthesis of evidence and opinion, evaluation of evidence and arguments, and recognition that some judgments are more solidly grounded and defensible than others. Beliefs are judged with respect to their reasonableness, consistency with the evidence, plausibility of the argument, and probability in light of the assembled information. The individual also recognizes that judgments may be reviewed and altered on the basis of new information, perspectives, or tools for inquiry" (Pascarella and Terenzini, 2005, p. 38). This is the kind of thinking that engineers draw on in high-level analytic problem solving.

The undergraduate years are an opportunity for a critical transition in cognitive development. Most students arrive at college at the last stage of the prereflective level, believing that knowledge is gained through personal experience or by finding out the right answers from authorities. Although they may lack the skills to deal with ill-structured problems, their growing "recognition that knowledge is sometimes uncertain" indicates that they are ready to move "toward more complex stages of thinking" and can start differentiating "categories of thought" (Pascarella and Terenzini, 2005, p. 37). Undergraduate education can advance students' reflective judgment so that they enter the stage of quasi-reflective thinking: able to use reason and evidence in forming, evaluating, and justifying judgments—to engage, in other words, in analytic problem solving.

What are the implications for engineering education? First, the curriculum and teaching and assessment strategies must be designed and enacted to help students realize their potential for cognitive growth. Second, because the undergraduate program yields the professional degree, the program must be designed to position students to continue to develop toward the reflective thinking—the high-level analytic problem solving—of experts.

FROM UNDERSTANDING TO ACTION These are significant professional responsibilities for engineering educators, ones that require thoughtful and creative attention to every aspect of the students' experience. In our campus visits, we saw many opportunities for faculty to put into action a new understanding of the process of learning and cognitive development. For example, faculty in engineering science courses can provide "scaffolding" within which students can learn to attend to the context of design problems with more disciplined awareness. Gradually, as the beginner masters the basic rules of the activity and acquires the fundamental knowledge underlying those rules, the teacher introduces more of the complexity of situations characteristic of the profession itself. As students acquire more facility, the instructor can increase the complexity of the problems presented, opening up to the full complexity of actual practice situations. This process should happen both in individual courses and over a program.

In moving from structured situations to more ambiguous ones, the role of the teacher is primarily to show the novice what to look for and then how to characterize unclear situations. Using feedback and coaching, the instructor's goal for student learning is the central engineering practice of formulating problems and solving problems. This is rarely a simple task. It requires careful movement from an initial approach to testing the approach by evidence. The instructor feeds back corrections to the initial approach. In this iterative process, the novice begins to learn from experience. The formal knowledge acquired earlier begins to serve largely as a disciplined basis for thinking and trying out solutions rather than a source of ready answers. Through design experiences of increasing levels of complexity and decreasing scaffolding, students are able to develop a repertoire of abilities to size up situations and approach the solution of problems with skill and confidence (Dreyfus, Dreyfus, and Athanasiou, 1986). In time, the student learns to approximate what experts do and develops skills for future learning on the job.

A Framework for Evaluating Engineering Education

Engineering, the profession that builds society, has profoundly affected the world through technological innovations. In turn, these innovations have affected the practice of engineering, facilitating not only new ways of thinking but also new global partnerships and alliances. Are today's approaches to teaching engineering learning appropriate to educating the engineers who will help to shape this new world? Is U.S. engineering education capable of fostering a new generation of engineers who will embark on solving problems with competency, responsibility, and accountability—in other words, as engineering professionals?

As we describe and discuss, over the next four parts of the book, the goals, curricular structures, pedagogies, and assessments employed in U.S. engineering programs, we ask the reader to consider three questions:

1. Where in their educational experience do students acquire and develop each dimension of professional expertise: engineering knowledge, skills of practice, and the understanding and commitment expected of today's professional engineer? How, if at all, do the traditional components of the engineering curriculum—engineering science, laboratory, and design courses—map onto these aspects of professional expertise?
2. How is this learning accomplished, and who among faculty and staff is responsible for each of these dimensions? Who, if anyone, is charged with ensuring that the continuity necessary for the students' developmental trajectory is maintained?
3. What counts as evidence that students are in fact moving toward competence in engineering knowledge, skills of practice, and understanding and commitment? What are the important markers of this progress, and how is such progress assessed?

reflective thinking, involves movement away from learning to do competent academic work (and to get high grades) toward involvement of the whole learner in appropriating the ways of thinking, performing, and understanding that characterize the expertise and identity of a beginning engineer.

Our hope is that engineering educators rise to the challenge of realizing these aims-more effectively. To that end, we offer a set of principles to guide the design of engineering education that seeks to prepare students for professional practice.

21

TOWARD A NEW MODEL FOR ENGINEERING EDUCATION

HOW MIGHT ENGINEERING EDUCATION move students from student thinking to engineering thinking, reflective judgment, and analytic problem solving? Developing the expertise of professional practice is an iterative process. The ideal learning trajectory is a spiral, with all components revisited at increasing levels of sophistication and interconnection. In this networked model, the traditional analysis, laboratory, and design components would be deeply interrelated: engineering knowledge remains central but is configured to include both technical and contextual knowledge; competencies of practice, laboratory, and design experiences are integrated into the whole, as are professionalism and ethics.

Integrated Goals for Learning

In a networked approach, the goals for student learning are integrated under the overarching goal of professional formation, positioning students to continue the development toward being new-century engineers or new-century professionals in related fields. Moreover, the faculty would make these goals explicit to students and follow their progress toward them.

This would not be difficult to effect. Consider the learning goals of technical courses, lab, and design, which we identify in Parts Two through Four. As we noted, some goals are explicitly acknowledged by the faculty, ABET, or the profession. Others are implicit, evident through the faculty's curricular and pedagogical choices. Most striking about the lists of goals is that they are so similar. They can be resolved into the following four cross-cutting goals:

- Developing a robust base of substantive knowledge of engineering science
- Developing robust skills for using knowledge to interactively formulate and solve problems: creativity, engineering intuition, practical ingenuity
- Developing the attitudes necessary to interactively formulate and solve problems: persistence and healthy skepticism, dynamism, agility, and flexibility
- Developing the skills and attitudes for effective leadership, teamwork, and communication

A networked program would be designed so that learning in one area supports learning in another, always with the understanding that, because engineers touch the world in far-reaching and profound ways, the aim is to develop professionals who can act in the "hybrid world" (Williams, 2002, p. 31) in which the engineering is for "us."

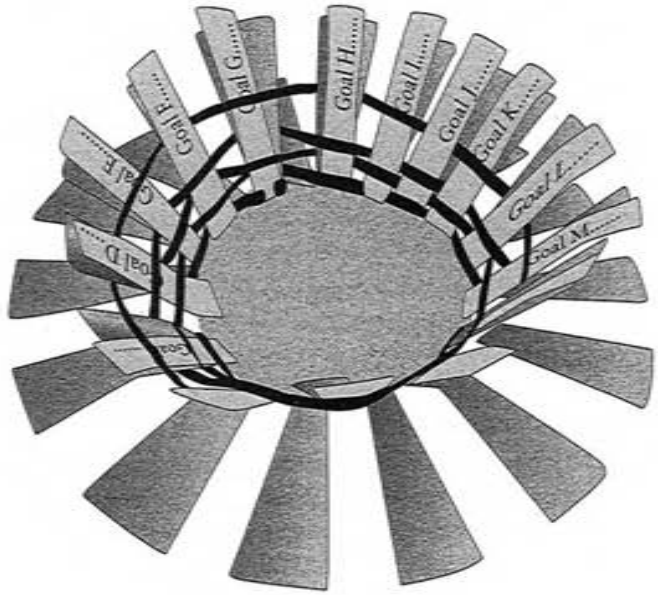
Students and faculty alike would understand that these cross-cutting goals for student learning are in service of the core values of the profession—commitment to being competent, responsible, fair, and accountable. The overarching goal of the program would be to position students for a lifetime of continuous learning and growth.

In other words, to draw on Shulman's encapsulation of a professional, undergraduate engineering programs would be designed to position students to begin providing a worthwhile service in the pursuit of important human and social ends. They would begin a lifetime of pursuit of knowledge and skills as they continue to develop the capacity to engage in complex forms of professional practice, learning to make judgments under conditions of uncertainty, learning from experience, and creating and participating in responsible and effective professional communities.

Imagining the Networked Model

With learning proceeding in a spiral rather than a linear configuration, concepts and tools are revisited with increasing degrees of sophistication in order to make sense of the puzzles of how things work. Concepts and tools are nodes in an interactive network in which the various components of engineering science, laboratory, and design, as well as professional identity are understood to influence one another. They also influence how each is taught. Instead of proceeding in a single linear movement from theory to application, the new model allows for and encourages,

Figure 21.1. Networked Components Model



for example, issues from design practice to influence what concepts are taught in engineering science courses and by what means. Indeed, perhaps the greatest advantage that a focus on professional practice can bring to students is to promote, throughout their undergraduate training, the habit of moving fluidly back and forth between particular situations and general principles, which is characteristic of engineering—and professional practice—at its best. The curriculum and teaching strategies are structured by the demands of professional practice. The student would move back and forth among the components, pursuing ever-deepening competence in core knowledge, skills, and commitments. The curriculum would entail weblike patterns of interaction, in which students' development in one component is used to frame and spur progress in the others. Hence the networked quality of this approach, which we illustrate in Figure 21.1.

Designing for the Future of the Field

We do not claim to have a detailed plan for transforming engineering education from a linear model that focuses on acquisition of technical knowledge to a networked model that has, as its core, the knowledge,

skills, and understanding of professional practice. Nevertheless, to help engineering educators meet the challenge ahead, we offer four design principles, illustrated with some promising examples: (1) provide a professional spine; (2) teach key concepts for use and connection; (3) integrate identity, knowledge, and skills through approximation of practice; and (4) place engineering in the world, encouraging students to make connections.

Provide a Professional Spine

As the integrated goals we offer suggest, requirements associated with what today are ancillary components of the typical program would instead be the major concerns around which the program revolves. During each year of their program, students would have experience with and engage in reflection on the meaning and demands of professional practice.

This emphasis on professional practice, the spine linking theory and practice, would give coherence and efficacy to the primary task facing schools of engineering: enabling students to move from being passive *viewers* of engineering action to taking their place as active participants or *creators* within the field of engineering. In this process, the student would begin to develop an identity as an engineer: a professional whose work is about providing worthwhile service in the pursuit of important human and social ends, who possesses fundamental knowledge and has the capacity to engage in complex forms of professional practice, able to make judgments under conditions of uncertainty.

The professional spine would be the engineering equivalent of the clinical dimension of medical preparation. Thus engagement in increasingly practice-like experiences would be a central feature of engineering education. These practice-like experiences can point toward both analysis and design as central tasks of engineering work, with laboratory courses and attention to professionalism and ethics contributing heavily to that goal—a thoroughly integrated approach to engineering education.

A PLACE TO EXPLORE PROFESSIONAL PRACTICE Lab and design courses, for example, could be reconceptualized to form this spine; the key is creating connections so that the focus is on professional practice and the integration of technical knowledge, skills, and understanding and commitment.

Laboratories already serve as a powerful tool for helping students learn to work with real hardware and systems, often collaboratively, so they are well suited to a practice-based approach. In some laboratory courses, students are challenged with designing, building, and demonstrating hardware that has some specified behavior, applying key technical concepts in all phases of the design-build-demonstrate cycle. Although the teacher generally specifies the particular behavior the system must display, in charting their course through the cycle students have greater autonomy than they might in engineering science courses. This kind of experience affords students the opportunity to learn that to become an engineer means explicitly joining a community of practice that draws flexibly on a variety of forms of knowledge and skill to formulate and solve problems of technological design. Science and mathematics then function as tools for disciplined thinking as well as ways of testing and improving imagined solutions.

Clearly, laboratory experiences in which students must master concepts to formulate problems and solve problems of increasing degrees of complexity have a critical role to play in the professional spine of the networked model. Weaving design experiences throughout all of the undergraduate years provides further opportunities to explore professional practice, connecting analysis and professional issues. As we note in Part Four, design has become more and more central to modern engineering work. Design experiences in the curriculum can lead students to draw upon conceptual, scientific knowledge while learning the skills of working with real materials. At the same time, students can be coached in design processes and in how to communicate and cooperate effectively with other parties to achieve a goal. These "other parties" include not only other students but, in an increasing number of programs, actual clients who bring to the experience a host of different perspectives and kinds of knowledge.

Done well, design courses enable students to recognize that engineering involves much more than following a fixed process or methodology; it involves ways of thinking (Neeley, 2007). The teaching practices cultivated by the studio settings of design courses exhibit the modeling, feedback, and close interaction between student and teacher, as well as student and student, that is known to produce effective learning. Well taught, design experiences also enable students to glimpse themselves as engineers at work and therefore have the potential to offer repeated and varied experiences that support the development of professionalism. This continuing attention to shaping students' sense of responsibility and purpose is essential to making the undergraduate years a powerful formative period with long-term positive impact. Helping students develop strong habits of professional thinking and acting are both, of course, central goals of the entire engineering curriculum.

EXAMPLES FROM THE FIELD In our field research, we encountered several powerful examples of how design can be used to give spine to programs. At Rowan University, for example, students undertake multidisciplinary design-project work each semester. As the students' technical and professional competencies mature, the sophistication and complexity of the assigned design projects grow from reverse-engineering existing consumer devices in the early courses to designing and prototyping leg-powered, stair-climbing, electro-mechanical robots systems in the later courses (Chandrupatla and others, 2001).

Some integrated design experiences also pay significant attention to the social context of the work and the nature of professional interaction with clients. EPICS illustrates how useful project-centered learning can be for supporting this kind of learning, as students engage in long-term, community-based design projects to develop solutions that not only have technical merit but also are sustainable and viable for real clients. In connection with these projects, the program assesses and gives credit for student work in the area of ethics and professionalism, which signals the importance of these ethical and professional aspects of learning—and of engineering work (Coyle, Jamieson, and Oakes, 2005; DeRego, Zoltowski, Jamieson, and Oakes, 2005). Because the EPICS projects serve pressing community and individual needs, participation in the program enables students to appreciate the personal satisfaction to be gained from professional work that serves a valuable public mission. This is no small matter, as the personal and social meaning of one's work has been shown to be critical for professional satisfaction and retention in a field. (See, for example, Colby, Sippola, and Phelps, 2001; Gardner, Csikszentmihalyi, and Damon, 2001.)

Although it was not a focus of our study, we noted other important opportunities to develop the professional spine of a program. Participation in extra-curricular and cocurricular activities (such as Engineers Without Borders, FIRST, Formula SAE, and mini-Baja), undergraduate research, and co-op placements give students exposure to actual practice situations and provide authentic problems to formulate and solve. Co-op experiences, for example, go a long way "to impart first-hand knowledge of . . . the execution in industry/government of engineering designs, business principles, and developments in all career fields" (Atkins, 2005, p. 62). Many programs make participation in such activities available to students, but in general it is up to the students to reflect on the experience. It is important that faculty make purposeful use of these experiences, drawing connections with the skills and knowledge the students are developing in their coursework.

Teach Key Concepts for Use and Connection

Organizing engineering education around a professional spine does not imply the neglect of the traditional core, engineering sciences. It does mean that faculty and other program designers will need to make some hard choices about what kind of theoretical, scientific, and technical knowledge is fundamentally important. Moreover, it requires that engineering educators reach for teaching strategies that encourage students to develop the thinking skills of engineering practice. Fortunately, research on learning points the way.

The danger in separating the learning of concepts from the sites of their application is that the concepts become mere "lists of disconnected facts" (Bransford, Brown, and Cocking, 2000, p. 24). Because, as we have seen, students learn more effectively when they can connect their efforts with the practice for which they are being prepared, there is an important pedagogical reason for providing a professional spine in engineering programs. Students can learn the core knowledge basic to engineering in ways they will remember, truly understand, and be able to use in appropriate ways.

For example, courses that provide basic or core knowledge, including the mathematics and science courses most students take in their first two years, can be enhanced by the use of illustrative cases drawn from actual engineering experience. However, over time, students need to learn not only how to apply key concepts when the problem clearly calls for them, but also to identify for themselves which key concepts are needed in complicated, open-ended problem-solving situations. For this reason, teaching key concepts comes even closer to learning in context when it employs a more inductive approach: presenting students with open-ended problems and asking them to identify the basic underlying concepts that are most applicable to understanding and solving the problem. The use of cases as emphases within engineering science courses exemplifies this potential.

A PLACE TO USE THE TOOLS OF ENGINEERING These developments are receiving theoretical support from the emerging understanding of how engineers use knowledge-based tools. For example, Cardella's 2006 study of the use of mathematics in engineering conceptual design revealed the complex and varied ways in which mathematics supports the work. Although content knowledge and knowledge of how to use tools and mathematical terminology—the so-called mathematical knowledge base—were important in the process, equally important were the

ability to tap into appropriate problem-solving strategies, skill in using and monitoring resources, personal beliefs about mathematics, and an understanding of domain-specific mathematical practices.

Gainsburg (2006), looking at the use of mathematics by structural engineers, found that mathematical modeling is central to and ubiquitous in their work, but found that the types of models that engineers actually use are not well reflected in the modeling tasks typically represented in education, certainly at the K–12 level and also, to a significant degree, in undergraduate education. The mathematics courses required for engineering students generally do not present the ways in which engineers use mathematical tools and concepts. Even when they teach math to engineering students, mathematicians are more likely to represent the evolution of mathematical principles and the way these principles are used by mathematicians (Wu, 1996; Redish and Smith, 2008).

The application of mathematics in engineering is not straightforward; it often involves approximation and estimation. This finding, we think, argues for the need to teach the application of mathematics to engineering as integral parts of mathematics courses for engineering students.

EXAMPLES FROM THE FIELD This is an area in which engineering education needs to develop new ways of teaching, and we identified some useful experiments toward this end. For example, at Olin College, faculty in mathematics, the sciences, and engineering collaborate on designing and delivering introductory courses that teach mathematics so that it reflects use in practice and connects with other technical tools (Kerns, Miller, and Kerns, 2005). In 1992, the Drexel University faculty began integrating material, including mathematics, from thirty-seven existing courses in the traditional lower-division curriculum into four interwoven sequences for freshman and sophomore engineering students (Quinn, 1995; Fromm, 2003). Stanford University offers freshman- and sophomore-level mathematics courses taught by engineering faculty in vector calculus, ordinary differential equations, and linear algebra. These courses are taught with an emphasis on engineering applications.

A PLACE TO DEVELOP USABLE KNOWLEDGE We believe that the other bodies of knowledge that are important for engineering—in particular, physics, chemistry, bioengineering, mechanics, and physiology—also need to be taught in ways that are most likely to yield *usable* knowledge. Research similar to that on mathematics in use is emerging; researchers are examining how scientific knowledge is used in practice, what leads to effective learning of science for use in engineering, and how the concepts taught in these subject matters is interrelated. (See McKenna, McMartin and Agogino, 2000; Tuminaro, 2004; *Journal of Chemical Education*, 2000; Mintzes, Wandersee, and Novak, 1998; Penberthy, Priest, Kosciuk, and Millar, 1997; Harris, Bransford, and Brophy, 2002; see also the work of VanNTH ERC at http://www.vanth.org.) These investigations provide insights for rethinking and reformulating curriculum and teaching strategies.

For example, the Integrated Mathematics, Physics, and Engineering Curriculum (IMPEC) at North Carolina State University requires that students take courses in mathematics, science, and engineering concurrently; a multidisciplinary faculty team integrates the ideas and concepts using traditional and alternative instructional methods, including cooperative learning, activity-based class sessions, and extensive computer simulations. Assessment of students participating in the IMPEC demonstrated higher pass rates in core courses than for students in conventional courses, along with marked increases over the term in self-rated confidence in abilities in chemistry, engineering, computing, speaking, and writing, while the confidence levels of a comparison group declined dramatically in chemistry and writing, and slightly in engineering, computing, and speaking (Ohland and others, 2003; Felder and others, 1998). Similar findings have been reported for students participating in Drexel's Enhanced Educational Experience for Engineers (E4) curriculum, noted earlier, which integrates mathematics, physics, chemistry, and biology as foundational elements of engineering. It is particularly noteworthy that the E4 curriculum has also resulted in higher rates of student retention and progress toward a degree, particularly among women and minorities (Quinn, 1995).

This new understanding of how tools such as mathematics and sciences are used in engineering work has the potential to stimulate highly productive (and perhaps highly charged) conversations among faculty, both inside and outside of engineering, who are responsible for educating future engineers. We believe that this body of research provides strong support for the benefits of shifting the basic model of engineering education toward a more networked form. With professional practice providing the spine through and around which the fundamental technical disciplines are woven, there is great potential to provide essential usable knowledge more coherently by emphasizing learning in context, which links engineering thinking more effectively with the mathematical and scientific disciplines.

Integrate Identity, Knowledge, and Skills Through Approximations to Practice

Teaching for professional practice calls for teaching strategies that embody the principles of effective learning that we described in Chapter Twenty: faculty need to make clear what expert practice looks like, modeling or otherwise making visible both thinking and doing. Faculty need to find creative ways to structure and support students' beginning efforts to imitate competent performance and to provide timely and informative feedback on those performances, through both informal means and formative assessments. To these requirements, we add one more: all these efforts should move in a common rhythm, starting from more distant and moving toward closer approximations of the full complexity of practice.

The importance of this principle of progressive approximation to practice is most evident in design and laboratory courses. Many faculty already understand that exercises in laboratory and design experiences are most effective when they are organized to challenge students repeatedly to acknowledge and work with ambiguity and finite resources in order to define a problem and create and execute a plan.

In some of the programs we visited, working on practice-related or integrative exercises starts early and progresses in complexity toward more authentic simulations of practice—or to practice itself, in some cases of capstone design studios. In the best of the examples we observed, the program scaffolds student learning, starting with simple laboratory and design exercises in the freshman-level courses, in which the number of aspects of practice is limited and students receive a high level of faculty input and feedback, and building toward exercises more representative of engineering practice by the senior year. The senior-level exercises often require that students coordinate with others and persist to see the problem through to its resolution, even if the first, second, and third approaches do not work. Some schools involve practicing engineers, who are able to confirm for students that many aspects of the senior-level exercises are representative of engineering practice, including the students' high level of autonomy and the calculated fading of their instructors' intervention.

We emphasize that a focus on professional practice does not mean that students should be immersed in the full complexity of authentic engineering practice from the outset. This is neither a realistic nor even a good idea. The recent work of Stanford education professor Pamela Grossman, looking at how various fields bring practice-oriented experiences into the classroom, questions the assumption—widespread in many fields of professional education—that more authentic educational experiences are necessarily better. She and her colleagues introduce the term *approximations of practice* to capture the idea that course-based experiences do and should vary in the degree to which that they authentically resemble the professional practices in which students will eventually be involved (Grossman and others, 2009).

Any particular approximation of practice is defined by two factors: (1) the nature of participation required of both the novice and the professional educator, and (2) what the novices experience and learn. Both factors relate to authenticity: "the extent to which these classroom-based experiences replicate or distort the conditions of real practice." Grossman describes how approximations can be made to vary from less authentic to more authentic by increasing the number of facets of practice that are highlighted, the students' level of participation, and the extent to which the time frame is close to real time (therefore, the degree to which it is an actual performance versus a rehearsal).

Grossman argues that educational experiences that more authentically replicate practice are not necessarily better at every stage of the learning process. Her case studies of professional preparation of teachers, clergy, and clinical psychologists illustrate instances in which it is more effective to focus intentionally on only some aspects of practice so as to master, through rehearsal, a subset of especially challenging skills. Drawing analogies from the worlds of athletics or music performance, one might compare this to focused practice and training on batting or running in baseball (done in conjunction with learning to perform those skills in the actual context of the game), or focused practice or rehearsal of scales and études (done concurrently with learning to play more complex musical compositions and to perform with an ensemble).

The principle, then, is to design learning experiences that are more systematic and intentional in the degree to which and the ways in which they approximate practice. In our observations, design and laboratory courses currently offer the best examples of this approach. Indeed, we observed that weaving design and laboratory experiences throughout the curriculum helps students make connections among the disparate areas of knowledge and skills, integrating these at various stages of their education as knowledge and skill develop.

However, it is important to reiterate a key point: a more practice-centered education does not mean abandoning the central and critical role that learning and applying technical and contextual knowledge plays in engineering education and practice; rather, it means reframing and teaching this knowledge in ways and in contexts that more directly connect it with engineering thinking and action.

So understood, the professional spine courses can connect with the goals typical of analysis courses by intentionally aiming to develop habits of integrated thinking in which the scientific, technological, and ethical dimensions of engineering become routine aspects of increasingly sophisticated professional thinking. By selecting which aspects of practice to make salient for the learners, educators can ensure that design courses aid in the learning of the network pathways back and forth between high-level concepts and the constraints of particular contexts without overburdening the learners with all the pressures and responsibilities of actual practice.

Place Engineering in the World: Encourage Students to Draw Connections

When, in an introductory design course at Michigan, the instructor asked students to think through the consequences of various design decisions by showing them castoff electronic communications tools such as cell phones, students were challenged to provide alternative designs with fewer negative social and environmental effects. As one student told us pointedly, the class discovered that human values and assumptions were already embedded in what seemed to be purely technical questions about the constraints on designing communication hardware. With equal force, they discovered that engineering inevitably means intervening in the world, so that all engineering projects carry with them responsibility for the effects of those interventions.

We saw that this course brought together the key principles of a networked model focused on professional practice. Students discovered through their own simulations of engineering intervention how important some conceptual tools were to safe and effective device design. They also discovered that being an engineer is a serious as well as a significant business. Like medical students on their first introduction to the clinical care of actual patients, the students discovered they needed to know a lot more than they did, and that they had to be able to understand connections better than they could at present—social and ethical connections as well as electrical and mechanical. Engineering work was suddenly connected to everything else in their college education and, indeed, everything else in their lives. They had discovered that engineering—and engineers—live in and participate in the world, with all its complexities.

Contrast those students' discovery with the way in which undergraduate courses are typically constructed, certainly in engineering and the sciences but in many other disciplines as well. A course is usually framed around a small set of principles and concepts, and students learn to understand those concepts by, at most, applying them to limited range of situations. Presenting concepts of principles from practice, separated from context, is known to weaken the motivation to learn. It also truncates the very idea of a college education and certainly of an adequate preparation of future engineers.

EXAMPLES FROM THE FIELD In our study, we encountered imaginative ways to overcome this problem. For example, in "Engineering Cultures," offered as an elective at Virginia Polytechnic Institute and State University (Virginia Tech), students learn about the professional identity of engineers in various countries and cultures, how their values, methods, ethical frameworks, and beliefs have evolved, and how one learns to work effectively with people who define problems differently from oneself. Cases in which both sides clearly have a defensible perspective, such as a 1920s dispute at General Motors between older manufacturing engineers and new R&D engineers, explore controversies or disagreements among engineers, illustrate engineers' life histories, and call attention to different ways of understanding what it means to be an engineer.

By focusing on the behavior of individual engineers and the consequences of these behaviors, students can connect issues of identity and professionalism as related to cultural traditions. A number of situation-based writing assignments (for example, resolving an issue from the standpoint of an engineer trained in another tradition) can help students understand that what counts as an ethical problem varies significantly from place to place. They learn to recognize that in a given situation of conflict or disagreement, some engineers may be predisposed to see an ethical problem at stake whereas others do not. In the words of Gary Downey, who teaches the course, "Our view in general is that helping students understand such differences is a necessary prerequisite to being a sensitive ethical problem solver in international environments" (Downey, 2006; see also Downey and others, 2006, and Downey, 2008). In addition to providing students with concrete examples of why the ABET standards around teamwork and communication are so important, these courses bring questions of professional identity and purpose into situations that are imaginable futures for the students in the course.

We saw the same approach, putting concepts into relationship with the demands of practice, in effective ethics teaching: Some faculty in both design and analysis courses, for example, ask students to pay attention to the values assumptions underlying trade-offs between design considerations such as product cost and safety.

International service learning projects in engineering illustrate a quite different approach to helping students confront the limits of their understanding of the contexts of their work, while acknowledging their responsibility for possible harm their interventions might do. Co-op and extracurricular programs that include this kind of experience provide a rich opportunity for students to connect conceptual and technical learning with the complexities of practice.

Another promising strategy for motivating and enabling students to widen their understanding of what they are doing and who they could become is the growing number of engineering programs that provide a general, non-field-specific knowledge base in the first one to two years, complemented with some components of engineering specialization. For example, the engineering program at the University of California–Berkeley is moving toward a common freshman curriculum including modules that introduce specific fields or branches of engineering. After this common first year, students select an engineering field or specialty. Howard's "Introduction to Engineering" provides beginning students a common core of understanding of the field, its branches, history, and various career paths. These approaches to specialization encourage students to think through their choice of engineering specialty in a more reflective and informed way than would otherwise be likely.

Significant intellectual resources for exploring identity, purpose, and context in engineering remain severely underutilized. Downey's "Engineering Cultures" and similar engineering ethics courses draw on the interdisciplinary field of science, technology, and society (STS) that we mentioned earlier. Beginning with the nascent environmental and social concerns about the impacts of technology that appeared in the 1970s, STS has developed important concepts and, as we have seen, ways of thinking and teaching about these matters that enable students to make sense of the social, ethical, and environmental contexts and responsibilities of engineering.

For this task, the linear model—with its overloaded, information-focused curriculum—can offer little. In contrast, a networked model with a focus on professional practice can offer much. Courses that reflect on engineering work and its significance, especially when connected to the professional spine, serve to provide a broad picture of the world toward which the student is headed. There may be a bright future for such courses, especially if the motivational value of increased integration is taken seriously.

There is some evidence that well-integrated (well-networked) design-and-knowledge courses taken early in the program may make students more likely to remain in engineering, because these courses provide a firmer view of the nature of engineering work than most of today's students bring with them to college. When faculty at Ohio State University replaced separate first-year engineering courses with an integrated two-course sequence that introduces engineering, graphics, and problem solving, and includes hands-on laboratory experiences and design/build projects, retention rates rose from less than 40 percent to well over 60 percent (Demel, Freuler, and Fentiman, 2004). Similarly, by introducing a first-year engineering design projects course, the University of Colorado has seen a 10-percent increase in student persistence by the seventh semester, from 54 percent to 64 percent, with the changes being especially marked for female students (Knight, Carlson, and Sullivan, 2007).

We believe that taking this principle one further step, to include reflection on the forms, history, and place of engineering in the larger world, is a natural development of these trends. This is not happening to any significant degree outside of STS programs, however. In fact, in our fieldwork we saw few examples of strong connections between engineering learning and the kinds of liberal arts education that could speak directly to these issues of the broader context and meaning of engineering. This observation reveals how poorly connected with the central goal of preparing the new-century engineer the typical liberal arts requirements really are.

Bringing Practice Forward

We believe that networked components centered on preparation for professional practice provide the way forward for engineering education. An important possibility opened by such an approach lies in its potential for incorporating the humanities and social sciences as sources of insight and skill for understanding and navigating social contexts. Perhaps most significant, placing design in interactive contexts as the end in view of engineering education would bring issues of ethical concern from the margins toward the center of attention. If engineers are professionals who draw upon both scientific and humanistic knowledge to formulate ways of intervening technologically to better the world, then it is not hard to introduce the notion of responsibility for the effects of one's interventions.

In a similar way, other aspects of context and identity begin to get more serious attention as well. Operating in such a new model, faculty would explicitly teach the abilities to learn from one's own and others' experience and to participate responsibly in an effective professional community. Engineering education would focus less on teaching technical skills and

more on developing professionals who are committed to remaining technically competent, accountable, and socially responsible for their work, because being technically competent today and tomorrow is a natural outcome of the conception of the engineer as professional. Competency, responsibility, and accountability would be held up as core features of professional practice. In this sense, one of our hopes is that integrated, networked components focused on preparation for professional practice would provide an intellectual rationale and incentive for making undergraduate engineering education more whole, precisely in order to make it more motivating and relevant to students as they begin to understand the demands of their professional futures.

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GETTING FROM HERE TO THERE

ALL EDUCATIONAL INNOVATIONS FACE the crucial question of means. This is not solely, or even primarily, a question of resources, but one of personnel. After laying out the why, what, and how of any new approach, there comes the question, who will teach it? For the engineering education we need, for today and the future, will this be the deal breaker? With all that is at stake for engineering in the United States, a failure to press forward for lack of faculty initiative and imagination would not only be disappointing; it would also be self-defeating.

We do not expect this to happen. On the contrary, from the excitement about reforms we observed on our visits, as well as from the movement generated by the work of the NSF and the NAE, we conclude that engineering education will be able to reshape itself to advance the cause of the profession in this new century. In that process, the engineering faculty will, of necessity, be the key players.

Although faculty are the primary architects of a revitalized approach to preparing the next generations of engineers, of course, they do not have a totally free hand in this. Like practicing engineers facing a design problem, faculty, too, must work interactively with others. The perspectives of professional organizations and societies and current students and alumni, the predilections of their colleagues, and institutional priorities all must be factored in. However, ultimately it is the energy, creativity, and initiative of the faculty that will determine how their programs might be made more integrated and cohesive. In other words, it is up to the faculty to create a program that is better aligned with practice both within individual courses and across the total student experience.

We are under no illusions as to what will be required. Reconceptualizing undergraduate engineering will demand an enormous effort on the part of faculty. It will involve more than learning about, designing, and

implementing integrated curricular structures and active pedagogies. It will involve fundamentally rethinking the role and even the makeup of the faculty, for the educational model we are recommending makes quite different demands on the instructor than does the old model. Among other things, the new model gives more importance to teachers and researchers who are sympathetic to professional concerns and have some interest in them.

Engineering faculty are key stewards of the engineering profession. It is their job to fan the creative fire, feed technological curiosity, and foster the social responsibility of the next generation of men and women engineers. We fully recognize that this is no small job, even with sufficient resources, recognition, and rewards, as faculty must balance and integrate teaching and other educational responsibilities with those of research and service.

The Role of Other Leaders and Stakeholders

Imagining strategies for effecting a transformation of engineering education quickly brings the realization that the engineering faculty will not be able to do all this alone. Nor should they, for the effects of their effort have implications throughout the program, institution, higher education, and field of engineering. They may be key leaders, but they cannot be the sole actors. They need engagement and support from many quarters.

Both engineering education and higher education at large offer rich networks of faculty, campus leaders, and national organizations working to align curriculum and teaching strategies with the demands of a new century and the discoveries about learning. However, it is not clear to what extent engineering faculty are taking advantage of the field's increased understanding of engineering work and student learning to inform their teaching practices. Although it is heartening to see that over 3,500 faculty attended the 2007 ASEE Annual Conference and that many take advantage of the continued annual offerings of the National Effective Teaching Institute (www4.ncsu.edu/unity/lockers/users/f/felder/public/NETI.html), we note that this is just a fraction of the U.S. engineering faculty. Campus leaders and administrators have a role to play in supporting their colleagues and in transforming the engineering programs that are so important to their institutions. Engineers, industry leaders, and the leaders of national professional engineering organizations likewise can contribute at many levels, whether in the classroom or through policy and resources.

Administration

The revitalization of engineering education we propose cannot happen without administrative leadership that is highly supportive and engaged in the endeavor. This can take a variety of forms, from providing faculty with release time for course creation, to fund-raising for new teaching laboratories, to developing recognition systems for faculty who are involved with curricular change, to being part of the leadership in all these efforts. This type of support is also critical for sustaining curricular renewal and is essential for building a faculty community that is emboldened to experiment with innovative pedagogies and curricular structures.

Local collaboration is sometimes easy to encourage and support: at Rowan University, for example, engineering faculty turned to their colleagues in the communications department to develop integrated writing assignments in design courses. There is, however, a larger need calling for the attention of program and institution administration: as professional educators, engineering faculty need to develop or deepen their knowledge about important lessons from research on student learning. Faculty members need to be supported in this learning as part of their basic teaching responsibility.

In today's university, this concern for the quality of student learning links the engineering school or program with the arts and sciences departments as well as other professional schools. For example, few faculty-reward models recognize continuous professional development around teaching as important, though the development of new areas such as the scholarship of teaching and learning (see, for example, Boyer, 1990; Huber and Hutchings, 2005) are beginning to change this situation for the better. Prince, Felder, and Brent's 2007 paper on the relationship between faculty research and teaching outlines the actions that the academic community might take to better utilize the growing understanding of how people learn and how to teach more effectively. Engineering could play a useful role by taking leadership in establishing cross-department and cross-field support for faculty study and development in incorporating the results of learning research into their teaching practice.

To develop the new prototypes, faculty will have to imitate the best of contemporary practice by developing new approaches to teaching, employing integrated, collaborative teaching efforts. A number of large and sustainable curricular efforts serve as examples. Cornerstone design courses using project-centered learning can accommodate large numbers of first-year students if multiple faculty members work in coordination. Faculty team efforts provide useful models; these include the

freshman-year redesign at Ohio State (Demel, Freuler, and Fentiman, 2004), the Learning Factory at Penn State (Lamancusa, 2006), the Integrated Teaching and Learning Lab at the University of Colorado, the Gateway Curriculum Reform Project led by Drexel (Fromm, 2003), and curricular reform efforts based on the Conceive-Design-Implement-Operate framework developed at Massachusetts Institute of Technology (Crawley, Malmquist, Ostlund, and Brodeur, 2007).

Many engineering schools will face significant obstacles to emulating these achievements. Such a level of collaboration in teaching and curriculum design may be new and daunting to some faculty members. In many instances, faculty reward systems are not equipped to recognize collaborative teaching contributions. Administrative leadership may balk at what looks like an expensive teaching arrangement unless faculty can establish that the investment will yield significant gains in student learning and can demonstrate that program assessment can complement and inform curricular revision.

This is not an easy time to serve as a dean of engineering, but it is probably the most important and exciting time in half a century to do so.

Practitioners and Industry

It is important that engineering educators engage practitioners from business, industry, and government. Practitioners can play several roles to assist in the effort to place professional practice at the center of engineering education. With professional societies, they can, of course, join a national call for change. They can also develop local, regional, and national partnerships with the academy and professional societies. At the local level, they can work along with individual schools to redesign programs.

They can also work with faculty to help bring approximations of professional practice into the classroom. They can work with faculty to develop ways in which students and practitioners can interact with one another as a component of or complement to coursework. From industry fieldtrips to invited lectures and client-sponsored design projects, these engagements can be organized as stand-alone courses or used as enhancements to more technically based engineering science courses.

For example, an interactive class session with a working engineer can combine short lecture segments with small-group learning exercises on the application of a set of technical ideas. Practitioners can guide students in observing and analyzing work practices in the field. Working engineers might facilitate collaboration with a company, over the course term, to solve a particular problem. Of course, the specific activities should be designed according to learning goals for the course and program.

Although faculty whose training and professional experiences are exclusively from the engineering academy are prepared to teach core engineering concepts and skills, they are not necessarily prepared to teach or integrate across the many domains of knowledge and skill (theory, practice, and professionalism) that make up engineering work. Programs will need to include those with engineering work experience and those with complementary disciplinary backgrounds. Practitioners can be engaged as adjunct faculty, for example, working beside regular faculty to bring a more practice-based perspective to a particular body of material. There are already examples in place: Massachusetts Institute of Technology has created the "professor of practice" faculty role, with assessment of performance and rewards in keeping with the job description. Practitioners can also provide useful insights to program-level review committees attempting to assess a program's overall approach and framework. Whatever the capacity they serve in, the successful integration of these faculty into a program requires that their unique contributions be understood and valued by the entire faculty as well as by the administration.

In all these cases, industry can play a valuable role as a partner in discussion with the schools and, where it seems mutually beneficial, as provider of resources for research and experiment.

National Leadership

Finally, national leadership organizations such as the NAE, NSF, and ABET, and the professional societies can play important, catalytic roles. Many of these organizations have already been influential in moving engineering education toward the future. They should continue to play multiple roles in enabling emerging prototype programs to become more integrated and practice-oriented. The national leadership organizations are vital in articulating the importance of educational innovations in their publications, speeches, and funding announcements. They are also central to the task of promoting, recognizing, and rewarding educational programs and faculty that boldly engage in thoughtful questioning of and experimentation with their educational practices.

We call on the national leadership organizations to support engineering programs in this national-level design problem and to provide resources and infrastructure for developing and sharing prototypes. Moreover, we call on national leadership to make this effort a national priority. Like a pressing professional design problem, such as developing

alternative energy sources or more efficient transportation, this educational challenge deserves to be addressed in a national conversation, including debates and idea sharing among the broadest possible range of stakeholders.

Bringing Professional Practice Forward

The work ahead is not easy. What we have so easily termed "pockets of innovation" represent enormous amounts of time and creative energy from faculty and many others. The scope and scale of a national effort would be exponentially greater.

However, who better to define the problem and design its solution than engineering educators? We imagine that the process will be as fruitful as the product, for the work calls for the exercise of new professional "muscles," new skills and thinking. It may also yield some surprising new colleagues across campuses and institutions, across the academy and the profession.

The work to be done is not simply worth the effort; it is vitally important. The public, national and global, has a serious stake in the preparation of engineers to design and manage our technological world. We are convinced that an approach that integrates knowledge, skill, and purpose through a consistent focus on preparation for professional practice is better aligned with the demands of more complex, interactive, and environmentally and socially responsible forms of practice. We hope others will join us in this conclusion and in the effort to educate competent, creative, and wise engineers for the years ahead.

How might we start this work? By reflecting, assessing, debating, designing, and prototyping a truly networked undergraduate engineering program, one that engages both teacher and student in learning in the context of professional practice. By engaging as colleagues and making the redesign of engineering education an intensive national undertaking for the next five years. By redesigning engineering education to prepare the new-century engineers that today's problems—and tomorrow's—demand.

APPENDIX
ABOUT THE STUDY

Our study placed special emphasis on the question of how educational practices support the preparation of engineering practitioners. Because we intended our profile of educational practices to be representative and richly descriptive, we employed both quantitative and qualitative research methods.

We began by examining national studies of engineering education and engineering workforce, including the National Science Foundation database, *Journal of Engineering Education*, and Frontiers in Education. From this, we wrote several papers describing national-level practices and selected forty engineering schools (or more than 10 percent of the engineering schools in the United States) for closer examination. This purposeful sampling of schools was based on a combination of several factors, including the Carnegie Classification; evidence of reflective practice among faculty, as demonstrated, for example, through publications in engineering education conferences; the particular programs offered; and recent and successful accreditation with the new ABET criteria (Prados, Peterson, and Lattuca, 2005).

From these forty schools we collected about one hundred ABET self-study reports spanning mechanical, electrical, bioengineering, and environmental engineering undergraduate education programs. We used these reports as a means of getting deeper insight into programmatic practices because they answer a consistent set of questions posed by the profession about programs and are therefore less variable than, for example, a school's presentation of itself on its Web site. A team of researchers read and coded the reports to identify typical or extraordinary practices, themes, and common issues as a means of refining our understanding of practices.

Programs for In-Depth Study

On the basis of our review of ABET self-study documents, and after piloting our methodology, we selected seven engineering schools for in-depth

investigation, looking at eleven programs in mechanical and electrical engineering, each with a unique but representative approach. We divided the institutions into two clusters: engineering programs at technology-oriented institutions and programs situated within universities.

The technology-oriented institutions included California Polytechnic State University (Cal Poly), Georgia Institute of Technology (Georgia Tech), and Colorado School of Mines (Mines). Cal Poly, which emphasizes "learning by doing," serves a diverse student population; the engineering program employs project-based learning (PBL) and has strong links with industry. Georgia Tech, a large public university, offers opportunities for students to participate in research and development activities. The engineering school also provides opportunities for students to participate in major competitions or industry projects through a strong cooperative education program. Mines, also a public university, is focused specifically on engineering and applied science. Its engineering division specifically offers an interdisciplinary undergraduate engineering degree that provides students with breadth while offering them an opportunity for disciplinary focus.

The engineering schools within universities that we visited were Carnegie Mellon University (CMU), Howard University (Howard), and the University of Michigan, Ann Arbor (Michigan). A former technical institute, CMU offers a flexible undergraduate engineering educational experience to serve a wide range of students with diverse backgrounds and interests. Students have some freedom in determining their program of study based on their interests or career goals. Howard, a historically African American university, emphasizes design and a culture that fosters leadership and commitment to community. The University of Michigan, Ann Arbor, gives students early exposure to design experiences while also promoting a strong research culture.

Our pilot school, Santa Clara University, not only allowed us to practice our methodology for site visits, but also helped inform our thinking: educating in the Jesuit tradition, the university seeks to impress on its students the importance of professional responsibility as they develop knowledge and skills.

Campus Observations

Our interdisciplinary research team spent two to three days at each campus early in 2002, interviewing over two hundred engineering students, faculty, and administrators, and observing more than thirty classes in mechanical and electrical engineering programs. In one-on-one interviews and focus groups, we explored faculty's and students' conceptions of engineering work; the program's goals, curricular arrangements, and teaching strategies; and future challenges and opportunities engineering education faces. In classroom observations, we gathered data on teaching and learning strategies and attitudes.

All interviews were digitally recorded and transcribed. Interview transcripts and observation field notes were then coded to identify themes and patterns that allow us to elucidate the ways in which today's engineering programs go about preparing students to engage in the complexities of professional practice.

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