Chapter 2

The Joy of Engineering

2.1 A JOYOUS CONFESSION

I have a confession to make. I am an unabashed, card-carrying engineering *chauvinist*. I believe that engineering is a terrific education and that engineering practice can be a joyful way to spend one's life. In a technological age, engineers are constant, yet largely unsung, contributors to our quality of life, the creators of the systems, processes, and products that we depend upon day to day. Every time you step on or off a modern airplane, you literally owe your life to the hard work of teams of anonymous engineers. Every time you bang out a memo or essay on your laptop computer, you owe a hearty thanks to thousands of unheralded hardware and software engineers. Everyday you wake up, make breakfast, go to work and return, you trust your safety to the handiwork of myriad infrastructure engineers who safeguard the water you drink, the highways you drive, and the electric power grid into which you plug.

Yet our culture hardly gives these engineering contributions a second thought. TV celebrates lawyers, doctors, businessmen, politicians, and even forensic scientists, but engineers are merely the steady Freddies and Janes that build, operate, and maintain the stuff we use. Ironically, it is in this sense that engineering is a victim of its own success. We *can* depend on the airplanes, the computers, the software, and the infrastructure, so there is little to dramatize in prime time. If only we engineers, as a group of professionals, would mess up more often, perhaps the foibles of flawed engineering practice would be sufficiently dramatic for prime-time TV. Yet, it doesn't seem quite right to be so blasé about a discipline and a group of people who are arguably so important to modern society's day-to-day safety and success. Moreover, our culture's lack of attention to the artifacts and people of engineering causes it to misunderstand engineering education, engineering practice, and engineers themselves in important ways.

This chapter critically examines an engineer's place in the world. Although it may continue to be difficult to convince nonengineers of the importance of what engineers study and do, it is important for engineers themselves to have a better understanding of key historical, philosophical, and methodological foundations of their discipline and profession. We start by viewing an engineering

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The Entrepreneurial Engineer, by David E. Goldberg

education as a new kind of liberal education and as a practical career launchpad. Thereafter we consider the role of engineering and engineers in the establishment of modern business practice. This leads to the incorporation of some economics in a discussion of the methodology of engineering practice and a discussion of four intellectual tensions faced by the postmodern entrepreneurial engineer.

2.2 ENGINEERING AS LIBERAL EDUCATION, LAUNCHPAD, AND LIFELONG LOVE

Not long ago, engineering education and working as an engineer were viewed as reliable ways to get a leg up into the middle class. Today, engineering education is a launchpad for a variety of careers. Moreover, it is increasingly being viewed as a broad education appropriate to a time of increasing technological sophistication, and this breadth leads today's savvy engineering graduates to enjoy the fruits of their education and careers in a variety of ways. In this section, we analyze the breadth of an engineering education by comparing the requirements of an engineering degree with those of an English degree. We examine some of the different careers that an engineering education can launch, and we consider a number of ways in which engineering is an engaging field of study and work.

2.2.1 Who Is Getting a "Liberal Arts" Education Today?

The notion of a broad liberal arts education goes back to the Greeks and Romans and has been at the center of the modern secular university. Engineering education has a somewhat shorter history, but the perception that engineering education is extremely narrow by comparison misses several key points:

- The modern engineering curriculum is remarkably balanced and substantially in line with key elements of a classical "liberal education."
- The centroid of knowledge has shifted toward matters technical to the point where a classical liberal education with little math or science emphasis and no study of technological artifacts is no longer a broad basis for understanding the world around us.

The first point to make is that engineering education can be remarkably balanced. Consider the breakdown of the general engineering curriculum at the University of Illinois at Urbana–Champaign shown in Table 2.1. The first 3 rows in the table total to 79 hours or 60 percent of the total. Interestingly, those hours would satisfy core or distribution requirements in almost every liberal arts major. The 22 hours under mechanics and engineering science specialize math and science topics to engineering practice and treat topics that upper-level undergraduate majors in science or math would cover. Only the 30 hours in the major are truly specialized and could not fit under the liberal arts rubric. Thus, only 23 percent of the 131 hours can be thought of as truly specialized, and that number

Table 2.1 Breakdown of an Undergraduate Engineering Education

Category	Semester hours
Humanities and social science	25
Secondary field (tech or nontech) + electives	18
Math and science	36
Mechanics and engineering science	22
Major design and analysis specialization	30
Total	131

is comparable to the number of hours that a liberal arts student would take in his or her own major.

If we turn this around and examine the composition of the requirements of a typical liberal arts degree, for example, an English degree, we notice a number of things (Table 2.2). First compare the total hours. Using the University of Illinois again as an example, an English major can graduate with 11 fewer hours than the general engineering major. Engineering curricula commonly require roughly one-half to three-quarters of a semester more to graduate than a comparable liberal arts degree. In other words, some of the specialization of an engineering degree is paid for by working longer.

But a closer look at the distribution of hours is even more interesting. Required social science and humanities hours outside the major are comparable in the two degrees; however, the English degree requirement of only 9 hours of math or science is striking. It hardly seems reasonable that a broadly educated person in an age of rapid technological advance should be able to get a bachelors degree with only 9 hours, or 7.5 percent of the total hours in the degree, studying math or science. Can a person claim to be broadly educated with such a paltry number of hours in exactly those subjects that are advancing most quickly? No, the centroid of knowledge has shifted—and continues to shift—toward science and mathematics, and the "liberal arts" degree of times past does not—in and of

Table 2.2 Breakdown of an Undergraduate English Major

Category	Semester hours
Humanities and social science	24
Minor subjects	18–21
Math and science	9
Electives	36–39
English specialization	30
Total	120

itself—serve to broadly educate those who receive it. Add in the loosening of rigorous core distribution requirements and core courses that has taken place since the 1960s and 1970s, and it is not a stretch to argue that the kind of rigorous engineering degree such as that profiled above is a broader, more appropriate degree for educating well-rounded people in an increasingly technologically intensive world.

2.2.2 Engineering as Launchpad

In times past, an engineering degree was largely expected to prepare individuals for a professional career working as an engineer. Although many engineering graduates continue to find employment as working engineers, an engineering degree is also being viewed today as good preparation for other careers. Large numbers of engineering students apply to medical school, dental school, law school, and business school following their undergraduate engineering education.

Some older engineering faculty members find this trend disconcerting and wish for the good old days when engineering students graduated and worked as engineers. Yet the broader acceptance of engineering education—and values—by those who don't work as engineers can be viewed as a blessing. First, a more technologically educated populace will better appreciate technology and the challenges of its care and feeding. Moreover, medical and legal professionals as well as high-level managers are often influential members of a community, and having such people both knowledgeable in and sympathetic to engineering and technological matters should be beneficial. Finally, discussions of increasing engineering influence often lead to suggestions about having engineers lobby government, Hollywood, or the media. But perhaps the more powerful kind of influence occurs when engineering students take their engineering education and win seats in legislatures, earn positions in movie and TV production, or find positions as working journalists. None of this is to recommend those particular career paths for those who are not interested in them, but the key point is that an engineering education is a broad one that can prepare its recipients for careers across the spectrum of human endeavor.

2.2.3 Ten Ways to Love Engineering

When I ask engineering students to tell me why they decided to come to engineering school, some will talk to me about their hobbies or interests (cars, radios, computers, software) and their eyes light up, and I'm reasonably confident that I'm talking to someone who will make engineering school work for them. When students start talking to me about high school guidance counselors, good grades in math and science, or high pay from engineering jobs, I get a little nervous that I'm talking to someone who hasn't found something to love about engineering yet. Engineers use math and science and like to think of themselves as fairly rational beings, but the engineers who succeed longest and best are those who have found something to love about their chosen path.

Fortunately engineering is multifaceted and we can find joy in engineering because it is

1. Creative
2. Intellectually stimulating and challenging
3. Concerned with the real world
4. Constructive
5. A people profession
6. A maverick's profession
7. Global
8. Entrepreneurial
9. Optimistic
10. An entry point to lifelong learning

First and foremost, ours is a creative profession. As engineers we create that which has never before existed, through a combination of imagination, ingenuity, and perseverance. We therefore have many opportunities to become engaged in the creative processes of idea generation and problem solving. This stands in stark contrast to those professions that train their practitioners largely to become proficient in extant technology and technique.

Engineering is also intellectually stimulating and challenging. Being a good engineer requires much knowledge and know-how, but no armchair intellectuals need apply. Ours is a profession that requires streetwise application of mind to means, where the touchstone of success is whether the job gets done.

This leads us to recognize that engineering is firmly rooted in the real world. This has a number of benefits. It forces us to face up to the limitations in our modeling, and it forces us to confront difficult variables that defy analysis—variables such as time, money, consumer preferences, the impact of government, and the impact of technology on society.

Moreover, engineering is an inherently constructive profession, attempting to make a better world through change. Contrast this to some other professions that add costs and paperwork to many transactions without adding direct value to the processes involved or products produced. Engineers often find great pleasure in being able to touch or see the results of their labors, taking great pride in their contribution to a completed product or project.

Ours is a people profession as engineers often work in teams. As marketing, manufacturing, and engineering considerations are integrated into the design process, engineers increasingly find themselves working on teams with many different types of individuals across a company. Of course, we've devoted a good bit of space in this book to emphasizing the habits necessary for good interpersonal relations, whatever the circumstances; but the engineer who is skilled in his or her dealings with others will also find many opportunities for engagement therein.

At the same time that engineering requires team effort, it can also call for outstanding individual effort. Many of the most creative and advanced engineering projects have required a champion to almost single-handedly overcome obstacles and single-mindedly bring an idea to fruition. Thus ours is a profession that finds a place for the engaged maverick at the same time it embraces the team and its players.

Our world has become a very small place. Jet travel allows us to become physically present almost anywhere in the world in less than a day. Satellites, fiber optics, and advanced computing allow us to become virtually present almost anywhere in the world in milliseconds. Such changes are making engineering a more global profession, where products are designed and built across borders, even across oceans. This situation creates opportunities for the engineer who is willing to learn other languages, customs, and cultures.

Some of the same technological influences that make engineering a more global profession are opening up new entrepreneurial opportunities. Engineering has had a long tradition of private practice and private enterprise, but the tumult in such fields as modern electronics, information technology, biotechnology, and nanotechnology has opened new vistas for the engineer-entrepreneur. As communications technology makes close ties at a distance a reality, more and more engineering functions will be farmed out to independent design shops at remote locations. At the same time, the tools of our trade have dropped in price; the small shop need be at little or no competitive disadvantage to the in-house engineering operation of a Fortune 500 firm. Moreover, miniaturization, machine-tool, and materials-handling technology is driving manufacturing toward point of sale. As we move in such directions, it should be clear that a company's competitive advantage will lie more in its intellectual property—in its designs—and less in its manufacturing and distribution capability. Although the present has been kind to the entrepreneur-engineer, the future holds many engaging opportunities for those with the enterprising spirit.

It almost goes without saying that ours is an optimistic profession. Our impulse as builders is reinforced by the knowledge that we have improved what was once a very hard life and the hope that our continued efforts can make things even better. Sometimes we have paid insufficient attention to the unintended consequences of our acts, but the genie of innovation prefers freedom to the confinement of the bottle, and once free he has largely served his masters well.

Finally, as pointed our earlier, even for those who get an engineering degree but choose not to practice as engineers, engineering education positions its recipients for lifelong learning and growing. Given the conversance with mathematics, science, technology, the humanities, and the social sciences required in a Bachelor's degree in engineering, those with an engineering education can pick up texts in almost any subject and learn. The broadly educated engineer of today is thus better positioned for lifelong learning and growth than those who have not struggled with the artifacts, knowledge, language, or details of technology.

Thus, the ways to find fulfillment through engineering are many, but the very breadth of the engineer's purview gives rise to a fundamental tension inherent in both learning and practicing engineering. This tug-of-war is our next concern.

2.3 THE FUNDAMENTAL TUG-OF-WAR

Engineering is an old and venerable practice, but in modern times engineers oftentimes find themselves in something of a professional vise. On the one hand, they find their work lives ruled by managers, accountants, and other business school graduates. On the other, they find their profession itself criticized by scientists and mathematicians as being the *mere* application of science and math to problems of practical import. Since its inception as a modern profession, engineering has been a combination of commerce and science (Layton, 1990). But the vise hold of these two disciplines undervalues the creativity of engineering analysis and design (Vincenti, 1990), and it misjudges the delicacy of the hybrid of analytical and interpersonal talents engineers must master to be successful in practice. Moreover, the squeeze play hides the historical record of engineering's role in the formation of both science and engineering.

We start by considering two historical inversions—one between science and engineering and one between business and engineering—that have permitted engineering, the field that arguably has historical priority in both cases, to be caught in the middle, both commercially and intellectually. We distinguish between the commercial and scientific aspects of the engineering mind using an economic model of the modeling process, and consider the spectrum of models from qualitative and quantitative implied by the economic model. This in turn leads to a discussion of four tensions facing the entrepreneurial engineer.

2.4 SCIENCE AND ITS LITTLE SECRET

I once was having a discussion with a colleague in physics from a major research university at a meeting sponsored by the National Academy of Science. He offered his opinion that engineering is "just applied science, nothing more, nothing less," and this sounds plausible enough to modern—even engineering—ears. Today's engineering education dwells on math and science first, and engineering subjects are taught as practical elaboration or embellishment of those more primary subjects. It wasn't always this way. If we return to the origins of modern science itself, we understand how the engineers of that time were inspiration for the remaking of the enterprise we now recognize as science. In particular, we review how the man often called "the father of modern science," Sir Francis Bacon, used 17th-century engineering practice as inspiration for his reformulation of the scientific method (Figure 2.1).

At the time, natural philosophy was stuck, and Bacon tackled the problem in his book *The Great Instauration.* His first task was to acknowledge the problem (Bacon, 1620/1994, p. 6):

Figure 2.1 Francis Bacon (1561–1626) (reproduced with permission of Maxwell C. Goldberg).

> *That the state of knowledge is not prosperous nor greatly advancing; and that a way must be opened for the human understanding entirely different from any hitherto known ... in order that the mind may exercise over the nature of things the authority which properly belongs to it.*

Interestingly, Bacon's motivation was in large part that of the engineer. The need for better science was so "the mind may exercise over the nature of things the authority which properly belongs to it."

His next job was to analyze why knowledge was not advancing as fast as it might. He laid blame at the feet of the vast majority of philosophers of his time who blindly believed in the ancient dictates of Aristotelian physics (p. 7):

> *Observe also, that if sciences of this kind had any life in them, that could never have come to pass which has been the case now for many ages—that they stand almost at a stay ... and all the tradition and succession of schools is still a succession of masters and scholars, not of inventors and those who bring to further perfection the things invented.*

Not only did Bacon question continued blind allegiance to the masters of the ideas of Greece, he foreshadowed his solution for recasting science with his curious choice of the words *inventors* and *things invented*. This led readily to a call for recasting the methods of philosophy along the lines of 16- and 17-century engineering practice (pp. 7–8):

> *In the mechanical arts we do not find it so: they, on the contrary, as having in them some breath of life, are continually growing and becoming more perfect. As originally invented they are commonly rude, clumsy, and shapeless; afterwards they acquire new powers and more commodious arrangements and constructions; . . . Philosophy and the intellectual sciences, on the contrary, stand like statues.*

Bacon lived during a time of increased technological improvement. For him, the contrast of rapid technological evolution with the dearth of progress in knowledge was almost unbearable. Moreover, his solution to this critical problem was clear. Philosophy must adopt the attitudes and methods of the "mechanical arts" in the invention of concepts. Quite clearly, in Bacon's time, engineering was not merely "applied science." Far from it. Bacon's grand plan for recasting science, systematizing scientific method, and advancing the state of knowledge was inspired directly by the application of engineering method to the invention of new concepts!

Thus, it is more than a little interesting that engineering, arguably the master discipline that showed the way out of the dead end of Aristotelian physics, has become subservient to the sciences it inspired. Indeed it is entirely proper that modern science should help drive the advance of modern engineering just as modern engineering helps drive the advance of modern science. But there is no historical basis for an engineering inferiority complex (physics envy) or related maladies of modern times. If anything, to those scientists who would say that engineering is the "mere application of science" it is entirely historically accurate—if equally haughty—to reply that science is the mere application of engineering method to the invention of concepts.

2.5 ENGINEERS: FIRST MASTERS OF MODERN ENTERPRISE

Bacon used the mechanical arts (engineering) to inspire the reformulation of natural philosophy, but modern memories are short and tend to think of science as the master discipline. An analogous historical inversion has occurred in business. In business today, enterprise is run by a professional class of trained managers, and engineers are viewed merely as one instrument of a larger capitalist enterprise. It wasn't always this way.

Prior to the 1850s, business was performed on a relatively small scale. What large-scale businesses there were could be organized along fairly decentralized lines, thereby requiring methods that were no more complex or coordinated than those of smaller enterprises. All that changed with the coming of the railroads (Chandler, 1977, p. 80):

> *Of the new forms of transportation the railroads were the most numerous, their activities the most complex, and their influence the most pervasive. They were the pioneers in the management of modern business enterprise.*

Because of their historical importance, Chandler is careful to identify these pioneers of modern business (p. 87):

> *The men who managed these enterprises became the first group of modern business administrators in the United States …*

To a man, they were engineers (p. 95):

> *The men who face these challenges were a new type of businessman. … The pioneers of modern management … were all trained civil engineers with experience in railroad construction and bridge building before they took over the management of the roads.*

Many of these same people had military training, and Chandler wondered whether the new business methods they developed were borrowed from the management of men and material in the military. Chandler rejects this hypothesis emphatically (p. 95):

> *Yet even for such officers, engineering training was probably more important than an acquaintance with bureaucratic procedures. There is little evidence that railroad managers copied military procedures. Instead all evidence indicates that their answers came in response to immediate and pressing operational problems requiring the organization of men and machinery. They responded in much the same rational, analytical way as the solved mechanical problems of building a bridge or laying down a railroad.*

Thus, in the early days of modern enterprise, engineers were the innovators who developed the methods—the profession—of modern business. As with the scientific inversion, here there is no historical basis for "business envy" or a "nerd inferiority complex." The businessperson who says that engineering is "mere technology applied to the needs of business" could more accurately be told that modern business is merely the application of engineering method to the design of commerce.

2.6 ECONOMY OF INTELLECTION: SEPARATING SCIENCE FROM ENGINEERING

Historical analysis helps shed some light on the professional vise grip engineers find themselves in, but modeling how engineers are different from scientists and businessmen is a more difficult matter. Here we distinguish engineers from scientists in terms of their *use of models* through an argument based on an *economy of intellection* (Goldberg, 2002).

Scientists and engineers both build and use models of physical phenomena—often mathematical models—but the motives and economics behind their model usage are distinct. Engineers create and use models to advance technology, whereas scientists primarily build ever more accurate models of observed phenomena.

2.6.1 Modeling Plane

All of these models live on a plane of error and cost (Figure 2.2). Engineers and inventors use models of relatively high error and low cost, whereas scientists and mathematicians build and use models of relatively low error and high cost. All this makes sense when viewed in the light of the distinct objectives of engineers and scientists. Scientists are in the business of reducing the error of current best models and should be expected to spend most of their time at the high C, low ε portion of the curve, pushing for lower and lower ε regardless the C.

The engineer's position is a little harder to understand and justify, but straightforward principles of economics come to the rescue. Imagine an engineer faced with the prospects of going from a model of error ε_1 to one of ε_2. The move incurs a marginal cost $\Delta C = C_1 - C_2$, but unlike the scientist, the engineer is generally not in the business of building better models for their own sake. No, the engineer is usually charged with improving some *technology*—some product, service, or process—and ostensibly the use of an improved model should yield some *benefit* to the technology of interest. In mathematical terms, there should be some marginal benefit, $\Delta B = \Delta B(\varepsilon_1, \varepsilon_2)$ to the technology that results from the use of a more accurate model. In practical terms, this benefit can come from better qualitative or quantitative understanding of the mechanisms underlying the technology, but for the engineer to justify the use of a higher cost model, some improvement should be expected. Moreover, if the benefit can be stated in monetary terms, the engineer can be said to be engaging in *economic* model

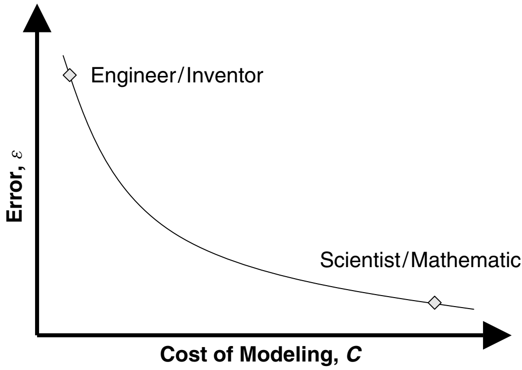

Figure 2.2 Models live on a plane of error and cost. Engineers generally use lower cost, higher error models to benefit some object technology. Scientists and mathematicians are usually more interested in the creation of new models. [Adapted with permission from Goldberg (2002).]

selection if the marginal benefit of the model to the technology equals or exceeds the marginal cost of the improved model:

$$\Delta B \geq \Delta C \tag{2.1}$$

If the engineer chooses the more expensive model when the above condition does not hold, the decision is said to be *uneconomic*, and at least some amount of the improved accuracy of the model is wasted.

Of course, none of the foregoing discussion should be taken to suggest that engineers actually perform the formal cost–benefit analysis as part of their modeling usage. The costs of modeling are not often explicitly calculated, and even if they were, the benefits of modeling are difficult to quantify and usually unknown in advance of the engineering design effort. Nonetheless, modern engineering education implicitly recognizes economy of thought in the engineering curriculum. For example, where physics courses teach Newton's second law first ($\Sigma F = ma$), the engineering curriculum teaches statics ($\Sigma F = 0$) before the second law. Spending a full semester on tedious equilibrium problems seems like a waste of time and effort to most physics professors, but by doing so, the engineering curriculum drives home the important lesson of *grabbing the cheaper model first.* Engineering in this sense is distinct from science, and the use of less precise models in the engineering process is economically essential; to do otherwise would be foolhardy, irrational, or both. Interestingly, the respect for economics that separates engineer from scientist is exactly what ties engineer to businessperson.

2.6.2 Spectrum of Models

Cost–error analysis of models suggests a one-dimensional spectrum of models from fairly high-error (low-cost) models to low-error (high-cost) models as shown in Figure 2.3. On the far left, we have wisdom that is known but difficult to articulate (unarticulated wisdom or tacit knowledge). Moving to the right we have qualitative knowledge articulated in words; much business knowledge is of this sort as is knowledge of history and many of the humanities. On the far right we have equations of motion that specify the trajectory of a dynamic system in some reasonably complete manner, and to the left we have so-called *facetwise models* (Goldberg, 2002) in which various simplifications are made to equations of motion or their solution to obtain a model of a single facet of a more complex motion system. In the middle of the spectrum we have the entry point into quantitative modeling using dimensional analysis and scaling laws.

At any given point in one's work life, engineers will be called on to use a combination of tacit knowledge, articulated qualitative knowledge, dimensional reasoning, facetwise models, and full equations of motion. Although the agility and breadth of modeling skill required is difficult to learn, it is essential that it be mastered.

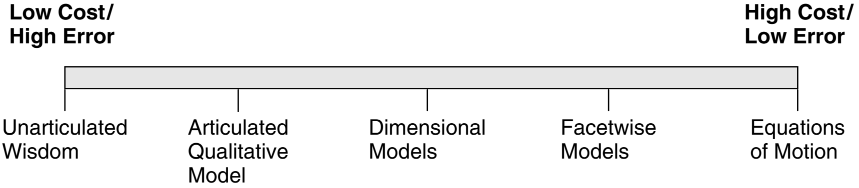

Figure 2.3 Spectrum of models goes from tacit knowledge (unarticulated wisdom) to full equations of motion. In between, qualitative and quantitative models of various degrees exist and should be mastered by competent entrepreneurial engineers. [Adapted with permission from Goldberg (2002).]

2.7 FOUR TENSIONS FACING THE ENTREPRENEURIAL ENGINEER

The modeling plane and the spectrum of models highlights a critical tension in engineering knowledge, the tension between qualitative and quantitative knowledge. Yet, the entrepreneurial engineer faces this and three other key tensions in trying to reconcile the demands of a fast-paced life driven by technology and markets:

- Qualitative versus quantitative mode of analysis
- Human-centered versus technology-centered focal point
- Centralized versus decentralized locus of control
- Mature versus immature knowledge

Each of these is briefly discussed:

Qualitative vs. Quantitative Engineers have a cultural predisposition to speak equations and generally go quantitative, but much business knowledge is qualitative in nature. Entrepreneurial engineers need to appreciate that many topics are well handled with words rather than equations. A good way to plug into this mode of thought is to (a) read a business newspaper on a regular basis (e.g., *The Wall Street Journal*), (b) read business case studies (e.g., from the Harvard Business School), (c) read popular business books and business textbooks, and (d) read more fiction and nonfiction generally. Entrepreneurial engineers must embrace the qualitative side of their brains at the same time they attempt to go quantitative on subjects that have previously defied analytical description.

Humans vs. Technology Another tension faced by the entrepreneurial engineer is the tension between a concern for humans and a concern for technology. Many engineers come to engineering because of their love for gizmos. I confess that I came to the profession as a card-carrying amateur radio operator who loved the smell of solder and the sound of a DX (long-distance) contact with hams (amateur radio operators) far away. Having said this, the entrepreneurial engineer lives in a world of customers, co-workers, investors, and other people, and it is important to understand that notions of truth in a technological setting are somewhat different for those of a social setting. The term *postmodernism* as used in its philosophical sense embraces notions of truth that depend on the influence of populations of people. Of course, extreme accounts that deny truth in science are untenable to scientists and engineers. Searle's account (1995) embraces science (brute facts) and social or institutional facts quite nicely and should be consulted by those seeking a useful foundation for both better understanding social and scientific knowledge. At a more practical level, human–technological conflicts will usually manifest themselves as economic or political concerns.

Centralized vs. Emergent The Cold War engineer was an inveterate planner, working as part of a large team at the core of a single organization to bring a technical artifact to fruition. On the other hand, the entrepreneurial engineer sees his or her activity within an organization as part of a larger system, an economy, in which planning is not always the rule. Economies are themselves a messy mix of the planned and the unplanned. Markets, on the one hand, emphasize the uncoordinated emergence of competitors and commerce, while at the level of organizations, planning and centralization are the key. Current results in nonlinear, complex adaptive systems, and networks are helping scientists and engineers better understand that portion of our world that is uncoordinated, but that understanding is not yet as mature as our understanding of the world of centralized control.

Mature vs. Immature Knowledge Entrepreneurial engineers live in a world where knowledge is required from both mature and immature disciplines. New technology oftentimes lives on the boundaries of different disciplines or the edge of the newly discovered. Either way this suggests that much of what is needed will come from immature disciplines. This would not seem to be much of a problem, except that mature disciplines have an inherent advantage over immature ones and tend to crowd out the new kids on the block. Mature disciplines are those where long years, decades, or centuries have given many researchers and pedagogues the ability to refine both knowledge and teaching sequences to the *n*th degree. On the other hand, the state of knowledge in immature disciplines will often be less than tidy. Methodology may be inconsistent, key questions may remain unanswered, and teaching may be poorly sequenced or spotty in coverage. Nonetheless, the entrepreneurial engineer must learn to use immature knowledge in areas of importance side by side with knowledge from old and venerable disciplines. Learning to embrace the new and the old together is challenging, but to prefer one over the other is needlessly limiting to the scope of an entrepreneurial engineer's range of influence.

SUMMARY

Engineering can be a joyful occupation, and this chapter started by examining how an engineering education is balanced, broad, and able to launch a variety of careers. This led to a discussion of 10 different ways to love engineering, ranging from finding joy in engineering as a creative and intellectually stimulating endeavor to understanding how engineering can be entrepreneurial, optimistic, and global. Because engineering is a blend of the technical and commercial, engineers often find themselves in a tug-of-war between science and commerce, and this chapter has tried to understand the engineer's position with respect to those two poles of the engineer's mind through historical analysis. Interestingly, the analysis turns conventional wisdom on its head, and engineering may be viewed as inspiration for both modern science and modern business in a historically rigorous sense.

The chapter has also attempted to bridge the gap between the scientific and commercial poles of engineering thought through an economic model of the modeling process. Although such modeling is rarely formal, engineers tacitly consider the marginal costs and benefits of the mathematical and scientific models they can apply to the development of a new technology. Balancing model rigor and cost in this way helps ensure that the costs of technological advance are well tied to the utility of the technology being advanced. Science is largely about building better models, and it is not surprising that the activity is less conscious of modeling costs. Of course, both kinds of activities are necessary, and both types of individual are doing the kind and style of work necessary to get their respective jobs done. This reasoning has also led to consider the spectrum of models from tacit knowledge to full equations of motion. The entrepreneurial engineer is advised to embrace appropriate models toward advancing opportunities in his or her enterprise.

The chapter has also considered four core tensions in the world of the entrepreneurial engineer. The tensions between qualitative and quantitative knowledge, between humans and technology, between centralized planning and emergence, and between mature and immature knowledge must be understood, then embraced. The very complexity of the world of entrepreneurial engineering demands an approach that is appropriately complex. The narrow disciplinary focus of the Cold War engineer with rigid ideas of methodology and content is unlikely to cast a broad enough net. The challenges of becoming a competent entrepreneurial engineer are great, but the rewards are commensurate to the challenge.

EXERCISES

1. Interview one or more working engineers at a large corporation and discuss with them the material of this chapter. Ask them to recall specific instances of experiencing the tug-of-war and how they dealt with it. Reflect on whether a different approach might have diffused the tension. Write a short essay discussing the interview and your reflections.
2. Consider your own dealings with business majors in college or at work. Recall whether you have experienced the historical inversion discussed. Would you now deal with such encounters differently and how so? Write a short essay discussing your recollections and reflections.
3. Consider your own dealings with mathematics or science majors in college or at work. Recall whether you have experienced the historical inversion discussed. Would you now deal with such encounters differently and how so? Write a short essay discussing your recollections and reflections.
4. Statisticians recommend that experiments be performed repeatedly to ensure that the results when averaged are statistically valid. Engineers might not always have the time or money to perform sufficient testing to satisfy the statistician's tests of statistical significance. Consider in a short essay whether it might ever be acceptable to perform

incomplete testing and relate your argument to the argument about the cost and benefits of engineering modeling.

5. In your technical specialty, give two specific examples each for (a) tacit or unarticulated knowledge, (b) qualitative articulated knowledge, (c) dimensional reasoning, (d) facetwise models, and (e) equations of motion.
6. The separation between qualitative and quantitative knowledge is not always as great as has been suggested. Give an example where qualitative reasoning and quantitative reasoning have interacted in classroom studies or work experience.
7. Read a text in an emerging scientific or engineering discipline. Characterize the ways in which the knowledge is less mature than that in longstanding fields in a short essay.
8. Modern market economies are a mix of planning and emergence, whereas communist regimes attempted to replace markets with centralized planning by the government. Write a short essay in which you consider (a) the proper balance between centralization and emergence and (b) an intellectual justification for drawing that line.
9. The modeling plane suggests that there is a marginal cost–benefit justification for the selection of a given model. Make a list of five benefits that could occur by using a more accurate model in practice. Make a list of five costs that could occur that would recommend the use of a less costly model in practice.