Chapter 1

Teamwork and Project Management in Engineering and Related Disciplines

Teamwork and Project Management is designed to help you prepare for professional practice in the global economy. Teamwork is receiving increased emphasis from employers, leaders in engineering education and researchers. The world has gotten smaller and our sense of interdependence has greatly increased, the importance of professional responsibility and ethics has magnified (although engineering ethics has always been central to engineering); and projects (and project-type organizations) are becoming much more common. All these changes, as well as further changes that are likely to occur, highlight the importance of learning, practicing, and continually refining the skills, concepts, principles, and heuristics in this book.

More and more the broader community is calling for engineering graduates who have not only the traditionally expected technical skills and widely sought-after problem-solving orientation, but also the set of six "professional" skills from the ABET list (Shuman, Besterfield-Sacre, and McGourty, 2005). These skills include communication, teamwork, and understanding ethics and professionalism, which Shuman, et al. label process skills, and engineering within a global and societal context, lifelong learning, and a knowledge of contemporary issues, which they designate as awareness skills.

Thomas Friedman wrote in 2000 that "the world is ten years old." Friedman's central notion was *globalization*, that is, "the inexorable integration of markets, nation-states, and technologies to a degree never witnessed before--in a way that is enabling individuals, corporations, and nation-states to reach around the world farther, faster, deeper, and cheaper than ever before, and in a way that is enabling the world to reach into individuals, corporations, and nation-states farther, faster, deeper, and cheaper than ever before" (p. 9). Four years later Friedman claimed that "the world is flat." He addressed the graduating class at Washington University in St. Louis on May 21, 2004, with the following assertion: "The job world you are entering is an increasingly flat world. That's right. I know that this great scientific university taught you that the world was round. I am here to tell you that the world is flat, or at least in the process of being flattened. That is actually the title of my next book, *The World is Flat: A Brief History of the 21st Century.* By that I mean the competitive playing field is being leveled. You are entering a world where more people have PCs. More people have Internet connections and the bandwidth to communicate. More people have good educations, and more people have the enabling softwares, like Google, Microsoft Net Meeting, or Instant Messaging, to gain knowledge, to innovate, and to spread new ideas."

Freedman argued that in this increasingly flat world, collaboration and connectivity as well as adaptability and a creative imagination are essential attributes. We're increasing the emphasis on collaboration and connectivity (networking) and creativity and innovation in this edition of *Teamwork and Project Management*.

Friedman (2005) described ten flatteners, the first three of which provide a platform for collaboration:

1. November 9, 1989: The Berlin wall came down and six months later Microsoft Windows came up
2. August 9, 1995: Netscape went public
3. Work Flow Software, such as that supporting around the clock design work (sometimes referred to as work that follows the sun)

Interestingly, these first three "flatteners occurred within life span of even the youngest engineering college student and they created the need for expanded skill and knowledge sets. Friedman argues that we need to "horizontalize" ourselves, that is, we need to learn how to connect and collaborate with others. Tim Brown (2009), CEO at IDEO, the product design firm, states that IDEO recruits T-shaped people--people with both disciplinary thinking (vertical) strengths and design thinking (horizontal) strengths.

Friedman's latest book (Friedman and Mandelbaum, 2011), *That used to be us: How America fell behind the world it invented and how we can come back*, notes that "Today's major challenges are different." They argue that globalization, the IT revolution, deficits and debt, and energy demand and climate change are occuring incrementally, that is, they are creeping up on us. Their formula for addressing the challenges involves focusing on five pillars that together constitute the country's strengths:

4. Providing public education for more and more Americans
5. Building and continual moderizing of our infrastructure
6. Keeping America's doors open to immigration
7. Government support for research and development
8. Implementation of necessary regulations on private economic activity.

All of these pillars involve projects and teamwork and several of them, two and five especially, require the involvement and commitment of engineers.

As I was reading Friedman and Mandelbaum (2011) I was reminded of Jane Jacobs' classic work, *The Death and Life of Great American Cities,* and especially how she helped re-shape our thinking about urban planning. Jacob's latest book, *Dark Age Ahead* (Jacobs, 2004) argues that North American civilization is showing signs decline due to the collapse of "five pillars of our culture that we depend on to stand firm," which can be summarized as family and community, education, science, representational government and taxes, and corporate and professional accountability. Note the similarity between the "pillars" and concerns about their demise.

In *A Whole New Mind: Moving from the Information Age to the Conceptual Age,* Dan Pink (2005) makes a compelling case for moving from the knowledge age to the conceptual age. In the conceptual age it is creators and empathizers who will have the most influence! According to Pink the drivers of this change are affluence, technology, and globalization. Note the similarities and differences to Friedman's flatteners.

This is the world in which you'll be working. It is very different from the world I started working in as an engineer in 1969, but it is the world I try to cope with every semester especially with graduate students in two professional masters programs in which I teach, Management of Technology and Infrastructure Systems Mangement and Engineering. The engineering graduates in these one-day-per-week, two-year programs are working full-time and most of the participants work globally. Their extensive international interaction and collaboration as well as the international travel (both physical and virtual) is indicative of the lives of many if not most engineers in the future.

The essence of the globalization economy (according to Surowiecki, 1997) is this notion: "Innovation replaces tradition. The present—or perhaps the future—replaces the past." Surowiecki's view is shared by the authors of the 2005 National Academy of Engineering report *Assessing the capacity of the U.S. Engineering Research Enterprise,* who wrote in their introduction, "American success has been based on the creativity, ingenuity, and courage of innovators, and innovation will continue to be critical to American success in the twenty-first century" (p. 7).

Surowiecki argues in subsequent work, *The Wisdom of Crowds* (2004) that "under the right circumstances, groups are remarkably intelligent, and are often smarter than the smartest people in them." David Perkins (2002) makes similar claims in *King Arthur's Round Table: How Collaborative Conversations Create Smart Organizations.* Perkins' (2002) central question is "What is organizational intelligence, why is it so hard to come by, and how can we get more of it" (p. 14). His general reply is: "How smart an organization or community is reflects the kind of conversations that people have with one another, taking conversation in a broad sense to include all sorts of interactions" (p. 14). Surowiecki and Perkins's ideas and recommendations are elaborated upon in this chapter. Our principal goal for you, the reader, is to provide guidance on how to engage in intelligent teamwork in engineering contexts that emphasize design and innovation.

As we start this journey together, I offer you some suggestions that I think will help you get the most from this book. The essence of the suggestions are *activity, reflection,* and *collaboration*. First, I encourage you to engage in the activities, especially the exercises in the book, as they will help connect you with the material and its real-world applications. Second, periodically throughout the book I'll ask you to stop and reflect. I encourage you to take advantage of the opportunity. My goal is to give you a chance to describe what you already know and to get you to think. Then when you read what I have to say about the topic, you'll have a basis for comparing and contrasting. Finally, I encourage you to collaborate with others. Working together is the norm in projects. Working together to learn the material in this book will make it easier, and very likely you'll remember it longer.

Ruth Streveler's reflection on a sports metaphor for learning (in the nearby box) will, I hope, help many readers maximize their benefit from the book.

A Sports Metaphor

Karl and I have worked together for many years on a variety of projects. During the past few years we co-designed and have been co-teaching a course, Content, Assessment and Pedagogy: An Integrated Engineering Design Approach. The course is project based and the participants re-design a course that they are teaching or plan to teach in the future. We use a variety of resources, and for the past few years have been using the book, *Making Learning Whole: How Seven Principles of Teaching Can Transform Education*, in which Harvard psychologist David Perkins uses baseball as a metaphor for explaining exemplary instructional methods. Perkins' seven principles summarized below, are relevant and applicable well beyond designing a course. I offer them to you as heuristics for preparing for teamwork and project management.

1. **Play the whole game**. When learning the kind of complex task often involved in project management, it is important to find a way to see the "big picture", the larger context of what you are learning. Because the complexity of the real situation may be overwhelming, Perkins suggests creating a "junior game" which simplifies the situation while maintaining all the elements of the real task. Junior games should be constructed to approximate practice, without getting bogged down with all the details. An example of a junior game in a business context would be creating and running a small business for a short period of time. Even if the business is selling lemonade at a school's sports events, you will still have the experience of learning about market research, customer service, bookkeeping, etc.
2. **Make the game worth playing**. Motivation plays an important role in learning. Find ways to link what you are learning to things that motivate you. Allow your curiosity to flourish. Switch your perspective. Instead of viewing of assignment as being "given" to you – think about how you can use them to learn something that interests you.
3. **Work on the hard parts**. Find ways to deliberately practice aspects of a learning task that are difficult for you. Don't avoid the hard parts – embrace them! Bumps in the road of learning are opportunities to excel! Remember that composers created études that provided creative and beautiful ways for musicians to practice difficult scales. How can you construct your own etudes? Find inventive ways to practice difficult elements in your learning.
4. **Play out of town**. Applying knowledge in a new setting, called *transfer,* is notoriously difficult to accomplish. You can help yourself transfer what you have learned by thinking of examples of how the target knowledge is used in different domains. Perkins calls this "low road transfer." "High road transfer" – which is more robust, is promoted when you strengthen your conceptual understanding of what you are learning and then reflect on how this fundamental knowledge might be used in different ways.
5. **Uncover the hidden game.** When learning in a new area, find ways to discover the "unwritten rules" of that domain. Tap into the tacit knowledge of experts in the field by asking them to talk you through their approach to a problem. Seeing their approach will give you insights into how you can tackle similar problems.
6. **Learning from the team**. Think about how you can *learn from* your teammates. When approaching a project with your team, employ strategies that encourage you to socially construct knowledge through true collaboration, rather than simply dividing to conquer.
7. **Learn the game of learning.** Become aware of the strategies you use to understand, retain, and apply new material. Learning about how you learn (called metacognition) will help you learn more efficiently and effectively.

I hope you will find these seven principles useful. May they help you attain your learning goals!

Ruth Streveler

My goal for this chapter is to create a context for teamwork and project management in engineering. Let's start by exploring the nature of engineering. Before you read ahead for various answers to the question "What is engineering?" please complete the following reflection.

What Is Engineering?

REFLECTION What is engineering? What does it mean to learn to engineer in school? What is your experience with engineering? Did you learn about engineering in high school? Do you have a brother or sister, mother or father, or other family relative or friend who is an engineer? Take a minute to reflect on where you learned about engineering and what your impressions of engineering are.

What did you come up with?

Because there are few high school courses in engineering, most first-year students have not had much exposure to engineering. Yet we are surrounded by engineering accomplishments; they are so ubiquitous that we don't notice most of them. One of the foremost thinkers and writers on engineering, mechanical engineering professor Billy Koen, is noted for asking four probing questions of his audiences (Koen, 1984, 2002). The first is this:

1. Can you name one thing in the room in which you are sitting (excluding yourself, of course) that was not developed, produced, or delivered by an engineer?

Koen finds that the question is usually greeted with bewildered silence. I have posed Koen's questions to hundreds of first-year students, and they come up with some great suggestions: the air (but how does it get into the room?), dirt (trapped in people's shoes), electromagnetic radiation (but the lights generate much more than the background). Almost everything that we encounter was developed, produced, or delivered by engineers.

Here is Koen's second question:

2. Can you name a profession that is affecting your life more incisively than engineering?

Again, students name several professions but on reflection note that if it were not for engineering, politicians would have a difficult time spreading their ideas; doctors, without their tools, would be severely limited in what they could do; lawyers wouldn't have much to read; and so forth. Things such as telephones, computers, airplanes, and skyscrapers—which have enormous effects on our lives—are all products of engineering.

Koen's third question is this:

3. Since engineering is evidently very important, can you now define the engineering method for solving a problem?

Many students respond with a puzzled look, as if I am asking an unfair question. They note that they have a ready response to the question "What is the scientific method?" Students list things like "applied science," "problem solving," and "trial and error," but very few (over the 20 or so years that I've been asking this question) say "design." Fortunately, the portion answering "design" is increasing.

If you were to ask practicing engineers what the engineering method is, they would likely respond "Engineering is design!" A group of national engineering leaders has said:

> Design in a major sense is the essence of engineering; it begins with the identification of a need and ends with a product or system in the hands of a user. It is primarily concerned with synthesis rather than the analysis which is central to engineering science. Design, above all else, distinguishes engineering from science. (Hancock, 1986)

Distinguished engineers such as von Kármán and Wulf support this claim:

> A scientist discovers that which exists. An engineer creates that which never was
>
> - Theodore von Kármán (1881-1963)

> The engineering method is design under constraints
>
> – Wm. Wulf, Past President, U.S. National Academy of Engineering

Koen (1971, 2003) argued that "The engineering method is the use of heuristics to cause the best change in a poorly understood situation within the available resources." He updated his definition at a presentation in 2011 (Koen, 2011). He argued that "The engineering method (design) is the "Use of state-of-the-art heuristics to create the best change in an uncertain situation within the available resources."

We'll explore the concept of engineering design next–and save Koen's fourth and final question for the end of the chapter. But first, let's explore the history of the term *engineer* and elaborate on engineering as a profession.

The term *engineer* is derived from the French term *ingénieur.* Vitruvius, author of *De Architecture*, written in about 20 B.C.E. wrote in the introduction that master builders were ingenious, or possessed *ingenium*. From the eleventh century, master builders were called *ingeniator* (in Latin), which through the French, *ingénieur,* became the English *engineer* (Auyang, 2004). Recapturing some of the ingeniousness of engineering is one of our goals in this edition.

Referring to engineers as "master builders" reminds me of another French connection, *bricoleur*. A *bricoleur* is a handyman or handywoman who uses the tools available to complete a task (Kincheloe and Berry, 2004). Using the tools available to complete a task is a central idea in this book, and engineer as *bricoleur* captures it very well.

A distinguishing feature of engineering is that it is a profession (Davis, 1998). Graduates of accredited engineering programs are expected to abide by the Codes of Ethics of Engineers for their respective professional organization. The Codes of Ethics consist of two parts, Fundamental Principles and Fundamental Canons. Here are these elements from the American Society of Civil Engineers (ASCE) (www.asce.org):

Fundamental Principles: Engineers uphold and advance the integrity, honor, and dignity of the engineering profession by:

1. using their knowledge and skill for the enhancement of human welfare and the environment;
2. being honest and impartial and serving with fidelity the public, their employers, and clients;
3. striving to increase the competence and prestige of the engineering profession; and
4. supporting the professional and technical societies of their disciplines.

Fundamental Canons:

1. Engineers shall hold paramount the safety, health, and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.
2. Engineers shall perform services only in areas of their competence.
3. Engineers shall issue public statements only in an objective and truthful manner.
4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest.
5. Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.
6. Engineers shall act in such a manner as to uphold and enhance the honor, integrity, and dignity of the engineering profession.
7. Engineers shall continue their professional development throughout their careers, and shall provide opportunities for the professional development of those engineers under their supervision.

In 1996 the ASCE added "sustainable development" to its Fundamental Canons, and in 2004 the *Civil Engineering Body of Knowledge for the 21st Century* added four outcomes to the eleven ABET outcomes:

1. an ability to apply knowledge in a specialized area related to civil engineering.
2. an understanding of the elements of project management, construction, and asset management.
3. an understanding of business and public policy and administration fundamentals.
4. an understanding of the role of the leader and leadership principles and attitudes.

Please notice that three of the four additional outcomes involve "soft skills" or what are increasingly being referred to as professional skills (Shuman, Besterfied-Sacre, McGourty, 2005).

The Fundamental Canons have a long history, and can be traced in part to the Code of Hammurabi (ca 1700 B.C.E.):

> If a builder builds a house for a man and does not make its construction sturdy and the house collapses and causes the death of the owner of the house, then that builder shall

> be put to death. If it destroys property, he shall restore whatever is destroyed, and because he did not make the house sturdy he shall rebuild the house that collapsed at his own expense. If a builder builds a house for a man and does not make its construction meet the requirements and a wall falls, then that builder shall strengthen the wall at his own expense.

The following reflection on the death of engineer Roger Boisjoly by David Radcliffe articulates how difficult it can be to uphold these principles.

The Courage to Engineer

Roger Boisjoly, a mechanical engineer who worked at Morton Thiokol, passed away in January 2012, although news of his death did not reach the mainstream media until a few days ago. Why is this significant? Roger Boisjoly exemplifies the moral courage that it takes to be an engineer. Based on his technical expertise and supporting evidence, he became concerned that the seals on solid booster rockets, made by Morton Thiokol, and which power the space shuttle on take-off, might fail in very cold weather. He strenuously warned his management and that of NASA of the possible consequences if the Challenger was launched in the very cold conditions that prevailed on the morning of January 28, 1986. His warning was not heeded, and we all know what happened.

But rather than being seen as a hero who tried to sound the alarm, Boisjoly was ostracized and suffered significantly as a result of being a true professional. An article in the *New York Times* outlines some of the pressure he endured (for this, see Martin, 2012).

Engineering is not just applied mathematics and science; it a deeply value-laden enterprise that involves choices that have real consequences for people and the planet. Decisions we make as engineers about what we choose to work on and how we choose to do things have an unavoidable moral and ethical dimension. I recommend you explore this case of an engineer who had the moral courage to stick by his professional opinion and hang the personal or social consequences; see the Online Ethics Center for Engineering and Research: http://www.onlineethics.org/cms/7123.aspx

In a famous minority opinion to the official report on the Challenger disaster, Appendix F, Nobel Prize-winning physicist Richard Feynman concluded with the following statement: "For a successful technology, reality must take precedence over public relations, for nature cannot be fooled." Even if we have a perfect set of calculations, if these do not model the actuality of nature, then there could be dire consequences. To engineer is to have the courage to make critical judgment calls.

Even if we are not called upon to display the moral courage shown by Roger Boisjoly in raising the alarm about the Challenger, we all have a role to play. In his *New York Times* article, Douglas Martin recalls that Boisjoly "was sustained by a single gesture of support. Sally Ride, the first American woman in space, hugged him after his appearance before the commission." "She was the only one," he said in a whisper to a Newsday reporter in 1988. "The only one."

Food for thought and cause for deep reflection on what it takes to engineer.

David Radcliffe

An article by Sheppard, Colby, Macatangay, and Sullivan (2005) exploring the question, "What is engineering practice?" opens with the following statement: "Professions, such as engineering, medicine, teaching, nursing, law, and the clergy share a common set of tenets; namely to:

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

David Billington (1986), author of *The Tower and the Bridge: The New Art of Structural Engineering,* Princeton University Press, 1985, summarizes one of the challenges of professional practice as follows: "Engineers are always confronted with two ideals, efficiency and economy, and the world's best computer could not tell them how to reconcile the two. There is never "one best way." Like doctors or politicians or poets, *engineers face a vast array of choices every time they begin work, and every design is subject to criticism and compromise.*"

James Adams (1991) argues that engineering school does not necessarily prepare people for professional practice (and may even deter some):

> Engineering: In School and Out – Engineering schools recognize the overlap in industry between engineering and science, and they design their curricula accordingly. Engineering education is strongly theoretical and geared toward math and science. This is partly because of the natural interests of people who are attracted to a professorial life and who set the curriculum. It is also because engineers can learn the more applied portions of their field on the job, while they are unlikely to learn math and science on the job. But because the activities of the engineering student have little relation to the activities of many practicing engineers, it is likely that engineering education discourages some students who would make excellent engineers and encourages other who will not. *The mentality to do well in engineering schools emphasizes the ability to work problem sets and get right answers. In engineering, there are never right answers and [there are] few problem sets.*

Engineering Design

If design is the essence of engineering, the next question is, What is design? What comes to mind when you consider the term *design*? Do you think of product design (such as automobiles), architectural design, set and costume design (as in theater), or interface design (as in computer)? Take a moment to collect your thoughts on design.

ABET, the group that accredits engineering programs, defined engineering design as "the process of devising a system, component or process to meet a desired need" (ABET, 2000).

Researchers who carefully observe the engineering design process are increasingly noting that it is quite different from the formal process typically described in textbooks. For example, Eugene Ferguson (1992, p. 32) writes:

> Those who observe the process of engineering design find that it is not a totally formal affair, and that drawings and specifications come into existence as a result of a social process. The various members of a design group can be expected to have divergent views of the most desirable ways to accomplish the design they are working on. As Louis Bucciarelli (1994), an engineering professor who has observed engineering designers at work, points out, informal negotiations, discussions, laughter, gossip, and banter among members of a design group often have a leavening effect on its outcome.

Recent work on engineering design indicates that design is a more social process than we once thought. Larry Leifer (1997) of the Stanford Center for Design Research claims that engineering design is "a social process that identifies a need, defines a problem, and specifies a plan that enables others to manufacture the solutions." Leifer's research shows that design is fundamentally a social activity. He describes practices such as "negotiating understanding," "conserving ambiguity," "tailoring engineering communications for recipients," and "manipulating mundane representations."

The state of the art definition of engineering design is from a 2005 article, "Engineering Design Thinking, Teaching, and Learning" (Dym, Agogino, Eris, Frey, and Leifer, 2005): "*Engineering design* is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints." The authors say good designers have the ability to:

- tolerate ambiguity that shows up in viewing design as inquiry or as an iterative loop of divergent-convergent thinking;
- maintain sight of the big picture by including systems thinking and systems design;
- handle uncertainty;
- make decisions;
- think as part of a team in a social process; and
- think and communicate in the several languages of design.

The role of failure in engineering design must be considered, despite the popular saying from Gene Kranz, flight director in Mission Control for the Apollo 13 moon launch, "Failure is not an option." Rumor has it that many engineering students embrace Kranz's statement and are afraid to fail, raising the concern that they are therefore uneasy about pushing themselves or their designs to the limit. Failure is an important part of engineering; in fact, engineers such as Henry Petroski argue that "Failure is always an option." Petroski (2003) writes in a *New York Times* op-ed piece, "The design of any device, machine or system is fraught with failure. Indeed, the way engineers achieve success in their designs is by imagining how they might fail." Petroski also devoted a book (2003) to this topic, *Small Things Considered: Why There Is No Perfect Design.*

Engineers are not alone in accepting (and learning from) failure. Consider these quotes from three innovators and entrepreneurs:

> The fastest way to succeed is to double your failure rate. (Thomas Watson, IBM)
>
> Fail often to succeed sooner. (Tom Kelley, IDEO)
>
> You must learn to fail intelligently. Failing is one of the greatest arts in the world. One fails toward success. (Thomas Edison)

Another way to conceptualize the role of failure is to consider the heuristic: use feedback to stabilize design (Koen, 2003). Sometimes the feedback comes from failure, but more commonly it comes from modeling, testing, prototyping, and other less catastrophic forms of failure.

If design is the heart of engineering and design is a social process, then it follows that teamwork and project management are essential to engineering. Many problems with engineering result from poor team dynamics and inadequate project management.

> *Design team failure is usually due to failed team dynamics.*
>
> Larry Leifer
> Director, Stanford Center for Design Research

A lot has been written about engineering and engineering design. Adams (1991), Hapgood (1992), and Ferguson (1992), for example, can give students considerable insight into engineering. I devoted two *Journal of Engineering Education* Academic Bookshelf columns to these topics. You can find summaries of several of the books on my website, www.ce.umn.edu/~smith. Follow the Teamwork and Project Management link. One of the most interesting insights into engineering design was presented in the ABC News Nightline show documenting the design process at the product design firm IDEO ("The Deep Dive," July 13, 1999). David Kelly, head of IDEO, challenged the viewer: "Look around—the only things not designed by humans are in nature." Five steps are key to IDEO's expertise in innovative design:

1. Understand the market/client/technology/constraints.
2. Observe real people in real situations.
3. Visualize new-to-the-world concepts and ultimate customers.
4. Evaluate and refine prototypes.
5. Implement new concepts for commercialization.

I hope you have an opportunity to view the IDEO Deep Dive on DVD or YouTube. Students I've shown it to exclaim, "I want to work at a place like that!" It is possible, however, if the engineering and business leaders are right, that many of us will be working in places where design is emphasized. Bruce Nussbaum wrote in *Business Week*, March 8, 2005, that "'Design thinking' can create rewarding experiences for consumers–the key to earnings growth and an edge that outsourcing can't beat." Nussbaum cites Roger Martin, dean of the Rotman School of Management at the University of Toronto, who is reshaping the entire MBA program around the principle that "businesspeople will have to become more 'masters of heuristics' than 'managers of algorithms,'" and that "design skills and business skills are converging." Martin's 2009 book, *The design of business: Why design thinking is the next competitive advantage,* provides elaboration on this idea. He writes, "Design thinking focuses on accelerating the pace at which knowledge advances from *mystery* (an unexplainable problem) to *heuristic* (a rule of thumb that guides us toward a solution) to *algorithm* (a replicable success formula).” I’ll elaborate further on Martin’s ideas in Chapter 2.

Until recently the predominant design approach used in engineering was “cradle to grave” and most things were designed to be thrown away. The concept of “away” was described in an interesting way as the “toilet assumption” by Bennis and Slater (1968) in their book *The Temporary Society.* The engineering design paradigm is slowly changing from “cradle to grave” to “cradle to cradle.” The idea of “cradle to cradle” was developed and championed by the international collaboration of Michael Braungart, a German chemist, and William McDonough, a U.S. architect (McDonough and Braungart, 2002).

Increasingly, design is conducted by globally distributed teams, and Shawn Jordan’s reflection provides insights into his research and experience.

In today’s fast-paced and innovation-driven world, the nature of the design problems facing industry often requires the use of cross-disciplinary teams in order to maximize innovation. Assembling face-to-face teams to solve the wide variety of design problems that exist is costly, time-consuming, and sometimes impossible, leaving companies with no choice but to call upon virtual cross-disciplinary engineering design teams to quickly and cost-effectively solve design problems. These teams are crucial to competitiveness in the future, but virtual team members need a stronger set of skills in order for virtual teams to be successful.

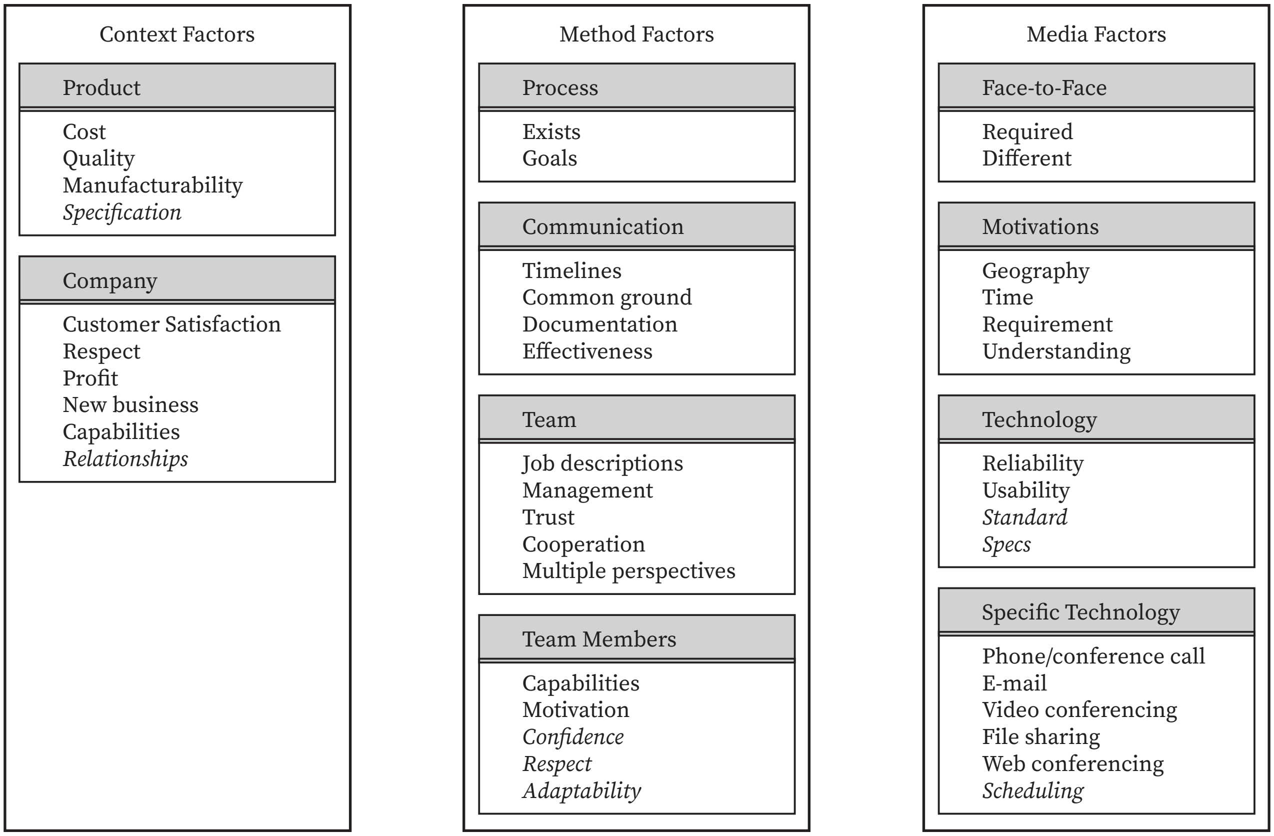
As part of my dissertation work, I spent 6 months embedded in a multi-national engineering design and manufacturing company to answer the question, *what factors contribute to the success of virtual cross-disciplinary engineering design teams in industry?* Three case studies were constructed on three distinctly different pre-existing virtual cross-disciplinary engineering design teams. One team was designing a process for working virtually, the second was redesigning an existing product to reduce cost, and the third was working as a part of a customer-led virtual team to design a brand new product. Team members completed questionnaires, participated in interviews, and went through observations of their virtual work experiences.

The results of this study showed that factors that contribute to the success of virtual cross-disciplinary engineering design teams fall into three major categories: the *context* in which teams work, the *method* by which teams do their work, and the *media* by which teams communicate. The specific factors are shown in Figure 1.

My study also found that virtual teams need (1) strong processes, (2) high-quality team members, and (3) higher performance in general on team-related success factors. Surprising was the heavy importance placed on process and team-related success factors (e.g., having clear job descriptions, strong management, trust and cooperation among team members, multiple perspectives represented on the team), compared with the significantly lesser importance placed on having the latest communications technology. A significant issue with the latest technology was reliability; many middle-aged workers would rather use conference calls or e-mail rather than spend 1/3 of a meeting trying to get a multi-national team connected into the same computer-based conference. Regardless of what technology you choose to use for your virtual team, make sure to support it with strong team processes to be successful!

Shawn Jordan

Figure 1.1 Virtual Cross-Disciplinary Engineering Design Team Success Factors*



* Factors (except those in italics) were independently identified in all three team cases in the study. Factors in italics were independently identified by one or more team cases in the study.

Innovation and creativity are getting a lot of attention in engineering circles. VandeVen, Polley, Garud & Venkataraman's (1999) research indicates that "The innovation journey is a nonlinear cycle of divergent and convergent activities that may repeat over time and at different organizational levels if resources are obtained to renew the cycle" (p. 16). Their view is similar to the divergent (brainstorming) and convergent (selecting among alternative prototypes, needs, constraints, etc.) cycles portrayed in the IDEO Deep Dive video. My current favorite definition of innovation is the one offered by Denning and Dunham (2010), in which they describe innovation "as the art of getting people to adopt change" and offer the following definition:

"Innovation is the adoption of new practice in a community."

Andrew Hargadon (2003) argues that "Extraordinary innovations are often the results of recombinant invention" (p. viii, ix). He cites science fiction writer William Gibson–"The future is already here, it's just unevenly distributed"–to help make his point. Brian Arthur's argues in his 2009 book *The nature of technology: What it is and how it evolves* that there are three fundamental principles of technology (Arthur, 2009):

1. All technologies are combinations
2. Each component of technology is itself in miniature a technology
3. All technologies harness and exploit some effect or phenomena, usually several

And he offers three related definitions of technology:

1. A means to fulfill; a human purpose.
2. An assemblage of practicers and components.
3. The entire collection of devices and engineering practices available to a culture.

Hargadon advocates for technology brokering, a strategy for exploiting the networked nature of innovation processes. Rather than producing fundamentally novel advances in any one technology or dominating any one industry, technology brokering involves combining existing objects, ideas, and people in ways that create breakthroughs, and may even spark technological revolutions. Technology brokering involves the concept of bridging:

1. Breakthrough innovation depends on exploiting the past.
2. Successful innovators better exploit the networked structure of ideas within unique organizational frameworks.
3. Breakthrough innovations depend on building communities--innovation is as much social as it is technical.

Edgar Schein (2003), who served as a consultant to Digital Equipment Corporation (DEC) for over 20 years, argued that innovation is predominantly a cultural artifact. He wrote "Culture is a complex force field that influences all of an organization's processes. We try to manage culture but, in fact, culture manages us far more than we manage it, and it happens largely outside of awareness" (p. 31).

Regardless of how you frame innovation and creativity it is likely to be of great importance to your success in engineering. Also, since innovation has become such an important and timely topic, a new chapter, Innovation in a team environment, written by Senay Purzer is now a part of this book.

Now that we've taken a glance at engineering and the role of design, let's turn to the role of teamwork and project management in engineering.

Teamwork and Engineering

> **REFLECTION** What have been your own personal experiences in working on a team (or group)? Were these good or bad expereinces? Have you worked as a member of a project team (in school or otherwise)? Can you recall any particular reason why you need to work as team (or group)? What were benefits (or the drawbacks)? Why do you think teamwork is (or is not) important in the practice of engineering? Take a moment to reflect on your experiences with teamwork and then think about the importance and role of teamwork in engineering practice.

How important is teamwork in the practice of engineering? National leaders in engineering and engineering education are advocating increased emphasis on teamwork and leadership skills as outlined in this book's Preface.

Table 1.1 Proportion Of Employers Who Say Colleges And Universities Should Place More Emphasis Than They Do Today On Selected Learning Outcomes

Selected Learning Outcomes	%
Concepts and new developments in science and technology	82
Teamwork skills and the ability to collaborate with others in diverse group settings	76
The ability to apply knowledge and skills to real-world settings through internships or other hands-on experiences	73
The ability to effectively communicate orally and in writing	73
Critical thinking and analytical reasoning skills	73
Global issues and developments and their implications for the future	72

Similarly, business leaders are stressing the importance of developing a broad range of skills. The 2003 Business-Higher Education Forum report, *Building a Nation of Learners*, listed the following skills and attributes of a nation of learners: leadership, teamwork, problem solving, time management, self-management, adaptability, analytical thinking, global consciousness, and basic communication (listening, speaking, reading, and writing). The quotes from Rockefeller and Welch that open Chapter 3 (p. 00) [proofreader: please fill in] stress the importance of teamwork from the perspective of a corporate chief executive officer (CEO), but what about its importance for engineering graduates?

The AAC&U *College Learning for the New Global Century* study included the results of an employer survey conducted by Peter D. Hart Research Associates (2006). The top two responses to the question, "Most important skills employers look for in new hires" were teamwork and critical thinking and reasoning. Areas where employers noted that more emphasis is needed in colleges and universities are show in Table 1.

Teamwork and project management are central to engineering. Learning how to organize and manage projects, and to participate effectively in project teams, not only will serve you well in engineering school, where there are lots of group projects, but also will be critical to your success as a professional engineer. The Boeing Company uses the checklist shown below when considering new applicants for employment.

Employer's Checklist—Boeing Company

- ✔ A good grasp of these engineering fundamentals:
  Mathematics (including statistics)
  Physical and life sciences
  Information technology
- ✔ A good understanding of the design and manufacturing process (i.e., an understanding of engineering)
- ✔ A basic understanding of the context in which engineering is practiced, including:
  Economics and business practice
  History
  The environment
  Customer and societal needs

- ✔ A multidisciplinary systems perspective
- ✔ Good communication skills
  Written
  Verbal
  Graphic
  Listening
- ✔ High ethical standards
- ✔ An ability to think critically and creatively as well as independently and cooperatively
- ✔ Flexibility—an ability and the self-confidence to adapt to rapid/major change
- ✔ Curiosity and a lifelong desire to learn
- ✔ A profound understanding of the importance of teamwork

Source: Briefings ASEE Prism, December 1996, p. 11.

The Boeing Company checklist has been undergoing updates and refinements, and the following were added (or revised extensively) in a list titled "Desired Attributes of a Global Engineer":

- An awareness of the boundaries of one's knowledge, along with an appreciation for other areas of knowledge and their interrelatedness with one's own expertise
- •An awareness and strong appreciation for other cultures and their diversity, their distinctiveness, and their inherent value
- •A strong commitment to teamwork, including extensive experience with and understanding of team dynamics
- •An ability to impart knowledge to others.
- The emphasis on teamwork is not entirely new, as shown in the following 1988 list of skills employers want their employees to have.

What Employers Want

- Learning to learn
- Listening and oral communication
- Competence in reading, writing, and computation
- Adaptability: Creative thinking and problem solving
- Personal management: Self-esteem, goal setting/motivation, and personal/career development
- Group effectiveness: Interpersonal skills, negotiation, and teamwork
- Organizational effectiveness and leadership

Source: Workplace Basics: The Skills Employers Want. 1988. American Society for Training and Development and U.S. Department of Labor.

The importance of teamwork in business and industry is also embedded in the concepts of concurrent (or simultaneous) engineering and total quality management. The following quote elaborates on this point:

> In concurrent engineering (CE), the key ingredient is teamwork. People from many departments collaborate over the life of a product—from idea to obsolescence—to ensure that it reflects customers' needs and desires. . . . Since the very start of CE, product development must involve all parts of an organization. Effective teamwork

> depends upon sharing ideas and goals beyond immediate assignments and departmental loyalties. Such behavior is not typically taught in the engineering schools of U.S. colleges and universities. For CE to succeed, teamwork and sharing must be valued just as highly as the traditional attributes of technical competence and creativity, and they must be rewarded by making them an integral part of the engineer's performance evaluation. (Shina, 1991, p. 23)

The increased emphasis on teamwork in engineering classes is partly due to the emphasis by employers, but it is also due to engineering education research on active and cooperative learning, and the emphasis of ABET. To maintain ABET accreditation, engineering departments must demonstrate that all of their graduates have the following 11 general skills and abilities (ABET, 2000):

1. An ability to apply knowledge of mathematics, science, and engineering
2. An ability to design and conduct experiments, as well as to analyze and interpret data
3. An ability to design a system, component, or process to meet desired needs
4. An ability to function on multidisciplinary teams
5. An ability to identify, formulate, and solve engineering problems
6. An understanding of professional and ethical responsibility
7. An ability to communicate effectively
8. The broad education necessary to understand the impact of engineering solutions in a global and societal context
9. A recognition of the need for, and an ability to engage in, lifelong learning
10. A knowledge of contemporary issues
11. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

As you no doubt have recognized, a confluence of pressures emphasizes teamwork in engineering education and practice. We need to leave room for the "maverick," but most, if not all, engineering graduates need to develop skills for working cooperatively with others—as indicated by the lists of the top three engineering work activities.

Top Three Main Engineering Work Activities

Engineering Total	Civil/Architectural
• Design—36%	1. Management—45%
• Computer applications—31%	2. Design—39%
• Management—29%	3. Computer applications—20%

Source: Burton, L., Parker, L., & LeBold, W. 1998. U.S. engineering career trends. *ASEE Prism* 7(9), 18–21.

The full list of work activity reported by engineers is shown in the Table 1.1. Note that 66 percent mentioned design and 49 percent mentioned management.

Table 1.2 Rank Order of Work Activities, 1993

Activity		% Mentioning
1.	Design66	
2.	Computer applications	58
3.	Management	49
4.	Development	47
5.	Accounting, etc.	42
6.	Applied research	39
7.	Quality or productivity	33
8.	Employee relations	23
9.	Sales 20	
10.	Basic research	15
11.	Production	14
12.	Professional services	10
13.	Other work activities	8
14.	Teaching	8

Source: Burton, Parker, and LeBold, 1998, p. 19.

Numous surveys of employers highlight the top skill needs. Below is a table of Employer Evaluation of Employee Attributes 2008-2009 Employer Survey from Minnesota Measures – 2009. Also cited in Sparks and Waits (2011).

Top Attributes (most frequent ratings of "very important" by employers – top five)

- Professionalism (punctuality, time management, attitude)
- Self direction, ability to take initiative
- Adaptability, willingness to learn
- Professional ethics, integrity
- Verbal communication skills

Middle Attributes (between top five and bottom five)

- Capability for promotion
- Creativity
- Ability to work in a culturally diverse environment
- Ability to work in teams
- Written communication skills
- Basic mathematical reasoning (arithmetic, basic algebra)
- Critical thinking and analysis
- Problem solving, application of theory
- General computer skills (word processing, spreadsheets)
- Knowledge of technology/equipment required for the job

Bottom Attibutes (Most frequent ratings of "not at all" or "not very important" – bottom five)

- Advanced mathematical reasoning (linear algebra, statistics, calculus)
- Technical communication

- Fluency in a language other than English
- Knowledge of specific computer applications required for the job
- Application of knowledge from a particular field of study

Employer's wish lists are making it into popular guides for college students. For example, Bill Coplin's (2003) *10 Things Employers Want You to Learn in College*, are Establishing a Work Ethic, Developing Physical Skills, Communicating Verbally Communicating in Writing, Working Directly with People, Influencing People, Gathering Information, Using Quantitative Tools, Asking and Answering the Right Questions, and Solving Problems

A few guides are available specifically for engineering students and graduates entering the engineering workforce. Krista Donaldson's 2005 *The Engineering Student Survival Guide* has lots of terrific suggestions for making the most of your undergraduate engineering education, tips that will help you thrive not just survive. Carl Selinger's 2004 *Stuff You Don't Learn in Engineering School* provides similar guidance to graduates entering the engineering workforce.

Some of this advice is based on research on what it takes to succeed in college. Richard Light's research with students, for example, revealed the following keys to making the most of college (Light, 2001):

1. Meet the faculty
2. Take a mix of courses, especially early on
3. Study in groups
4. Write, write, write
5. Speak another language
6. Consider time–successful students manage their time effectively
7. Hold the drum–get involved in professional and social activities

Fundamental Tools for the Next Generation of Engineers and Project Managers

REFLECTION What is your plan for developing a broad range of skills? How about for making the most of your engineering education? Take a moment and reflect on your plan and your progress to date.

I've stressed the importance of teamwork for engineering education and practice, but teamwork isn't all that's needed. If engineers are going to become "the master integrators," as emphasized by Joe Bordona (1998), three additional tools are fundamental:

- Systems/systems thinking/systems engineering
- Models, Modeling, and Heuristics
- Quality (I defer this discussion to Chapter 12)

The Art and Practice of the Learning Organization

1. *Building shared vision.* The idea of building shared vision stresses that you never quite finish it—it's an ongoing process.
2. *Personal mastery.* Learning organizations must be fully committed to the development of each individual's personal mastery—each individual's capacity to create their life the way they truly want.
3. *Mental models.* Our vision of current reality has everything to do with the third discipline—*mental models*—because what we really have in our lives is constructions, internal pictures that we continually use to interpret and make sense out of the world.
4. *Team learning.* Individual learning, no matter how wonderful it is or how great it makes us feel, is fundamentally irrelevant to organizations, because virtually all important decisions occur in groups. The learning units of organizations are "teams," groups of people who need one another to act.
5. *Systems thinking.* The last discipline, the one that ties them all together, is *systems thinking.*

Source: Senge, 1993.

The Systems Approach

Employer checklists like Boeing's and the new ABET accreditation criteria emphasize systems and the systems approach.

A system is a whole that cannot be divided up into independent parts (Ackoff, 1994). Systems are made up of sets of components that work together for a specified overall objective. The systems approach is simply a way of thinking about total systems and their components.

Five basic considerations must be kept in mind when thinking about the meaning of a system: (1) the total system's objectives and, more specifically, the performance measures of the whole system; (2) the system's environment: the fixed constraints; (3) the resources of the system; (4) the components of the system, their activities, goals, and measures of performance; and (5) the management of the system (Churchman, 1968).

Systems thinking is a discipline for seeing wholes—a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static "snapshots." It is a set of principles and a set of specific tools and techniques (Senge, 1990). An implication of the systems approach is that it is important to get everybody involved to improve whole systems (Weisbord, 1987). The systems approach is commonly implemented through learning organizations (see the box "The Art and Practice of the Learning Organization").

A systems theme is one of the integrating threads in this book. The concepts of systems and of the learning organization are important not only to your study of teamwork and project management but to many other things you will be studying in engineering. Here, for example, are eight principles for learning from Xerox (Jordon, 1996, p. 116):

1. Learning is fundamentally social.
2. Cracking the whip stifles learning.
3. Learning needs an environment that supports it.

4. Learning crosses hierarchical bounds.
5. Self-directed learning fuels the fire.
6. Learning by doing is more powerful than memorizing.
7. Failure to learn is often the fault of the system, not the people.
8. Sometimes the best learning is unlearning.

This list from Xerox indicates that the ideas in this book are important not only for your project work but also for your day-to-day work in engineering school.

Nelson and Stolterman's 2003 *The Design Way* provides many connections to systems and systems thinking as well as a sound foundation and fundamentals of design competence. The authors' adamancy about design is regularly revealed in provocative statements such as "Humans did not discover fire–they designed it. The wheel was not something our ancestors merely stumbled over in a stroke of good luck; it, too, was designed. The habit of labeling significant human achievements as 'discoveries,' rather than 'designs,' discloses a critical bias in our Western tradition."

Nelson and Stolterman (2003) make many connections between design and systems thinking. For example they write "The systems approach is the logic of design. Such an approach requires that close attention be paid to relationships and the phenomenon of emergence when evaluating any subset of existence. If the designer's intention is to create something new, not to just describe and explain, or predict and control, it is especially important to take a systems approach" (p. 74). I recommend this book to help deepen your understanding of systems and design, and I'm confident that deep understanding of both these concepts as well as the interaction between them is essential for success in engineering in the 21st century.

An emerging area of systems that is gaining momemtum is complexity and complex adaptive systems (Axelrod & Cohen, 2001; Miller & Page, 2007). Page (2009) claims that a "system can be considered complex if its agents meet four qualifications: diversity, connection, interdependence, and adaptation." (p.4) and "the attributes of interdependence, connectedness, diversity, and adaptation and learning generate complexity." (p. 10). Furthermore, Page (2009) notes that "interdependence refers to whether other entities influence actions, whereas connectedness refers to how many people a person is connected to." (p.11). Preparing students with a deeper understanding of complex systems is essential, since complex systems (1) are often unpredictable and can produce large events as well as withstand trauma, (2) produce bottom-up emergent phenomena, and (3) produce amazing novelty (Page, 2009).

Systems, systems thinking, and especially complex adaptive systems will be revisited in Chapter 15.

Models, Modeling, and Heuristics

Modeling in its broadest sense is the cost-effective use of something in place of something else for some cognitive purpose (Rothenberg, 1989). A model represents reality for the given purpose; the model is an abstraction of reality, however, in the sense that it cannot represent all aspects of reality. According to Rothenberg, models are characterized by three essential attributes:

1. *Reference:* A model is of something (its *referent*).
2. *Purpose:* A model has an intended cognitive *purpose* with respect to its referent.
3. *Cost-effectiveness:* A model is more *cost-effective* to use for this purpose than the referent itself would be.

I often give students this problem that I first learned about from Billy Koen to help them learn about these attributes of modeling: Determine the maximum number of Ping-Pong balls that could fit in the room you're sitting in. First I give them about 20 seconds and ask each person to guess. Next I ask them to work in groups for 5 or 10 minutes to develop not only a numerical estimate but also a description of the method they use and the assumptions they specified. At this stage, students typically model the room as a rectangular box and the ball as a cube. They then determine the number by dividing the volume of the room by the volume of a ball. I ask them what they would do if I gave them the rest of the class period to work on the problem. They report that they need measuring tools and a container of Ping Pong balls, and after receiving these materials, set off to work. Sooner or later a student says, "Who cares how many Ping-Pong balls could fit in the room!" I thank that student and report that we can now stop. In any problem that involves modeling, the purpose must be specified. Without knowing the purpose, we don't know how exact an answer must be or how to use the model. In fact, the 20-second answer might be good enough. This problem is also featured in our book *How to model it: Problem solving for the computer age* (Starfield, Smith and Bleloch, 1990).

An essential aspect of modeling is the use of heuristics (Starfield, Smith, and Bleloch, 1994), which may be generally defined as methods or strategies that aid in discovery or problem solving. Although difficult to define, heuristics are relatively easy to identify using the characteristics listed by Koen (1984, 1985, 2003):

1. Heuristics do not guarantee a solution.
2. Two heuristics may contradict each other or give different answers to the same question and still be useful.
3. Heuristics permit the solving of unsolvable problems or reduce the search time to a satisfactory solution.
4. The heuristic depends on the immediate context instead of absolute truth as a standard of validity.

Thus, a heuristic is anything that provides plausible aid or direction in the solution of a problem but is in the final analysis unjustified, incapable of justification, and fallible. It is used to guide, to discover, and to reveal. Heuristics are also a key part of Koen's definition of the engineering method:

The engineering method is the use of heuristics to cause the best change in a poorly understood situation within the available resources. (p. 70)

Typical engineering heuristics include (1) rules of thumb and orders of magnitude, (2) factors of safety, (3) circumstances that determine the engineer's attitude toward his or her work, (4) procedures that engineers use to keep risk within acceptable bounds, and (5) rules of thumb that are important in resource allocation.

My colleague and coauthor, Tony Starfield, has been thinking, teaching, and writing about heuristics for many years and his reflection in the box below provides his collected wisdom Starfield (1999, 2005).

Modeling Heuristics

1. Keep it simple. Use the leanest model for the purpose at hand.
2. Be sure you've defined your objectives clearly.
3. Think yourself into the problem. Plan your output. What will you do with it and how do you expect it to look? For example, do you need numbers out to three decimal places?
4. Be prepared to explain your model. Graphs, pictures, and histograms are better than words or numbers to explain model results.
5. Anticipate your results. If you get what you anticipate--good! If actual results do not agree with anticipated results, make sure you understand why.
6. Look for upper and lower bounds. What is the biggest number? Smallest number? If they are close, there may be no need to look further. If not, you need to study further.
7. Choose appropriate spatial and temporal scales. What do you see or not see at a particular step in building the model?
8. Choose suitable time/space steps. Look for magic numbers (time or spatial scales that simplify and suit the structure of the problem).
9. Keep a list of assumptions and review them frequently. Have the "guts" to make assumptions. List your assumptions as you develop the model.
10. Think about what level of detail you will need to meet the purpose of the model. If in doubt, leave it out. Make assumptions. Revisit those assumptions later.
11. Cut through "Gordian" knots. Gordian knots are things that are messy. There are no clear means to untie them easily (they are also called a can of worms). Either leave it out or find a simple way through it. Make simplifying assumptions. Build your model around your purpose not around knots.
12. Don't be held up (stymied) by lack of data.
13. Plan for a sensitivity analysis (i.e., vary the values of parameters). What things do I need to change to see how sensitive the model is to changes in the data or assumptions? Get a series of answers for a feel of how the model works.
14. Finding the right notation (i.e., numbers or symbols to represent model formulas or calculations) helps you think through the model. This is a way for you to describe your model.
15. If a formula is used, be sure to understand why it fits. Be cautious of pulling formulae out of books and using them without understanding them. All have baggage and assumptions, including statistics.
16. Never write down a formula without first writing it down in words so that you understand the process. Then write it as a mathematical equation. If you need to add to or adjust a formula, never try to just "fix it." Go back to the statement in words and redevelop it.
17. Write parameters into a model as symbols, not numbers, so you can change their values easily (i.e., sensitivity analysis).
18. Use prototypes.
19. Consider using salami tactics. You can't get the whole salami at once nor can you solve the whole problem at one time. Ask for one slice of the salami then ask for another one. Slice the problem and solve it as a series of steps. Get a whole model (or a whole salami) one slice at a time. (Besides, if you try to eat a whole salami at one time you will probably get a stomachache. If you try to solve the whole model at one time you will probably get a headache.) Keep in mind that your objective is the whole salami.
20. Maintain intellectual control. You control your model, so don't let the model control you. (If you don't understand the model, you cannot expect others to understand it).
21. Press ahead. Don't get bogged down. Get something working as soon as possible. When you start seeing what your model does, you can see what your model does right and wrong. Be prepared that some models may just have to be abandoned. This concept is called rapid prototyping.

– Tony Starfield

As you can no doubt tell, Tony Starfield has been thinking and writing about and teaching models and modeling for a long time. His university courses and workshops with professionals focus on helping people learn how to model complex phenomena, mainly ecological modeling. He stresses heuristics in his courses and workshops and encourages students and workshop participants to be on the lookout for heuristics in all aspects of their lives.

Here's a complementary set of modeling heuristics from an operations research textbook (Ravindran, Phillips, and Solberg, 1987):

1. Do not build a complicated model when a simple one will suffice.
2. Beware of molding the problem to fit the technique.
3. The deduction phase of modeling must be conducted rigorously.
4. Models should be validated prior to implementation.
5. A model should never be taken too literally.
6. A model should neither be pressed to do, nor criticized for failing to do, that for which it was never intended.
7. Beware of overselling a model.
8. Some of the primary benefits of modeling are associated with the process of developing the model.
9. A model cannot be any better than the information that goes into it.
10. Models cannot replace decision makers.

Some of my favorites from this list are Number 2 because you learn powerful tools and techniques in engineering school but not necessarily the understanding of where and how to use them; Number 8 because I've seen an enormous amount of learning as I've observed students building models; and Number 9 because I've seen too many examples of GIGO (garbage in, garbage out).

A more recent definition from researchers who design activities and environments to help people learn to model is: Modeling, at its core, is a way of thinking used in order to represent, describe, or explain a system with another system for a purpose (Lesh and Doerr, 2003; Moore, 2008).

Tamara Moore's reflections on developing modeling thinking provides insights into how to advance your understanding.

Modeling Thinking

Modeling abilities play an important role in engineering. So, engineering educators are interested in facilitating students' development of these abilities. Model-Eliciting Activities (MEAs) are client-driven, team-based tasks that we've been using in undergraduate engineering education to help students build competent modeling abilities. MEAs allow participants to demonstrate their knowledge in multiple ways. Solution processes in MEAs often involve shifting back and forth among a variety of relevant representations or models. Within MEAs, students develop, construct, describe, or explain engineering systems.

As Karl and I have been working together over the last several years, we have begun to think about why is modeling so important to engineers and STEM professionals in general. These conversations have lead to us thinking deeply about what are the most important skills for engineers to know. At the top of our list is modeling… why is this? Because, engineering is a field (along with finance, business, agriculture, etc.) that relies on modeling to make many important decisions about how systems are performing. MEAs were created to focus on the modeling abilities (mathematical and otherwise) that are needed in this environment – especially as our technology-based age of information is changing so rapidly. If we spend too much time teaching specific skills, in just a few short years after a student graduates, that skill is likely to be outdated. However, modeling is more robust. It is a way of thinking that is adaptable to new situations and new technologies.

MEAs create learning environments that are safe to explore these skills that are beyond just pure mathematical or science abilities. Teamwork, communication, and ethical considerations are all examples of skills that you need to be comfortable working with and in. Work on MEAs can help you construct, describe, and explain complex systems in ways that are reusable and shareable while at the same time honing your teamwork, communication, and other relevant skills.

The NanoRoughness Problem is an example of an MEA. Generally, MEAs start with some type of background reading to introduce students to the problem and its context. In the NanoRoughess Problem, there are three types of short introduction activities for students to complete as individuals. Before the problem, there is a one-page information sheet provided as background on the Atomic Force Microscopy (AFM) machine and how it works. This is important because most students are not familiar with this technology or how it works, and the product of the AFM machine is integral to the problem. Second, the students are asked to think about roughness by answering the following prompts:

How do you define roughness?

What procedure might you use to measure the roughness of the pavement on a road?

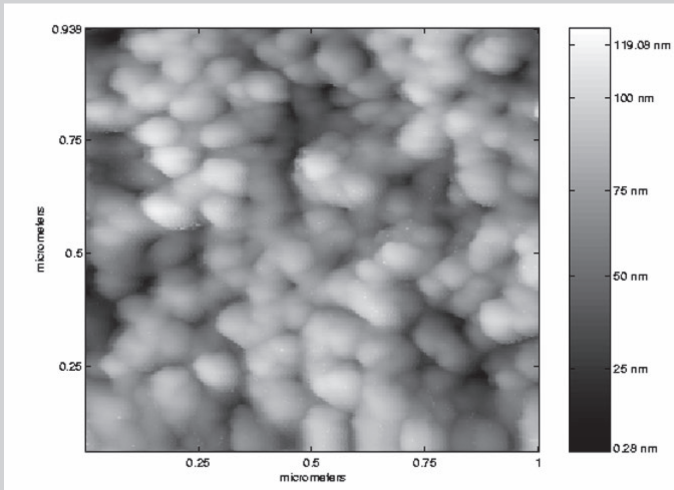
Give an example of something for which degree of roughness matters. For your example, why does the degree of roughness matter? How might you measure the roughness (or lack of roughness) of this object

Third, the students read a profile on the company that they are working for which is a company that develops coatings for orthopedic and biomedical implants. This sets the context for the problem. This individual work is important because all students need to be able to enter into the problem meaningfully, and we all process information at different rates. Have you ever been in a team where one person was off and running before the others really even understood what was being asked? This is a common problem in teaming. Getting everyone on even ground before beginning is important, both when learning about teaming and when you are out in the workforce working with your colleagues.

Next, student teams of 3 to 4 students work together on the modeling part of the problem. In the NanoRoughness Problem, the teams of students are asked to develop a procedure to measure roughness given AFM images of three different samples of gold. In order to motivate the problem, a realistic context in which a company specializing in biomedical applications of nanotechnology wishes to start producing synthetic diamond coatings for joint replacements is provided. The company intends to extend its experience with gold coatings for artery stents to this new application. They want to use the model for roughness on this new application, thus the need for the model to measure roughness. The company only has AFM samples of gold that students can use to develop the procedure for measuring roughness, but later the company intends on using the procedure to measure the roughness of gold. The image here is an example of one of these images.

The teams must communicate their model back to the company providing explicit details about their procedure. I have written an article that details this MEA and another called the Alu-

Figure 1.2 Electron Photomicrograph of Gold Coating



minum Bat Problem. If you are interested, you can find it at http://matdl.org/jme/files/2008/06/moore_jme_model_eliciting_activities.pdf.

When thinking about a problem that is as complex as this one, I bet you can imagine that, in order to get a good solution to this, different perspectives are valued. You want to think about this problem from many different aspects and consider many different ways of attacking this problem. Considering that a diversity of thought will strengthen the model, it makes sense then that when you build a team, varied backgrounds and different strengths are likely to make the product better. Consider Karl's section on the importance of diversity in Chapter 2. We have found that teams do better on MEAs when the teams are more diverse in thought and background, as long as they are willing to work together. We also know that all types of students are more likely to deeply engage in these types of problems than in the more traditional book problems.

So, what do you need to know about modeling? When you interpret a situation, you do not simply apply logical mathematical and scientific models to the system. You also engage feelings, values, dispositions, beliefs, and many other personal ways of thinking to the problem. These different ways of thinking can both strengthen and bias your models. So learn to think about what you bring to the table and use it to the best advantage. Problem solving is difficult, but also incredibly rewarding. Modeling is a form of problem solving, and as such, people who are good at it use tools to help them when they get stuck. These tools are often referred to as heuristics. Karl refers to heuristics in this section... something to think about with heuristics is that problem solving heuristics must be learned through the process of solving problems. It won't be effective for you to take this list and just try to implement them. We know... we've tried to get students to learn it that way starting over 50 years ago to no avail. However, once you have had a chance to work on complex modeling problems, like MEAs, reflecting about what you did and about the heuristics allows you to make meaning about your process and therefore be able to generalize it. Once you have generalized some of your processes, you have begun building your own set of heuristic tools. And as you encounter the next problem, think back to your tools and look for similar structure in the problems.

I hope the ideas presented here will help you in your journey to developing systems thinking, modeling, and problem solving skills. These are so important to your career and to life.

- Tamara Moore

We encourage you to be on the lookout for heuristics in the courses and projects you encounter, and most importantly, to develop your own heuristics.

Models and heuristics will constitute a major part of this book. The critical path method (CPM) is a procedure for modeling complex projects with interdependent activities. Visual representations include Gantt charts and network diagrams. My goal is for you to develop the skills and confidence necessary to organize, manage, be a participant in, and lead project teams. This goal is consistent with current thinking about the purpose of engineering schools. Deming associate and engineering educator Myron Tribus (1996) summarized the purpose of engineering schools as follows:

The purpose of a School of Engineering is to teach students to create value through the design of high quality products and systems of production, and services, and to organize and lead people in the continuous improvement of these designs. (p. 25)

Notice that Tribus considers management an integral part of engineering. He also elaborates on the importance of group work for learning to engineer:

The main tool for teaching wisdom and character is the group project. Experiences with group activities, in which the members of the groups are required to exhibit honesty, integrity, perseverance, creativity and cooperation, provide the basis for critical review by both students and teachers. Teachers will need to learn to function more as coaches and resources and less as givers of knowledge. (p. 25)

We've covered a lot of ground in this chapter and have hopefully given you a lot to think about as you learn more about teamwork and project management in engineering. We encourage you to stop and reflect periodically (as we are encouraging you to do in this book). Remember to assess both your strengths and your weaknesses, celebrate your accomplishments and problem-solve and plan the things you need to improve.

A Reflection on Teamwork and Project Management| in Engineering

As I finished writing the first edition of this book in 1999, I was reminded of a book from 1978 that I read more than 20 years earlier—*Excellence in Engineering* by W. H. Roadstrum. I was unable to locate my copy (I probably loaned it out) but did find the second edition, *Being Successful as an Engineer* (Roadstrum, 1988). In this edition, Roadstrum remarks, "Engineering is almost completely divorced from this concept of routine and continuous. Engineering work is project work" (p. 7). Engineering is project work! This is the essence of Roadstrum's book. The first two chapters, "What Engineering Is" and "The Engineer," cover ground similar to the material presented in this chapter, but from a perspective about 25 years ago. Chapters 3 and 4 are "The Project and the Project Team" and ""Project Control." Although I had not looked at Roadstrum's book for several years, I was struck by the overlap between his book and mine.

Being Successful as an Engineer addresses a broad range of topics, including problem-solving, laboratory work, design, research and development, manufacturing and quality control, systems, proposal work, human relations, and creativity. Roadstrum writes, "Design is the heart of the engineering process—its most characteristic activity." Furthermore, he states, "If you and I are going to understand engineering, we'll have to understand design" (p. 97).

Roadstrum further elaborates on the role of the project engineer:

> Every engineer looks forward to the time when he can have a project of his own. A project engineer has the best job in the business. He has ultimate responsibility for the work as a whole. He is the real architect of the project solution. Even more than his colleagues, he looks at the job as a whole from the beginning. He watches carefully to make all details come together into a timely, economical, fresh, and effective meeting of the need. (p. 166)

Roadstrum's book and ideas no doubt influenced my decision to develop skills and expertise in teamwork and project management; however, the specific reference lay dormant until now. I hope my book will influence your experience and practice of teamwork and project management in engineering.

A final note: This chapter opened with a discussion of Professor Billy Koen's probing questions. Koen's fourth question is this: "Lacking a ready answer [to the third question, What is the engineering method?], can you then name a nationally known engineer who is wise, well-read, and recognized as a scholar in the field of engineering—one to whom I can turn to find out what engineering really is?" To whom would you turn? Difficult, isn't it? No other profession lacks knowledgeable, clearly recognized spokespersons. I sincerely hope you'll help provide the leadership to make engineering better known.

Questions

1. What is engineering? How does engineering differ from science? What role does design play in engineering?
2. What is a model? Why are models useful in teamwork and project management and in engineering?
3. What is a system? Why are many books on teamwork and project management organized around a systems approach?

Exercises

1. Summarize your course work and experiences with engineering and design. What are some of the key things you've learned about engineers and engineering? Do you have relatives or friends who are project managers or engineers? If so, talk with them.
2. Why should you, as a first-year engineering student, be interested in teamwork and project management? Take a minute and reflect. Jot down at least three reasons why a first-year engineering student should be interested in these practices. What did you come up with? Did you say, for instance, that teamwork and project management are integral to professional engineering practice?
3. List your good experiences with projects and teamwork. Have you ever been on a team that had extraordinary accomplishments? If so, describe the situation, especially the characteristics of the team and project that led to extraordinary success. What were

some of the factors? a sense of urgency? a project too complex or timeline too short for one person to complete? a need for synergistic interaction?

References

Accreditation Board for Engineering and Technology (ABET). 2000. *Criteria for accrediting engineering programs*. Baltimore, MD: Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology.

Ackoff, Russell L. 1994. *The democratic corporation: A radical prescription for recreating corporate America and rediscovering success.* Oxford, UK: Oxford University Press.

Adams, James L. 1991. *Flying buttresses, entropy, and o-rings: The world of an engineer.* Cambridge, MA: Harvard University Press.

Arthur, W. Brian. 2009. *The nature of technology: What it is and how it evolves*

Auyang, Sunny Y. 2004. *Engineering: An endless frontier*. Cambridge, MA: Harvard University Press.

Axelrod, R., & Cohen, M. D. 2001. *Harnessing complexity: Organizational implications of a scientific frontier.* New York: Simon & Schuster.

Bennis, W.G. and Slater, P.E. 1968. *The temporary society*. New York: Harper & Row.

Billington, David P. 1986. In defense of engineers. *The Wilson Quarterly*, January.

Bordogna, Joseph. 1998. *Realizing the New Paradigm for Engineering Education: The Professional Engineer in 2010.* Engineering Foundation Conference, Baltimore, MD, June 4, 1998.

Brown, Tim. 2009. *Change by design: How design thinking transforms organizations and inspires innovation.* New York: Harper Business.

Bucciarelli, Louis. 1994. *Designing engineers.* Cambridge, MA: MIT Press.

Burton, Lawrence, Linda Parker, and William K. LeBold. 1998. U.S. engineering career trends. *ASEE Prism* 7(9): 18–21.

Business-Higher Education Forum. 2003. *Building a nation of learners: The need for change in teaching and learning to meet global challenges*. Washington, DC: Business-Higher Education Forum.

Chapman, William L., A. Terry Bahill, and A. Wayne Wymore. 1992. *Engineering modeling and design.* Boca Raton, FL: CRC Press.

Churchman, C. West. 1968. *The systems approach.* New York: Laurel.

Coplin, Bill. 2003. *10 things employers want you to learn in college: The know-how you need to succeed.* Berkeley, CA: Ten Speed Press.

Davis, Michael. 1998. *Thinking like an engineer: Studies in the ethics of a profession*. Oxford: Oxford University Press.

Denning, Peter J. and Dunham, Robert. 2010. *The innovator's way: Essential practices for successful innovation.* Cambridge, MA: MIT Press.

Donaldson, Krista. 2005. *The engineering student survival guide, 3rd ed.* New York: McGraw-Hill.

Dym, Clive L., Agogino, Alice M., Eris, Ozgur, Frey, Daniel D. and Leifer, Larry J. 2005. Engineering design thinking, teaching, and learning. *Journal of Engineering Education,* 94 (1), 103[\#208]120.

Employer's Checklist—Boeing Company. 1996. Briefings. *ASEE Prism* 6(4), 11.

Ferguson, Eugene S. 1992. *Engineering and the mind's eye.* Cambridge, MA: MIT Press.

Friedman, Thomas L. 2000. *The Lexus and the olive tree: Understanding globalization.* New York: Anchor Books.

Friedman, Thomas L. 2005. *The world is flat: A brief history of the 21st century.* New York: Farrar, Straus and Giroux.

Friedman, Thomas L. and Mandelbaum, Michael. 2011. *That Used to Be Us: How America Fell Behind in the World It Invented and How We Can Come Back.* New York: Farrar, Straus and Giroux.

Gabriele, Gary A. 2005. Advancing engineering education in a flattened world. *Journal of Engineering Education,* 94 (3), 285[\#208]286.

Hancock, J. C., Chairman (1986). *Workshop on undergraduate engineering education.* Washington, DC: National Science Foundation.

Hapgood, Fred. 1992. *Up the infinite corridor: MIT and the technical imagination.* Reading, MA: Addison-Wesley.

Hargadon, Andrew. 2003. *How breakthroughs happen: The surprising truth about how companies innovate*. Cambridge, MA: Harvard Business School Press.

Jacobs, Jane. 1961.

———. 2004. *Dark age ahead*.

Jordon, Brigitte. 1996. 8 principles for learning. *Fast Company,* October/November, p. 116.

Koen, B. V. 1984. Toward a definition of the engineering method. Engineering Education 75: 151–155.

———. 1985. Definition of the engineering method. Washington, DC: American Society for Engineering Education.

———. 2003. Discussion of the method. Oxford, UK: Oxford University Press.

———. 2011. Engineering Method: What It Is; What It Isn't. Philosophy of Engineering and Engineering Education Workshop. ASEE/IEEE Frontiers in Education Conference.

Kranz, Gene. 2001. *Failure is not an option: Mission Control from Mercury to Apollo 13 and beyond*. New York: Simon and Schuster.

Leifer, Larry. 1997. *A collaborative experience in global product-based learning.* November 18, 1997. National Technological University Faculty Forum.

Lesh, R., & Doerr, H. M. (2003). Foundations of a models and modeling perspective on mathematics teaching, learning, and problem solving. In R. Lesh, & H. M. Doerr (Eds.), *Beyond constructivism: Models and modeling perspectives on mathematics problem solving, learning, and teaching* (pp. 3-34). Mahwah, NJ: Lawrence Erlbaum Associates.

Light, Richard J. 2001. *Making the most of college.* Cambridge, MA: Harvard University Press.

Martin, Douglas. 2012. Roger Boisjoly, 73, Dies; Warned of Shuttle Danger. *New York Times.*

http://www.nytimes.com/2012/02/04/us/roger-boisjoly-73-dies-warned-of-shuttle-danger.html

Martin, Roger. 2009. *The design of business: Why design thinking is the next competitive advantage*. Boston, MA: Harvard Business Press.

McDonough, W. and Braungart, M. 2002. *Cradle to cradle: Remaking the way we make things.* New York: North Point Press.

Miller, J., & Page, S. E. 2007. *Complex adaptive systems: An Introduction to Computational Models of Social Life*. Princeton, NJ: Princeton University Press

Minnesota Measures – 2009. St. Paul, MN: Minnesota Office of Higher Education Performance.

Moore, T. J. (2008). Model-Eliciting Activities: A case-based approach for getting students interested in material science and engineering. *Journal of Materials Education, 30*(5-6), 295 - 310.

National Academy of Engineering. 2005. *Assessing the capacity of the U.S. engineering research enterprise.* Washington, DC: The National Academy Press.

Nelson, Harold G. and Erik Stolterman, 2003. *The design way: Intentional change in a unpredictable world*. Englewood Cliffs, NJ: Educational Technology Publications.

Page, S.E. 2009. *Understanding complexity*. The Great Courses. Chantilly, VA: The Teaching Company.

Papalambros, Panos Y., and Douglass J. Wilde. 1988. *Principles of optimal design: Modeling and computation.* Cambridge, UK: Cambridge University Press.

Perkins, David. 2002. *King Arthur's round table: How collaborative conversations create smart organizations*. New York: Wiley.

———. 2009. *Making Learning Whole: How Seven Principles of Teaching Can Transform Education*

Peter D. Hart Research Associates. 2006. *Report of Findings Based on Focus Groups among Business Executives*. Washington, DC: Peter D. Hart Research Associates

Petroski, Henry. 2003. *Small things considered: Why there is no perfect design*. New York: Knopf.

Petroski, Henry. 2003. Failure is always an option. *New York Times,* August 29, 2003. Pink, Daniel H. 2005. *A whole new mind: Moving from the information age to the conceptual age.* New York: Riverhead Books.

Ravindran, A., Don T. Phillips, and James J. Solberg. 1987. *Operations research: Principles and practice*, 2nd Edition. New York: Wiley.

Ray, Michael, and Alan Rinzler, eds. 1993. *The new paradigm in business: Emerging strategies for leadership and organizational change.* Los Angeles: Tarcher/Perigee.

Roadstrum, W. H. 1988. *Being successful as an engineer.* San Jose: Engineering Press.

Rothenberg, James. 1989. The nature of modeling. In *Artificial intelligence, simulation and modeling,* edited by L. E. Widman, K. A. Loparo, and N. R. Nielsen. New York: Wiley.

Schein, Edgar H., et.al. 2003. *DEC is dead: Long live DEC–The lasting legacy of Digital Equipment Corporation*. San Francisco: Berrett-Koehler.

Selinger, Carl. 2004. *Stuff you don't learn in engineering school: Skills for success in the real world.* New York: Wiley.

Senge, Peter. 1990. *The fifth discipline: The art and practice of the learning organization.* New York: Doubleday.

———. 1993. The art and practice of the learning organization. In *The New Paradigm in Business: Emerging Strategies for Leadership and Organizational Change (A New Consciousness Reader)*, edited by Alan Rinzler and Michael Ray. Los Angeles: Tarcher.

Sheppard, Sheri, Anne Colby, Kelly Macatangay, and William Sullivan. 2005. What is engineering practice? Presented at 2005 Harvey Mudd Design Workshop.

Shina, S. G. 1991. New rules for world-class companies. Special Report on Concurrent Engineering, edited by A. Rosenblatt and G. F. Watson. *IEEE Spectrum* 28(7): 22–37.

Shulman, Lee S. 1998. Theory, Practice, and the Education of Professionals. *The Elementary School Journal,* Vol. 98, No. 5, pg. 511[\#208]526.

Shuman, Larry, J., Besterfield-Sacre, Mary, & McGourty, Jack. 2005. The ABET "Professional Skills" – Can They Be Taught? Can They Be Assessed? *Journal of Engineering Education. 94* (1), 41[\#208]56.

Sparks, E. and Waits, M.J. 2011. *Degrees for what jobs? Raising expectations for universities and colleges in a global economy.* National Governors Association.

Starfield, Anthony M. 1999. *Principles of modeling*. Unpublished workshop notes. Fort Collins, CO. May 17[\#208]24, 1999.

Starfield, Anthony M. 2005. *Heuristics or rules of thumb for modeling*. Personal communication. July 14, 2005.

Starfield, Anthony M., Karl A. Smith, and Andrew L. Bleloch. 1994. *How to model it: Problem solving for the computer age.* Edina, MN: Burgess.

Surowiecki, James. 2004. *The wisdom of crowds: Why the many are smarter than the few and how collective wisdom shapes business, economies, societies and nations*. New York: Doubleday.

Surowiecki, Jim. 1997. Decision Time. *Rogue missives.* January 6, 1997. http://www.fool.com/Rogue/1997/Rogue970106.htm (accessed 3/9/03).

Tribus, Myron. 1996. Total quality management in schools of business and engineering. In *Academic initiatives in total quality for higher education,* edited by Harry V. Roberts, 17–40. Milwaukee: ASQC Quality Press.

Van de Ven, Andrew H., Douglas E. Polley, Raghu Garud, and Sankaran Venkataraman. 1999. *The innovation journey.* Oxford: Oxford University Press.Bottom of Form

Washington University in St. Louis, *Thomas L. Friedman's Commencement address,* May 21, 2004, http://news-info.wustl.edu/news/page/normal/887.html (accessed 4/14/05).

Weisbord, Marvin R. 1987. *Productive workplaces: Organizing and managing for dignity, meaning, and community.* San Francisco: Jossey-

Bass. "Would you tell me, please, which way I ought to go *"Would you*