1

Introduction to Discovering Engineering

1.1 INTRODUCTION

You are beginning an exploration of engineering that will continue throughout your life. This chapter will explore the ways that this journey may begin. In Section 1.2, you will be asked to examine your own motivation for becoming an engineer. In Section 1.3, some surprising advice on how to discover engineering is shared. In Section 1.4, the clock is turned back 175 years to show how history affects your engineering education.

1.2 WELCOME TO ENGINEERING

In some ways, it is amazing that you found engineering in the first place. Most people select careers and academic programs based on their high school experiences. You probably took math and science classes in high school, perhaps even some technology classes. However, you probably did not take *engineering* classes in high school.

Some of your high school friends may be comfortable with their exposure to chemistry or French or English literature in secondary school. They may be looking forward to majoring in one of those fields in college. Although their college experiences will challenge and extend them, your friends probably have a pretty good idea what to expect in college based on their high school experiences.

You may be a little envious. After all, you took a chance on a field that is a little less familiar to you. Your motivation for doing so is unique to you.

SECTIONS

OBJECTIVES

After reading this chapter, you will be able to:

- identify why people choose engineering as a career;
- find engineers to speak with about engineering;
- list what you should expect in your engineering education.

PONDER THIS

What is *your* motivation for becoming an engineer?

Key idea: Engineering is the right place for people who have curiosity, a strong work ethic, a desire to help other people, and a deep respect for math and science.

Many students pursue a degree in engineering because they performed well in math and science classes in high school. Some engineering students have relatives who are engineers. Some pursue engineering because the job opportunities and salaries for recent engineering graduates are pretty good. Whatever your motivation, you are taking a small leap of faith in entering a profession that may seem a mystery to you right now. Have no fear: if you have curiosity, a strong work ethic, a desire to help other people, and a deep respect for math and science, then you have found a home in engineering. For a few stories about why working engineers chose engineering, see *Focus on Choosing Engineering: So Why Did You Become an Engineer?*

FOCUS ON CHOOSING ENGINEERING: SO WHY DID YOU BECOME AN ENGINEER?

Every engineer has a unique answer to the question: Why did you choose engineering? Compare your motivation for becoming an engineer with the following stories from practicing engineers.

Helping People

My long-term goal has been to work for and with people, that's why I became an engineer. I like helping people, and that's why I want to use my talents to better other people's lives. This project is exactly the kind of thing I want to do with the rest of my life.

—*From a Northwestern University senior, commenting on her involvement in a project to build a toy car for disabled children* (http://www.asme.org/mechanicaladvantage/fall98/CHILD'SPLAYCARPAGE.HTM)

Problem Solving

When the tragic Challenger disaster occurred in 1986, I found myself not only touched by the loss, but also driven to understand why, and motivated to ensure such a tragedy did not happen again.

—*From a Lockheed Martin mechanical engineer* (http://www.lmaeronautics.com.about/eweek/why)

Math and Science

I always liked science and math anyway, so the idea of working in a profession where one can apply the laws of nature for the benefit of mankind was very inspiring.

—*From a civil engineer working at the Philadelphia District of the U.S. Army Corps of Engineers* (*District Observer ONLINE*, Jan–Feb 2000)

Curiosity

Growing up on a 200-acre cotton farm in middle Georgia, I became fascinated and elated with the mechanical equipment that was becoming available to do work on the farm.

—*From another Lockheed Martin mechanical engineer* (http://www.lmaeronautics.com/about/eweek/why)

Impact

One of the reasons why I became an engineer is because I believe engineering is a profession that allows you to predict the future. As I tell my students, "... (Y)ou can use (the laws of physics) to predict how something ... should work. Then, you can ... build that something and test it. If it works the way you thought it should, then you effectively forecast the future."

—*From Dr. James Meindl, electrical engineering professor at the Georgia Institute of Technology* (*Georgia Tech Alumni Magazine Online*, Vol. 72, No. 1, Summer 1995)

1.3 HOW TO DISCOVER ENGINEERING

Key idea: Discover engineering by talking to engineers.

So how do you learn more about the engineering profession? First, *put down this book.* No words on the page can help you realize the richness and satisfaction of your career. No book can bring alive the dramatic and compelling history of engineering, where two steps forward are invariably followed by one step backward. And no mere textbook can do justice to the triumphs, diversity, and human stories of the engineers themselves.

Textbook authors usually do not tell you to stop reading their text. But engineering is not about textbooks. It is about people: people who learn, people who translate ideas into reality, people who solve problems, people who communicate their ideas to others, and people who behave responsibly. To truly discover engineering, you must talk to engineers. But how do you find them?

PONDER THIS

How can you find engineers to speak with about engineering?

Key idea: Learn more about your future career by finding engineers at a university.

The best place to find engineers is at your university. Almost all engineering faculty are trained engineers,[°] and many have work experience outside of the university. Find a faculty member to help you understand the profession. Many universities have freshman mentoring programs, where freshmen are assigned faculty mentors or advisors. If your school does not have such a program, read the departmental brochures or Internet information and find a professor in an area that interests you. Call him or her for an appointment. Be persistent: the faculty are as busy as you are.

Engineering societies are another great source of information about this practice. These societies are professional organizations; some societies are general in scope, while others focus on a specific discipline. The major discipline-specific engineering societies are listed in Table 1.1. Other discipline-specific organizations are listed in Table 1.2. Table 1.3 lists the main engineering societies that are not associated with a specific engineering field. In Table 1.4, engineering societies focused on increasing the diversity of engineers are shown. For more information about any of these organizations, search on the Internet. For a story about historical diversity in engineering, see *Focus on Diversity in Engineering: The Real McCoy?*

TABLE 1.1 Major Discipline-Specific Engineering Societies

Name	Date Started	Number of Members
American Institute of Chemical Engineers (AIChE)	1908	58,000
American Society of Civil Engineers (ASCE)	1852	120,000
American Society of Mechanical Engineers (ASME)	1880	125,000
Institute of Electrical and Electronics Engineers (IEEE)[a]	1884	330,000
Institute of Industrial Engineers (IIE)	1948	24,000

[a] The American Institute of Electrical Engineers (founded in 1884) and the Institute of Radio Engineers merged in 1962 to form IEEE.

[°] You must be a registered professional engineer to use the title "professional engineer." Almost all engineering faculty have received training as engineers, but not all faculty are registered professional engineers.

TABLE 1.2 Other Discipline-Specific Engineering Societies

Name	Discipline[a]
American Academy of Environmental Engineers (AAEE)	civil
American Ceramic Society (ACerS)	several
American Institute for Medical and Biological Engineering (AIMBE)	several
American Institute of Aeronautics and Astronautics (AIAA)	mechanical
American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME)	several
American Nuclear Society (ANS)	several
American Public Works Association (APWA)	civil
American Society for Quality (ASQ)	industrial
American Society of Agricultural Engineers (ASAE)	civil
American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE)	mechanical
American Society of Naval Engineers (ASNE)	several
American Society of Safety Engineers (ASSE)	several
Associated General Contractors of America (AGC)	civil
Association for Facilities Engineering (AFE)	industrial
Biomedical Engineering Society (BMES)	several
Human Factors and Ergonomics Society (HFES)	industrial
National Association of Power Engineers (NAPE)	several
Society of American Military Engineers (SAME)	several
Society of Automotive Engineers (SAE)	mechanical
Society of Fire Protection Engineers (SFPE)	several
Society of Manufacturing Engineers (SME)	several
Society of Petroleum Engineers (SPE)	chemical
Society of Plastics Engineers (SPE)	chemical
SPIE—The International Society for Optical Engineering[b]	several

[a] "Discipline" refers to the major engineering area(s) (chemical, civil, electrical, industrial, and mechanical engineering) targeted by the society.

[b] Originally, this was the Society of Photo-Optical Instrumentation Engineers.

TABLE 1.3 General Engineering Societies

Name	Date Founded
American Association of Engineering Societies (AAES)	1979
American Consulting Engineers Council (ACEC)	1910
American Society of Engineering Education (ASEE)	1893
Junior Engineering Technical Society (JETS)	1957[a]
National Council of Examiners for Engineering/Surveying (NCEES)	1920
National Society of Professional Engineers (NSPE)	1934
Tau Beta Pi[b] (TBΠ)	1885

[a] JETS was established in 1950 and incorporated in 1957.

[b] Tau Beta Pi is the national engineering honor society. Several disciplines have their own national honor societies (e.g., Sigma Gamma Tau for aerospace engineering and Eta Kappa Nu for electrical engineering).

TABLE 1.4 Engineering Societies Focused on Diversity in Engineering

Name	Date Founded
American Indian Science and Engineering Societies (AISES)	1977
Mexican American Engineers and Scientists (MAES)	1974
National Action Council for Minorities in Engineering (NACME)	1974
National Society of Black Engineers (NSBE)	1976
National Organization of Gay and Lesbian Scientists and Technical Professionals (NOGLSTP)	1983
Society of Hispanic Professional Engineers (SHPE)	1974
Society of Woman Engineers (SWE)	1950

student chapter: a student-run organization or club associated with a national society.

The easiest way to meet engineers in professional societies is through student chapters. A ***student chapter*** is a student-run organization affiliated with a national society. Student chapters of engineering societies typically have a faculty advisor and a practicing engineer who serves as a liaison to the parent society. Most of the organizations listed in Tables 1.1 through 1.4 have student chapters. The student chapters may invite practicing engineers to share their experiences with students. Look for opportunities to speak with the presenters.

Another way to learn from engineers in professional societies is through participation in National Engineers Week. National Engineers Week was established by the National Society of Professional Engineers in 1951 to increase public awareness of the profession. It is held each year during the week of George Washington's birthday (February 22) to acknowledge Washington's contributions as a surveyor. The local activities during National Engineers Week will provide a great opportunity to learn from professional engineers.

Key idea: To learn more, speak with professionals at engineering firms or engineering departments.

Finally, practicing engineers are a wonderful source of information. Many offices, departments of large companies, and government departments offer office tours and internship programs. Summer jobs and co-op programs provide good opportunities to ask questions. The telephone book and Internet are useful guides to engineering practice in your area. In addition, ask the career planning staff at your university to help locate practicing engineers who have volunteered to act as student mentors.

1.4 ENGINEERING EDUCATION: WHAT YOU SHOULD EXPECT

For many engineers, the discovery of engineering begins with their college years. To see what is in store for you as you begin your engineering education, it is instructive to look back in time. Engineering education has a long history in the United States. Engineering education, as with engineering itself, began with military applications.

In the United States, the first formal training program for engineers began in 1794, when Congress added the rank of cadet to the Corps of Artillerists and Engineers. The Corps was assigned to the garrison at West Point. A four-year degree program began at West Point in 1817, under the direction of Sylvanus Thayer (1785–1872). Civilian education in engineering began in 1820 at the American Literary, Scientific, and Military Academy (now Norwich University) in Norwich, Vermont, under the guidance of Alden Partridge (1785–1854).

The work of Thayer and Partridge expanded the traditional university curriculum to educate soldiers and citizen-soldiers about the applied sciences. A different approach was developed by Amos Eaton and Stephen Van Rensselaer. In 1824, they founded the Rensselaer School (now called Rensselaer Polytechnic Institute in Troy, New York) to "teach the application of science to the common purposes of life" (Griggs, 1997).

FOCUS ON DIVERSITY IN ENGINEERING: THE REAL MCCOY?

BACKGROUND

Engineering has made great strides in becoming more diverse and increasing the participation of previously underrepresented groups. Few people realize that one of the most productive engineers of the post–Civil War era was African-American. Elijah McCoy was born in Colchester, Ontario, on May 2, 1844. McCoy's parents were former slaves who fled from Kentucky before the outbreak of the Civil War. (In fact, McCoy's wife was born in 1846 at an Underground Railway station.) After receiving training as a mechanical engineer in Scotland, McCoy moved to Detroit and obtained a job as a fireman on the Michigan Central Railroad.

THE PROBLEM AND ITS SOLUTION

In his job, McCoy became aware of a problem that plagued the railroads and other industries that relied on steam engines. Steam engines required lubrication, which, in the mid-19th century, was usually accomplished by hand. Hand lubrication meant that the machinery had to be turned off or idled to be oiled. McCoy realized that a well-designed automatic lubricator would solve the problem and allow equipment to be run continuously.

McCoy's solution was to improve the hydrostatic lubricator based on a drip cup. In a steam engine, steam from the boiler fills the cylinder and pushes the piston back. In the McCoy lubricator, a small portion of the steam was used to pressurize the lubricator body containing the oil. The pressurized oil drips continuously into the cylinder, thus lubricating the cylinder and piston. The steam condenses into water inside the lubricator body and the oil floats on top. Eventually, the water drains off and the oil is replenished.

The device was patented in 1872. With McCoy's improved lubricator, the continuous operation of steam engines was easier and the transcontinental railroad (completed in 1869) was exploited.

MCCOY'S CONTRIBUTIONS

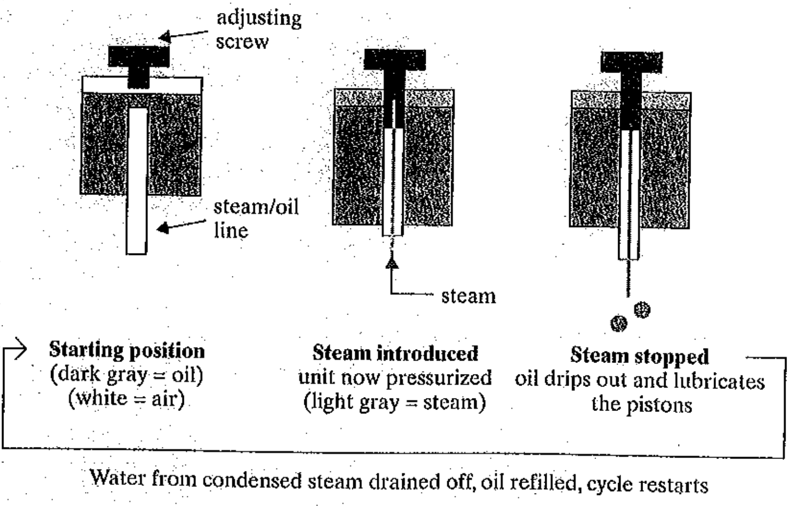
Elijah McCoy's contributions to lubrication have been exaggerated by some historians and underemphasized by others. While McCoy did not invent the hydrostatic lubricator, he contributed significantly to its optimization and usage. In fact, McCoy's original patent was titled "*Improvement* in Lubricators for Steam-Engines" (emphasis added). Elijah McCoy was a prolific inventor. He was eventually responsible for 57 patents, most involving lubrication equipment. One of his greatest contributions to the field was the graphite lubricator. By suspending graphite in oil, McCoy developed a device to lubricate the then-emerging superheated steam engines.

As with many inventors, McCoy had to assign a number of his patents to investors in his companies. As a result, he did not reap great financial benefits from his inventions. McCoy died at age 85 and was inducted into the National Inventors Hall of Fame in 2001.

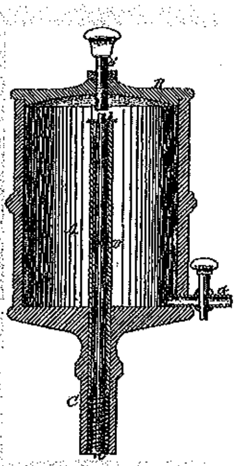
IS HE THE "REAL MCCOY"?

The story goes that McCoy's device was prized for its performance, even above the many other automatic lubrication devices that were patented later. Engineers were purported to have asked if their machinery was equipped with "the real McCoy."

Elijah McCoy



Charles "Kid" McCoy



McCoy's lubricator

Did Elijah McCoy's inventions contribute to the popularization of the phrase "the real McCoy"? This question may be impossible to answer. Several people (and objects) from the mid-19th century could be the source of the phrase. Explanations range from Elijah's lubricator to boxer Norman Selby (the Light Heavyweight Champion of the World in 1904, who fought under the name "Kid McCoy") to Mssrs. Mackay's whiskey (made in Edinburgh and marketed as "the real Mackay.")

Regardless of the etymology of "the real McCoy," it is remarkable that a black railroad fireman could have a significant impact on railroad operations within a dozen years of the end of the Civil War. Elijah McCoy stands as a testament to problem solving, perseverance, and intelligence. In these characteristics, he truly was a real McCoy.

Amos Eaton based the program on five rules of education. Eaton's rules are reproduced next, with the original spelling and punctuation (Griggs, 1997). Although the engineering profession and engineering education have changed greatly in almost 200 years,[*] Eaton's rules are still meaningful today. In this section, Eaton's rules shall be interpreted for the 21st-century engineering curriculum.

1.4.1 Eaton's First Rule: "... make practical applications of all the sciences ..."

Key idea: Discover engineering through problem solving and hands-on work.

> "Let the student make practical applications of all the sciences, with the immediate direction and shewing [showing] of the teacher, before studying any elementary rules. For example, shew him in taking the courses and distances around a field with the compass and chain, before he studies any of the rules of surveying—let him measure a pile of wood and attempt to calculate it before teaching him duo-decimals; let him use optical instruments, under the teacher's shewing, before studying optics, let him give an experimental course on chemistry, before reading any work on chemistry; excepting a textbook of experimental description while in the course of experimenting."

Engineering education must be a marriage of fundamental science and practical applications. *Let the applied problem serve as your introduction to and motivation for theory and analysis.* As Amos Eaton might have put it: engage the hands first and the mind will follow.

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[*] For example, Eaton speaks of students using only the pronouns "he" and "him," since women engineers were rare in the late 19th century. In addition, the original engineering program at the Rensselaer School could be completed in one year!

1.4.2 Eaton's Second Rule: "... take the place of the teacher ... [in] exercises."

> "Let the student always take the place of the teacher on his exercises. He must make every subject his own and then teach his fellow and the schoolmaster, as though there were not a book in the world which treated on this subject, and he was the very oracle of science. Extemporaneous lectures on Tuesday, Wednesday, Thursday, and Friday, and written lectures on Mondays, is a good exercise for that student, in the acquisition of knowledge. He must not speak without a specimen in hand, or the apparatus before him."

Key idea: Learn by teaching others.

Teaching others is a valuable learning strategy. To master engineering fundamentals, practice explaining your reasoning to faculty and fellow students. Most professors feel that teaching deepens their understanding and appreciation of any material. In the last sentence of the quote, note again Eaton's emphasis on the practical problem.

1.4.3 Eaton's Third Rule: "... attend to but one branch of learning at the same time."

> "Let a student attend to but one branch of learning at the same time. Personal exercise in the afternoon, at surveying, engineering, collecting plants and minerals, inspecting factories, machines, and agricultural operations, may be permitted. For, although reflection is required, such exercises call such different faculties into action, that the mind is not thereby burdened or fatigued."

Unfortunately, engineering curricula usually do not allow the luxury of immersing the students in only one subject at a time. In fact, the modern engineering curriculum ensures that the courses you will take are integrated together and build on one another. However, *you can focus on one topic at a time*. A key to success in engineering is mastering the material from one lecture or set of readings before the next lecture occurs.

Key idea: Take the time to master material before new concepts are presented.

It is absolutely critical that you give yourself time to master the material. As Eaton said, "reflection is required." In high school, you may have been able to master some material by sitting passively in class and listening to your teacher. In your engineering courses, you will need to think and talk about the material *outside* of the classroom. You must give yourself the time to think, to make mistakes, and to explore. In reading this text, use the *Ponder This* questions as a springboard for reflection.

In this rule, Eaton once again urges you to return to practice. Talking to professionals, going on field trips at every opportunity, and searching the Internet are some 21st-century versions of Eaton's "personal exercises" (see also Section 1.2).

Finally, Eaton's advice about the importance of using "different faculties" of the mind should serve as a guide to your college education. Use liberal arts and social science courses to exercise the different parts of your brain. These courses are every bit as valuable as your technical courses.

1.4.4 Eaton's Fourth Rule: "Let the amusements and recreation of students be of a scientific character."

> "Let the amusements and recreation of students be of a scientific character. Collecting and preserving minerals and plants, surveying, and engineering, are good amusement."

Eaton's idea of amusement may not jibe with *your* idea of amusement, but the sentiment is important. Eaton's comment focuses on how you spend your time away from the classroom. In modern times, this rule should remind you to get involved with

Key idea: Join student clubs and enter student engineering contests.

student clubs and student engineering contests. In addition, consider getting involved in service-oriented organizations (such as Habitat for Humanity) where your engineering skills can be used to help others immediately. Also, look for engineering in your everyday life—from the automatic teller machine to the roller coaster at your local amusement park to your cell phone.

Eaton also is speaking about commitment. To be a successful engineer, it is ***not*** necessary to spend every waking moment with your nose in a technical journal. However, *you must make a commitment to getting your degree* or graduation day will never come. Success in engineering is all about using your time wisely to achieve your goals. Start now: make earning an engineering degree a high priority in your life.

1.4.5 Eaton's Fifth Rule: "Let every student daily criticize those whose exercise he has attended."

Key idea: Challenge your instructors and respect the value of good technical communication skills.

> "Let every student daily criticize those whose exercise he has attended. Such as to point out all errors in language, gesture, position, and manner of performing experiments, etc. The teacher must always preside during the hour of criticism. No exercise sharpens the faculty of discrimination like this, while it causes each student to be perpetually on his guard."

Give constructive feedback to your instructors. Challenge them as they challenge you. Learning requires two-way communication, giving you the responsibility to interact with your instructors. Eaton's fifth rule is also a reminder of the importance in the engineering profession of both *technical communications* (i.e, avoiding "errors in language, gesture, position") and *data collection* (i.e., avoiding errors in the "manner of performing experiments").

1.5 SUMMARY

Your discovery of engineering has begun. It is sincerely hoped that your sense of discovery will be just as keen 40 years from now as it is today. Although you may have some trepidation as you begin your exploration of engineering, know that engineering is the place for you if you are curious, have a strong work ethic, wish to help other people, and respect and enjoy math and science. Discover engineering by talking with engineers, including your professors, members of professional societies (and the student chapters of professional societies), and practicing engineers. Consider the wisdom of Amos Eaton when discovering engineering in your classes.

SUMMARY OF KEY IDEAS

- Engineering is the right place for people who have curiosity, a strong work ethic, a desire to help other people, and a deep respect for math and science.
- Discover engineering by talking to engineers.
- Learn about your future career by finding engineers at a university.
- To learn more, speak with professionals at engineering firms or engineering departments.
- Discover engineering through problem solving and hands-on work.
- Learn by teaching others.
- Take the time to master material before new concepts are presented.
- Join student clubs and enter student engineering contests.
- Challenge your instructors and respect the value of good technical communication skills.

Problems

1.1. Find and record the Internet home page of each society listed in Table 1.1. Organizations often write a mission statement that succinctly states their goals and aspirations. Read the mission statement of each organization.

1.2. Using Table 1.1, pick two societies that interest you the most and explain why they interest you.

1.3. Summarize the purpose and goals of three societies listed in Tables 1.2 through 1.4.

1.4. Using the library and the Internet, write a short essay on the contributions to engineering education from Sylvanus Thayer, Alden Partridge, Amos Eaton, or any other pioneering educator in a technical field.

1.5. Devise a way to teach a high school student about a technical topic using the approach suggested in Eaton's first rule. Pick a topic that you learned about in high school or are learning about now. Possible topics might be Newton's laws of motion, Boyle's law, or Ohm's law.

1.6. State an applied problem that interests you. Looking at the curriculum for your field of study, list the courses that you think will help you solve this problem.

1.7. How can you use the ideas in Eaton's second rule to study engineering?

1.8. Write a paragraph on the opportunities at your university to teach others.

1.9. Make a list of the liberal arts and social science courses that you plan to take and explain why they interest you.

1.10. Ask an engineering professor how teaching deepens his or her understanding and appreciation of engineering.

1.11. Make a list of "amusements and recreation ... of a scientific character" in your community. Pick an activity to participate in this year.

1.12. Attend a meeting of a service-oriented organization in your community. Write a short paragraph about how you might use your engineering training to help the organization.

1.13. Attend a meeting of an engineering student club. Write a short paragraph about the plans of the student club for the year.

1.14. Make a list of local engineering firms in the discipline of most interest to you. Visit a local office and report on your visit.

2

What Is Engineering?

SECTIONS

OBJECTIVES

After reading this chapter, you will be able to:

- identify the elements that all engineering disciplines have in common;
- describe how engineers help others.

2.1 INTRODUCTION

The question posed by the title of this chapter may seem a bit strange. After all, you do not have to ask the meaning of brain surgery, soccer, or veterinary science—and there are many more engineers in the world than brain surgeons, professional soccer players, or veterinarians. Your familiarity with engineered *systems* (highways, buildings, computers, and factories, to name a few) does not tell you much about the *process* that made those systems. The process is engineering. In this chapter, you will explore the characteristics that engineers and engineering disciplines have in common.

2.2 DEFINING ENGINEERING

What is engineering? This simple question has a very complex answer. Engineering is a diverse collection of professions, academic disciplines, and skills. You can start your exploration of engineering with the dictionary. Your ego may be boosted to learn that the word "engineering" stems from the Latin *ingenium*, meaning skill. (Other words sharing this Latin root include "ingenious" and "ingenuity.") Engineers are skilled at what they do. But what do they do? The dictionary offers you further insight. The Latin root *ingenium* comes from *in* + *gignere*, meaning to produce or beget (also the source of the words "generate" and "kin"). Thus, engineers are skilled producers or creators of things.

This exercise in word origins does not do justice to the field of engineering. Many definitions of "engineering" and "engineer" are possible. Most definitions have some elements in common.

PONDER THIS **Based on your experiences, what is your definition of engineering?**

Key idea: Engineers are professionals who apply science and mathematics to useful ends, solve problems creatively, optimize, and make reasoned choices.

Common elements in the definitions include the following:

- Engineers apply science and mathematics to useful ends.
- Engineers solve problems creatively.
- Engineers optimize.
- Engineers make choices.
- Engineers help others.
- Engineering is a profession.

You will examine each of these elements in more detail in this chapter.

2.3 ENGINEERING AS AN APPLIED DISCIPLINE

2.3.1 Knowledge Generation versus Knowledge Implementation

Almost everyone would agree that engineering is the application of science and mathematics to practical ends. Indeed, the emphasis on practice and application always is in the mind of the engineer. They care more about *using* basic knowledge than *generating* basic knowledge. They care more about converting basic science into technology and converting technology into useful products than in expanding basic science.

However, the emphasis on application tells only part of the story of engineering. The pure engineer may be concerned only with practice, just as the pure scientist is concerned only with generating new knowledge. In reality, both practicing scientists and engineers contribute to the complicated and rewarding process of converting ideas into reality. The pure scientist and the pure engineer are extremes of a spectrum of skills required to make new things.

2.3.2 The Role of Engineering

The role of the engineer in turning ideas into usable ideas or objects[*] is illustrated in Figure 2.1. Both scientists and engineers use mathematics and natural sciences as their tools. Engineers focus on answering the questions that lie on the more applied side of the spectrum. In your career as an engineer, it is likely that you will help develop and implement technology. You will likely work from the middle to the right side of the spectrum

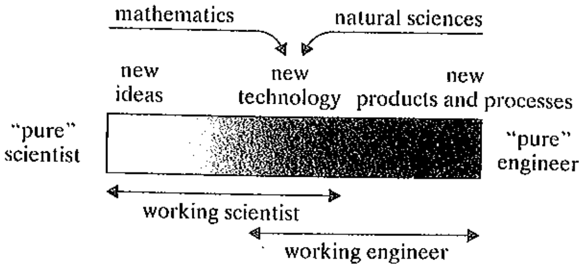

Figure 2.1. Spectrum of Skills in Engineering and Science.

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[*] Engineers develop both *products* (e.g., ballpoint pens, toasters, microprocessors, and satellites) and *processes* (e.g., better ways to stock inventory, new approaches to manufacturing compact discs, and innovative ways to treat wastewater).

in Figure 2.1. As an engineer, you will acquire a pool of skills required to translate new knowledge into usable ideas.

You are urged to return to Figure 2.1 throughout your career. It may help you remember that knowledge generation and product design are two ends of the same spectrum. Neither skill is useful without the other.

Figure 2.1 is a good road map for getting the most out of your courses. For example, if you are suffering from motivational problems in your science and mathematics courses, think about how the material can be applied. Speak to your science and mathematics professors about the practical use of the material. Ask engineering mentors how they use basic science and mathematics in their everyday professional lives.

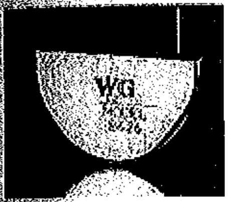
EXAMPLE 2.1: APPLICATION OF SCIENTIFIC PRINCIPLES

In your high school or freshman chemistry course, you may have learned about the unit of chemical concentration called the *mole*. At first glance, the use of molar units of concentration may seem very theoretical and not applied. Give an example of how each main engineering discipline can use this concept.

SOLUTION

Engineers use different sets of units to solve different kinds of problems. Molar units express the proportions in which chemicals combine. Therefore, they are very useful for solving problems involving *combining proportions*.

Almost every engineering discipline uses molar units for some applications. For example, a civil engineer (in the environmental engineering specialty) might use molar units for determining doses of chemicals to react with pollutants and solve pollution problems. A chemical engineer may use moles to determine the ratios of chemicals used to synthesize polymers on a commercial scale. An electrical engineer would use molar units to determine the number of electrons per time (also called the current) produced by an electrochemical cell (such as a battery). Molar units could be used by an industrial engineer to design monitoring devices to make the workplace safer. Mechanical engineers use the concept of the mole to optimize material properties. All engineers may work together to use molar units to design sensors capable of detecting chemical or biological agents.



Lithium iodine batteries as small as 4 mm thick have been used in implantable cardiac pacemakers for over 20 years (Photo courtesy of Greatbatch, Inc.)

2.4 ENGINEERING AS CREATIVE PROBLEM SOLVING

2.4.1 Solving Problems

Engineers solve problems. These three simple words have far-reaching ramifications on the life of an engineer. First, since engineers solve problems, engineering work is usually motivated by a concern or roadblock. This idea may conjure up an image of lone warriors furiously performing dense calculations in a cubicle under a green-shaded desk lamp.

No image of engineering could be more incorrect. In reality, engineers often solve other people's problems. Thus, engineers must be able to *listen to a concern* and *map out a solution*. Whether the problem is to make cars that pollute less or to make oil refining more efficient or to reduce the manufacturing cost of a child's toy, engineers must be able to understand problems that their clients face. In this way, engineering is a very people-oriented profession.

2.4.2 Standard Approaches to Solving Problems

Second, engineers must be skilled in using standard approaches to solve problems. We all respect the brilliant physician who can leap to a diagnosis using intuition and experience. We marvel at the aircraft mechanic who spots the mechanical problem by "feel."

However, we also know that *every* physician must be able to follow standard diagnostic procedures and *every* mechanic must be familiar with the inspection checklist. Similarly, engineers must know the well-established protocols used in solving many problems.

2.4.3 Creative Approaches to Solving Problems

Key idea: The solution to engineering problems involves both standard and creative approaches.

Third, engineers must be creative in solving problems. Just like the physician and aircraft mechanic, engineers must supplement the standard solution methods with creativity and insight. Engineering is a highly creative profession. As Theodore von Kármán (1881–1963), a well-known Hungarian-born specialist in fluid mechanics and aerodynamics, put it, "The scientist describes what is; the engineer creates what never was" (Mackay, 1991). This quotation should not be interpreted as minimizing the creativity of scientists. Rather, it points out that engineers must have vision to create something that did not previously exist.

2.5 ENGINEERING AS CONSTRAINED OPTIMIZATION

2.5.1 Constraints

constrained optimization: determining the best solution to a problem, given limitations on the solution

Key idea: Engineering solutions are often constrained.

Engineering, like life, is about ***constrained optimization***. In high school, it was likely that you did not strive to be the *best* student you could be. Rather, you strived to be the best student you could be *given that* you had to work part-time or you had family obligations or you were active in community groups. In other words, your time available for studying was *constrained* by other activities.

Similarly, engineers always face constraints in solving problems. As an example, electrical engineers rarely seek to design the fastest computer chip. To be useful, computer chips must exhibit other characteristics as well.

PONDER THIS

List some constraints on computer chip design.

We could list the various constraints on computer chip design, but a better goal is just to say that we seek to develop the fastest computer chip of sufficiently small size with adequate heat dissipation characteristics that can be mass-produced at a reasonable cost.

Is it *ever* valuable to build the fastest chip? Absolutely! An electrical engineer specializing in the research side of research and development (R&D) may, in fact, seek to design the fastest computer chip. Some major breakthroughs in engineering have been generated by engineers and scientists who ignored constraints. However, most engineers seek to put ideas into practice. This means taking the real world and its constraints into account when designing engineered systems.

Key idea: Engineering solutions must take into account the probability of failure.

One aspect of the constrained nature of engineering is that engineers live in a probabilistic world. In other words, engineers must consider the *chances* of certain events occurring, including the probability of failure. A civil engineer does not design a bridge that will never fall down. Such a bridge would be infinitely expensive. Rather, the civil engineer examines the probabilities that certain loads will occur on the bridge from traffic, earthquakes, and wind. A bridge is designed to perform acceptably for a specified period of time under the anticipated loads and stresses. Similarly, an environmental engineer does not design a drinking water treatment plant to remove *all* pollutants completely. Such a plant is probably not possible (and if it was possible, the drinking water it produced would be unaffordable). Instead, engineers design treatment plants to meet water quality standards and minimize risk at a socially acceptable cost.

Due to constrained optimization in a probabilistic world, engineers must constantly ask: How strong is strong enough? How clean is clean? Have I thought of everything that could go wrong?[*] An example of extremely constrained optimization is given in the *Focus on Constrained Optimization: A Square Peg in a Round Hole.*

2.5.2 Feasibility

The ability of an engineering project to meet its constraints is often expressed in terms of feasibility. There are several aspects of feasibility, which will be introduced here. *Technical* (or engineering) *feasibility* measures whether or not a project meets its technical goals. It addresses several questions, such as "Does the new road handle the traffic?" and "Is the upgraded electrical transmission system more efficient?"

Key idea: To be successful, engineering projects must be technically, economically, fiscally, socially, politically, and environmentally feasible.

Most of your undergraduate course work is focused on technical feasibility. However, it is not sufficient for an engineering project to be technically feasible. Engineering projects also must be economically feasible. *Economic feasibility* addresses whether the project benefits outweigh the project costs. In the examples above, economic feasibility addresses whether the road benefits (e.g., tolls collected, elimination of slowdowns, and increased safety) are greater than the road construction and maintenance costs or whether the money saved from the more efficient transmission systems will pay for the upgrade work. Sometimes, the benefits and costs are difficult to quantify. What is the value of a five-minute reduction in commuting time or one less incidence of cancer for every one million people? To answer these questions, engineers may seek the advice of social scientists and economists.

Another factor to consider is *fiscal feasibility*. Fiscal feasibility measures whether sufficient funds can be generated to build the project. Many engineering projects would be profitable (i.e., are economically feasible), but are not built because start-up money cannot be acquired. The difference between economic and fiscal feasibility is important. For large, multimillion-dollar engineering projects, obtaining money through loans or bonds to achieve fiscal feasibility may be the critical step. Engineers who ignore fiscal feasibility will never see their ideas translated into reality.

The last type of feasibility is social, political, and environmental feasibility. Engineers cannot work in a vacuum. Engineering projects must be socially acceptable, have political backing, and result in an acceptable environmental impact. Many engineering projects remain only on paper because societal and political support was lacking. Should you, as an engineer, be upset because some projects die due to nontechnical issues? No. It should remind you that engineers are part of the fabric of society. The public cares about the impact of engineering projects. As a result, you must consider the social consequences of your proposal along with the technical details.

FOCUS ON CONSTRAINED OPTIMIZATION: A SQUARE PEG IN A ROUND HOLE

BACKGROUND

Engineering is about constrained optimization. The need to "make the best with what you have" is demanding when the constraints are the most severe. For example, a space vehicle located 200,000 nautical miles from Earth presents some of the most severe constraints that an engineer will face.

Such was the case with *Apollo 13*, launched April 11, 1970. The crew of the spacecraft—Commander James A. Lovell, Lunar Module Pilot Fred W. Haise, Jr., and Command Module Pilot John L. Swigert, Jr.—was hard at work and enjoying the ride. Suddenly, about 56 hours into the flight, the crew heard a loud noise (which is never a good sign in a spacecraft). The pressure in Cryogenic Oxygen Tank 2 had begun to rise

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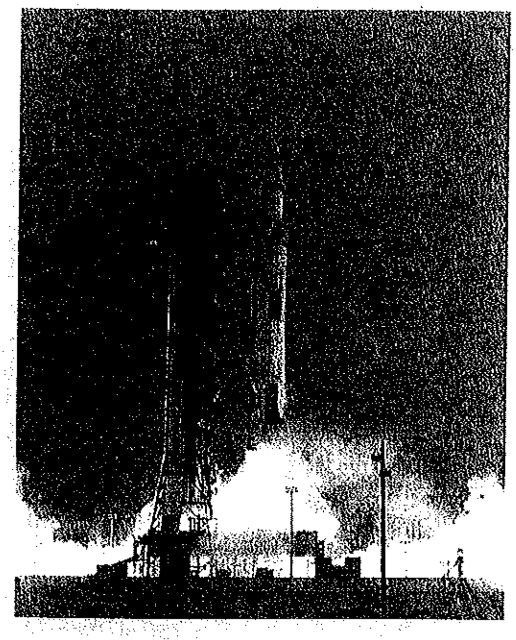
[*] For an insightful and entertaining discussion of this question as it pertains to civil engineering, see Petroski (1992).



Launch of Apollo 13, Saturday, April 11, 1970

very quickly. Within two minutes, the tank lost pressure. Why did this matter? Electricity on *Apollo 13* was generated by a fuel cell, where oxygen and hydrogen were combined. No oxygen meant no power—and no way to return to Earth.

PROBLEMS AND SOLUTIONS

The ground crew quickly assessed the situation. The three people in space required three things to return to Earth alive: power, water (to drink and to cool the equipment), and oxygen. With the fuel cells virtually inoperable, the only source of power was the batteries in the Lunar Module (LM, the *Aquarius*). It became clear that the LM, with its own ample oxygen supplies, would become the lifeboat for the crew. But the LM had its own problems. Its batteries would need to be recharged to provide enough power for the journey home. However, there was no direct electrical connection between the Command Service Module (CSM, the *Odyssey*) and the LM to recharge the batteries. Engineers on the ground discovered a way to leak current slowly from the CSM to the batteries. By turning off nonessential equipment, the crew limped home with an amazing 20% of the LM power left.

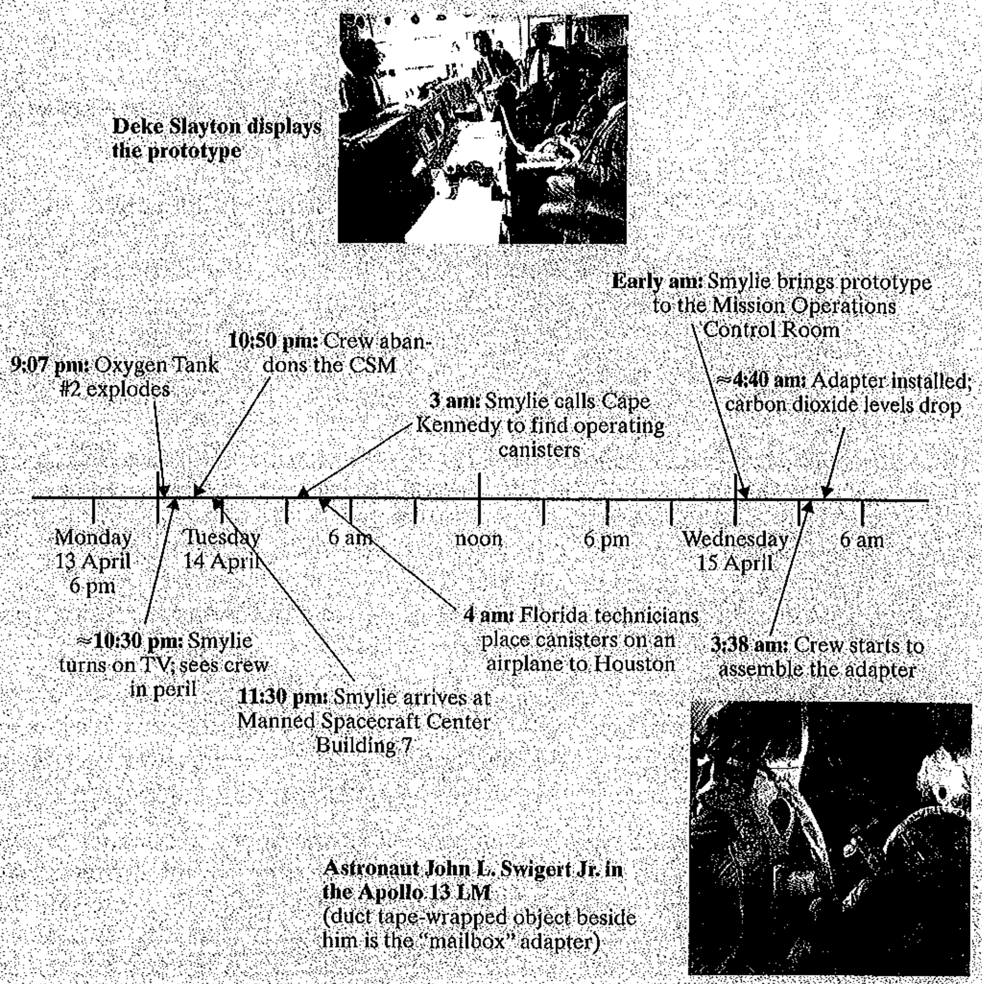
The problem with water could be addressed only by drinking less. The crew cut its water ration to 200 milliliters per person per day (a little over one-half of a soft drink can). The crew lost a collective 31 pounds on the trip home, arriving in poor health and with 10% of the water supply remaining.

The LM had a sufficient oxygen supply, but the ground crew soon realized that *another* air supply problem would threaten the astronauts: the build-up of carbon dioxide (CO_2) exhaled by the crew. The CO_2 was removed by lithium hydroxide (LiOH) canisters through a chemical reaction. The LM was designed to transport two members of the crew from lunar orbit to the surface of the Moon. It had a sufficient canister capacity to remove the CO_2 produced by two people for about 30 hours, not the CO_2 exhaled by three people for the long trip back to Earth. Even by allowing the CO_2 levels to rise a little, the canisters could operate for only about 187 person-hours, when at least 288 person-hours would be needed. The solution? The CSM had its own LiOH canisters. But as luck would have it, the CSM canisters had *square* connectors that would not fit in the *round* fittings of the LM.

CONSTRAINED OPTIMIZATION

In a brilliant feat of constrained optimization, the ground crew had to develop an interface between the square CSM canisters and the round LM fittings from material available to the astronauts. (The near-impossibility of this task is shown dramatically in a famous scene from the movie *Apollo 13*.) The adapter, called the "mailbox," was designed by ground engineer Ed Smylie. (In NASA-speak, the adapter is known officially as the "supplemental carbon dioxide removal system.") It was made of two CSM canisters, a space suit exhaust hose, cardboard from instructional cue cards in the LM, plastic stowage bags from liquid-cooled undergarments, and one roll of duct tape. (Ironically, much of this material would have been otherwise unused by the astronauts. The cue cards contained instructions for lifting off from the moon and the undergarments were to be worn on moonwalks.)

Timeline for the Apollo 13 Carbon Dioxide Crisis
(all times are Central Standard Time for Houston, TX)



Deke Slayton displays the prototype

Astronaut John L. Swigert Jr. in the Apollo 13 LM
(duct tape-wrapped object beside him is the "mailbox" adapter)

The efforts of engineer Ed Smylie, the other Houston personnel, and the astronauts were truly unbelievable. Only about 30 hours elapsed between the time Smylie turned on his television set to learn of *Apollo 13*'s problems and the time that the astronauts finished building the mailbox in space. (See the accompanying timeline.) Smylie and his assistant, Jim Correale, had no operational LiOH canisters to test the interface. Working canisters from Florida (intended for *Apollo 14* or *Apollo 15*) were airlifted to Houston to enable testing of the device. After testing on the ground, the ground crew issued about an hour's worth of instructions by radio so that the astronauts could construct the adapter in space.

The *Apollo 13* flight had a very happy ending, due to the bravery of the astronauts and the ingenuity of the engineers. When faced with an overwhelmingly constrained problem, the engineers created a solution that saved the lives of three American heroes.

2.6 ENGINEERING AS MAKING CHOICES

Key idea: Engineers make recommendations by selecting from a list of feasible alternatives.

feasibility assessment: evaluation of the feasibility of an engineering project

The discussion thus far has centered on what engineering *is* rather than what engineers *do*. So what *does* an engineer do? Engineers listen carefully to the problem. (See Section 2.4.1.) Using accepted and creative methods (see Sections 2.4.2 and 2.4.3), they develop a list of feasible solutions or alternatives. Here, "feasible" means that each solution is technically, economically, fiscally, and socially/politically/environmentally feasible. (Evaluating whether a project is feasible is called a ***feasibility assessment***. See Example 2.2 for an example.) Finally, engineers select an alternative from among the feasible solutions and recommend it to their client.

In a real sense, engineering is about generating alternatives and selecting feasible solutions. The selection step sets engineers apart from other professionals (e.g., technicians and designers) who may be trained to do the calculations and run the software, but may not be trained to make recommendations. To recommend an alternative, an engineer has to balance the technical, economic, fiscal, and social/political/environmental issues. A person trained only to crunch numbers will fail in this critical decision-making task. A person trained only to crunch numbers is not an engineer.

EXAMPLE 2.2: FEASIBILITY ASSESSMENT

Conduct a feasibility assessment for buying a used car to commute to a part-time job.

SOLUTION

A feasibility assessment determines the technical, economic, fiscal, and social/political/environmental feasibility of an alternative.

Technical feasibility: Technical feasibility probes whether the alternative will solve the problem. In this case, you need to ask whether buying the car will allow you to commute to work safely and reliably. Perhaps the car you can afford will not be sufficiently reliable. Perhaps other more reliable alternatives exist, such as public transportation.

Economic feasibility: Economic feasibility questions whether the benefits of the alternative exceed its costs. The costs of car ownership include depreciation, financing, insurance, taxes and fees, fuel, maintenance, and repairs. For a used 2000 Honda Accord two-door LX coupe in Buffalo, New York, the purchase and ownership costs average about $7,570 per year for the first five years (as determined by the cost calculator at www.edmunds.com). The benefits include your ability to get to your part-time job and the freedom and convenience that car ownership engenders. Other alternatives (such as a monthly bus pass) may have lower costs, but they do not have the freedom and convenience of car ownership.

Fiscal feasibility: Fiscal feasibility probes whether you can get the start-up funds to finance the project. In this example, purchasing the car is fiscally feasible if you can qualify for a reasonable car loan.

Social/political/environmental feasibility: In this example, social/political/environmental feasibility centers on environmental impact. In spite of the large social, political, and environmental costs of reliance on the internal combustion engine, car ownership remains socially acceptable in North America. You could consider, as an alternative, a car with lower environmental impact. (Buying a new Toyota Prius has about twice the purchase + interest + depreciation costs of the Honda, but about half the fuel + maintenance + repair costs.)

2.7 ENGINEERS AS HELPING OTHERS

Professions can be characterized in many ways. Some people are attracted to the so-called caring professions.

PONDER THIS **Make a list of caring professions.**

Caring professions include medicine, nursing, social work, and teaching. Did your list include engineering?

Engineering is also one of the caring professions. Why? Nearly every project that an engineer completes satisfies a need or concern of the public. For example, if you become an electrical engineer, you may develop sensors to make more powerful neonatal incubators. Perhaps as a civil engineer, you may work on earthquake-resistant buildings or develop drinking-water treatment systems for less developed countries. (Water-related diseases, the leading cause of death globally, is responsible for 14,000 deaths *per day* because more than one billion people on the planet lack access to safe drinking water.) Maybe you will become a chemical engineer and work on ways to mass-produce HIV medications, making such drugs affordable to every HIV-positive person in the world. Perhaps you will go into industrial engineering and devise systems to help nonprofit organizations better serve their clients. (Volunteers from several professional and student chapters of the Institute of Industrial Engineers recently helped make a women's shelter in Pittsburgh become more efficient to save resources.) Or maybe you will become a mechanical engineer and develop a robust heart valve for premature infants. Whatever field of engineering interests you, know that you can use your training to make the world a better place and to make people's lives healthier and more fulfilling.

2.8 ENGINEERING AS A PROFESSION

Finally, engineering is a profession. This means, of course, that engineers get paid for what they do. In addition, it means that to be called an engineer, you must meet certain requirements. Just as the public must be assured that a person called a dentist or lawyer is fully certified, so the public must know that a person using the title "engineer" has been trained properly. The process of meeting the requirements is called *registration*. A registered engineer holds the title *professional engineer*, or PE.

All professions have ethical standards. Engineers, as professionals, must meet high standards of professional ethics.

2.9 SUMMARY

The dictionary tells us that engineers give birth to things creatively. In particular, the work of engineers is characterized by six elements. First, engineers apply science and mathematics to useful ends. Second, engineers solve problems using both standard and creative approaches. Third, engineers optimize solutions subject to the constraints of the real world. The constraints are often grouped under the headings of technical feasibility (will the system perform the task for which it was designed?), economic feasibility (do benefits outweigh costs?), fiscal feasibility (are start-up funds available?), and social/political/environmental feasibility. Fourth, engineers make reasoned choices. They select and recommend feasible alternatives. Fifth, engineers help others. Without a public to serve, engineering as a profession would not exist. Finally, engineers are professionals. This means that engineers may seek professional registration and must meet ethical standards.

SUMMARY OF KEY IDEAS

- Engineers are professionals who apply science and mathematics to useful ends, solve problems creatively, optimize, and make reasoned choices.
- The solution to engineering problems involves both standard and creative approaches.
- Engineering solutions are often constrained.
- Engineering solutions must take into account the probability of failure.
- To be successful, engineering projects must be technically, economically, fiscally, socially, politically, and environmentally feasible.
- Engineers make recommendations by selecting from a list of feasible alternatives.
- Engineering is a profession and engineers have ethical responsibilities.

Problems

2.1. What are the six main elements of engineering?

2.2. Some pharmaceuticals are manufactured by genetically engineered bacteria to produce the drug. Discuss the role of the engineer (if any) in the following steps of the development of a new drug:

- Synthesis of the drug for animal tests
- Genetic engineering of the bacteria
- Mass production through bacterial synthesis
- Clinical trials
- Development of the time-release capsules and transdermal patches
- Efficiency study of the manufacturing process, and
- Design of the marketing strategy

2.3. Explain the differences in the contributions to society of scientists and engineers. Which contribution appeals more to you and why?

2.4. Give an example of constrained optimization in an engineering problem.

2.5. For Problem 2.4, what is a possible solution, given the constraints? How would the solution change if the constraints were different?

2.6. From your local newspaper, find an example of an engineering project that was not implemented because it was not economically or fiscally feasible.

2.7. Explain the difference between economic feasibility and fiscal feasibility.

2.8. Give an example of an engineering project that is economically feasible, but not fiscally feasible. Give an example of an engineering project that is fiscally feasible, but not economically feasible.

2.9. From your local newspaper, find an example of an engineering project that was not implemented because it was not socially, politically, or environmentally feasible.

2.10. For your answer in Problem 2.9, how would you change the project to make it feasible?

2.11. Talk with an engineer in government service (e.g., a town, city, or county engineer) about the difference between economic and fiscal feasibility. Illustrate the difference with an example from your community.

2.12. Two towns are separated by a river and wish to exchange goods. List several alternative solutions to this problem. Perform a feasibility assessment and rank the alternatives according to their feasibility. (Be sure to include all types of feasibility.) Recommend a solution to the problem.

2.13. Make a list of the professions that are licensed by your state. What do the professions have in common? Which licenses are in technical fields?

2.14. Which agency in your state licenses engineers? (Try searching the Internet for your state name and the phrase "professional engineer.") How many engineers are licensed in your state?

2.15. How do engineers in your area participate in public service?

Problems

1.1. Find and record the Internet home page of each society listed in Table 1.1. Organizations often write a mission statement that succinctly states their goals and aspirations. Read the mission statement of each organization.

1.2. Using Table 1.1, pick two societies that interest you the most and explain why they interest you.

1.3. Summarize the purpose and goals of three societies listed in Tables 1.2 through 1.4.

1.4. Using the library and the Internet, write a short essay on the contributions to engineering education from Sylvanus Thayer, Alden Partridge, Amos Eaton, or any other pioneering educator in a technical field.

1.5. Devise a way to teach a high school student about a technical topic using the approach suggested in Eaton's first rule. Pick a topic that you learned about in high school or are learning about now. Possible topics might be Newton's laws of motion, Boyle's law, or Ohm's law.

1.6. State an applied problem that interests you. Looking at the curriculum for your field of study, list the courses that you think will help you solve this problem.

1.7. How can you use the ideas in Eaton's second rule to study engineering?

1.8. Write a paragraph on the opportunities at your university to teach others.

1.9. Make a list of the liberal arts and social science courses that you plan to take and explain why they interest you.

1.10. Ask an engineering professor how teaching deepens his or her understanding and appreciation of engineering.

1.11. Make a list of "amusements and recreation ... of a scientific character" in your community. Pick an activity to participate in this year.

1.12. Attend a meeting of a service-oriented organization in your community. Write a short paragraph about how you might use your engineering training to help the organization.

1.13. Attend a meeting of an engineering student club. Write a short paragraph about the plans of the student club for the year.

1.14. Make a list of local engineering firms in the discipline of most interest to you. Visit a local office and report on your visit.