Design Concepts for Engineers

Fourth Edition

Mark N. Horenstein

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MARK N. HORENSTEIN

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About This Book

Design Concepts for Engineers is a text intended for introductory courses in engineering. It teaches the basic principles of design and related design tools from a basic level while drawing on examples from the many engineering disciplines. In a text of this sort, all disciplines cannot be fully represented all the time, but the discussions and examples are basic enough that students from just about any engineering discipline should find the book useful. In all cases, the focus of the book is on the design process, rather than on the technical details of any one engineering field. In some cases, the latter are provided only to help the student grasp the key issues relevant to the design process. While calculus is used in a few places, a knowledge of basic algebra is all that is required for the student to fully engage the text. Use of computers and discussions of documentation are constant themes as well, although specific knowledge of any one programming language is not required, nor is one expressly featured over another. Each chapter is written as a stand-alone module, in that no one chapter refers to or requires reading of any other chapter. Conversely, the text is easily used in its entirety.

Design is an open-ended process in which a problem has multiple solutions. Writing a solutions manual for a design text can therefore be a difficult task. Nevertheless, an Instructor's Resource Manual accompanies this book to guide the instructor in the assignment of the various exercises and end-of-chapter problems. For selected, opened-ended design problems, the manual provides guidelines for the instructor rather than specific answers. These guidelines will help lead students through the design process. Specific answers are provided for questions or problems that are more analytical in nature.

What follows is a brief summary of the contents of each chapter in the book. Chapter 1 presents an overview of the many fields of engineering by providing a short description of each as well as excerpts from the Web page of that discipline's principal professional society. The list of disciplines is meant to be comprehensive, but not exhaustive. Chapter 2 begins with multiple definitions of the word "design." It introduces one version of the design cycle while emphasizing that other versions may be appropriate for different design tasks. The chapter introduces the concept of brainstorming and gives examples of brainstorming sessions. The chapter concludes with specific design examples that illustrate the multiple approaches one can take in arriving at a finished product. The word "product" as used in this chapter refers to the objective of the design process, and not necessary a physical object for sale.

Chapter 3 focuses on project management. The central themes of the chapter include teamwork, organization, time management, and the all-important task of documentation. The chapter ends with a brief discussion of legal issues as they relate to intellectual property.

Chapter 4 introduces the student to numerous engineering tools. While the degree of relevance may vary with the discipline, the individual sections should be of use to most majors. The concepts of units, dimensioning and tolerance, graphing, prototyping, reverse engineering, and computer analysis, as well as spreadsheets and solid modeling, are among the topics covered in this chapter.

Chapter 5 addresses the human-machine interface. It discusses how people interact with machines, the ergonomics of design, and the concept of cognition. The chapter ends with numerous case studies of both good and bad human-machine interfaces.

Chapter 6 provides an overview of classic engineering disasters as well as recent newsworthy failures. The chapter focuses on how engineers learn from mistakes, rather than on a simple chronicling of engineering mishaps.

Chapter 7 addresses head on the topic of interpersonal communication. The skills of speaking, writing, and giving oral presentations are discussed in detail, and several good examples are provided in each category.

I have enjoyed writing this latest addition of *Design Principles for Engineers*. I hope you and your students and enjoy the book as well.

ABOUT THE AUTHOR

Mark N. Horenstein is a Professor in the Department of Electrical and Computer Engineering at Boston University. He has degrees in Electrical Engineering from M.I.T. and U.C. Berkeley and has been involved in teaching engineering design for the greater part of his academic career. He frequently teaches first-year engineering courses, and he also devised and developed his department's senior capstone design course. In the latter, students work for a virtual engineering company developing products and systems for real-world engineering and social-service clients. Professor Horenstein does research in the areas of electromechanical design and applied electromagnetics.

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MNH—Boston, MA, 2009

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CHAPTER 1

What Is Engineering?

Objectives

In this chapter, you will learn about:

- The numerous fields of engineering
- Engineering as a career
- The relationship between engineers and other professionals
- Engineering professional organizations
- The foundations of engineering design: knowledge, experience, and intuition

If you're reading this book, you are probably enrolled in an introductory course in engineering. You may have chosen engineering because of your strong skills in science and mathematics. Perhaps you like to take things apart or play in cyberspace. You may have an interest in engineering as a way to help people. Maybe you simply followed the advice of your high school guidance counselor. Whatever your reason for studying engineering, you are entering a career filled with discovery, creativity, and excitement. Imagine yourself several years from now, after you've finished your college studies. What will life be like as an engineer? How will your college classes relate to your work and career? This book will help provide you with a vision of the future while teaching you some important engineering skills.

As an aspiring engineer, you have much to learn. You must master the basic foundations of engineering: math, physics, chemistry, and biology. You must study the specialized subjects of your chosen discipline—for example, circuits, mechanics, structures, materials, or computation. You must also learn how to stay on top of technological advances by embracing a program of lifelong learning. This latter need is crucial because the world embraces new technologies on a daily basis. The wise engineer keeps abreast of them all. Your college courses will provide you with the knowledge and mathematical skills that you will need to function in the engineering world. But you must also learn about the important practice of design. The ability to build real things is the hallmark of the engineer. Design sets engineers apart from professionals in the basic sciences. While physicists, chemists, or biologists draw general conclusions by observing specific phenomena, engineers move from the *general* to the *specific*. Engineers harness the laws of nature and utilize them to produce devices, systems, and structures that perform tasks, meet human needs, or solve problems. The design process defines the essence of the engineering profession, and you must become proficient at it on your path to success. This book will introduce you to the basic principles of design and will help you to apply them to your class assignments, design projects, and future job responsibilities.

Table 1-1 Some Traditional Engineering Disciplines

Aeronautical	Computer	Mechanical
Agricultural	Electrical	Naval
Architectural	Environmental	Nuclear
Biomedical	Food	Ocean
Chemical	Industrial	Petroleum
Civil	Materials	Systems

1.1 ENGINEERING HAS MANY FIELDS

The fields of engineering are numerous. A perusal of the websites of engineering colleges around the world, for example, will reveal an almost endless variety of engineering programs of study. Although the names may vary from school to school, most engineers are trained in one of the traditional engineering disciplines listed in Table 1-1. (These disciplines are listed alphabetically with no preference implied.)

The National Academy of Engineering (NAE), in celebration of the accomplishments of engineers during the 20th century, publicized the following statement at the turn of the millennium:

> "The impact of engineers on society has been immense. One hundred years ago, life was a constant struggle against disease, pollution, deforestation, treacherous working conditions, and enormous cultural divides unbreachable with current communications technologies. By the end of the 20th century, the world had become a healthier, safer, and more productive place, primarily because of engineering achievements."[1]

The NAE noted, for example, that the increase in human life expectancy, from about 45 years in 1900 to over 75 years in many countries as of 2010, could be attributed more to engineering accomplishments than to all the advances in medical knowledge combined.

As part of its recognition of engineers, the NAE released a list, replicated here as Table 1-2, of the top 20 engineering accomplishments of the past century. The primary discipline represented by the accomplishment has been added in parentheses.[2]

This list is notable because of the large number of engineering disciplines represented. What is also evident is the cross-disciplinary nature of almost all the citations on the list. Engineers from many fields were needed in order to make each of these milestone accomplishments possible. In fact, each field of engineering embraced by this list has its own important role in the technological progress of the world. It has been, and will continue to be, the job of colleges and universities to train today's students to become tomorrow's engineers.

From reading Tables 1-1 and 1-2, one might conclude that engineers are highly specialized professionals who have little interaction with people from other fields.

[1]National Academy of Engineering press release, February 22, 2000.

[2]*National Engineers Week* statement by former astronaut Neil Armstrong, February 2000.

Table 1-2 List of the Top 20 Engineering Accomplishments of the 20th Century (Published by the National Academy of Engineering in 2000)

1. Electrification (Electrical)	11. Highways (Civil)
2. Automobiles (Mechanical)	12. Spacecraft (Aerospace)
3. Airplanes (Aerospace)	13. Internet (Computer)
4. Water Supply and Distribution (Civil)	14. Imaging (Electrical)
5. Electronics (Electrical)	15. Household Appliances (EE and ME)
6. Radio and Television (Electrical)	16. Health Technologies (Biomedical)
7. Agricultural Mechanization (Mechanical)	17. Petroleum and Petrochemical Technologies (Petroleum)
8. Computers (Computer)	18. Laser and Fiber Optics (Electrical)
9. Telephones (Systems)	19. Nuclear Technologies (Nuclear)
10. Air Conditioning and Refrigeration (Mechanical)	20. High-performance Materials (Materials)

In reality, the opposite is true. The best engineers are multidisciplinary individuals who are familiar with many different fields and specialties. The key to successful engineering is a broad multidisciplinary education. Gone are the days where engineers can be content to rest in narrow cubbyholes of training. Many of the great engineering accomplishments of the past century were made possible by interactive teams of engineers from a multitude of disciplines. Although engineers are multidisciplinary by nature, most are indeed trained at the college level in a specific degree program and spend much time utilizing their specialized training. For this reason, we'll begin our study of engineering and design by reviewing the characteristic features of some of the more popular branches of engineering. These fields are presented in alphabetical order.

1.1.1 Aeronautical Engineering

Aeronautical (or aerospace) engineers use their knowledge of aerodynamics, fluid mechanics, structures, control systems, heat transfer, and hydraulics to design everything from rockets, airplanes, and space vehicles to high-speed bullet trains, low-drag fuel-efficient cars, and helium-filled dirigibles. Since the days of the Wright brothers, aeronautical engineers, working in teams with scientists and other types of engineers, have made human flight and space exploration possible. Aeronautical engineers find employment in many industries, but they typically work for big companies on large-scale projects. Some of the more noticeable accomplishments of the aerospace industry have included the Apollo moon landings of the 1960s, NASA Space Shuttle missions, deep space exploration, the International Space Station, the jumbo jet, and a new generation of fuel-sipping aircraft. Commercial ventures into space have even come to fruition. Figure 1.1, for example, shows SpaceShipOne, a manned space ship designed and built by Scaled Composites, a private aerospace company. On October 4, 2004, SpaceShipOne propelled itself into history, becoming the first private manned spacecraft to exceed an altitude of 328,000 feet (twice within 14 days) to claim the $10 million Ansari X-Prize.

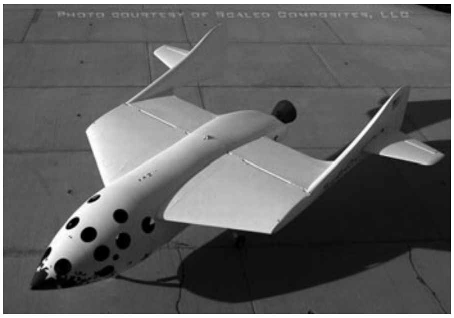


Figure 1.1
SpaceShipOne—The first privately funded commercial manned space flight. (*Photo courtesy of Scaled Composites, LLC.*)

1.1.2 Agricultural Engineering

Agricultural engineers apply the principles of hydrology, soil mechanics, fluid mechanics, heat transfer, combustion, optimization theory, statistics, climatology, chemistry, and biology to the production of food on a large scale. This discipline is popular at colleges and universities located in heavily agricultural areas. Feeding the world's population is one of the most formidable challenges of the 21st century. The amount of arable land on the planet is fixed, but the demand for food must keep pace with the world's steeply rising population. Agricultural engineers will play an important role in this endeavor by applying technology and engineering know-how to improve crop yields, increase food output, improve farming of minimally productive land, and develop cost-effective and environmentally sound pest control and farming methods. Agricultural engineers work with ecologists, biologists, chemists, and natural scientists to understand the impact of human agriculture on the earth's ecosystem.

1.1.3 Biomedical Engineering

The biomedical engineer (or bioengineer) works closely with physicians and biologists to apply modern engineering methods to medicine and human health, and to obtain a better understanding of the human body. Engineering skills are combined with a knowledge of biology, physiology, and chemistry to produce medical instrumentation, prostheses, assistive appliances, implants, and neuromuscular diagnostics. Biomedical engineers have participated in designing numerous devices that

have helped improve medical care over the past half-century. Many biomedical engineers enter medical school upon graduation, but others go to graduate school or seek employment in a health or medical-related industry. The rapidly emerging world of biotechnology, which bridges the gap between engineering and molecular genetics, is also the province of the biomedical engineer. This discipline examines the fundamental functions of cells and organisms from an engineering point of view. Many of the secrets of future medicine lie at the genetic level, and the biomedical engineer will help lead the way to new medical discoveries. Nanotechnology also plays a central role, because cells exist on the nanoscale. The human genome project, for example, has relied heavily on the expertise of bioengineers working in concert with biologists, chemists, and experts, and has created a newly emerging area of technology called *bioinformatics*. The latter field spans the disciplines of bioengineering and computer science. The biomedical engineer is also involved in the emerging areas of microfluidics and nanomaterials. In microfluidic, tiny bioprocessing systems are built on small chips of silicon or other materials. This technology, which is part of the field of micro- and nano-electromechanical systems (MEMS and NEMS), is sometimes referred to as "lab on a chip." In nanomaterial technology, artificially engineered materials provide an interface between human tissues and everything from bone and skin grafts to *in-vivo* drug delivery systems. The discipline of biomedical engineering also encompasses the field of *bionics*—a technology that attempts to merge biological organisms with manufactured components as one integral whole.

1.1.4 Chemical Engineering

The chemical engineer applies the principles of chemistry to the design of manufacturing and production systems. Whenever a chemical reaction or process must be brought from the laboratory to manufacturing on a large scale, teams of chemical engineers are needed to make it happen. Chemical engineers design the reaction vessels, transport mechanisms, mixing chambers, and measuring devices that allow the process to proceed on a large scale in a cost-effective way. Chemical engineers are employed in many industries, including construction, microelectronics, biotechnology, food processing, and environmental analysis, as well as industries that manufacture petroleum products, petrochemicals, plastics, cosmetics, and pharmaceuticals. Because of the widespread use of such materials, much of our global economy relies on the work of chemical engineers for its success. Their skills are needed wherever a manufacturing process involves organic or inorganic chemical reactions on a production scale. Chemical engineers must rely on their knowledge of mathematics and science—particularly chemistry—to overcome technical problems in a safe and economical manner. Chemical engineers are typically employed by large companies that produce products for worldwide distribution.

1.1.5 Civil Engineering

Civil engineers are responsible for the infrastructure of our society. The civil engineer is concerned with the design and construction of the world's infrastructure. Civil engineers design transportation systems, roads, bridges, buildings, and airports, as well as other large structures such as water treatment plants, aquifers, and waste management facilities. One classic example of civil engineering on a grand scale, shown in Figure 1.2, is the Hoover Dam in Black Canyon on the Colorado River, about 30 miles southeast of Las Vegas, Nevada. Designing such large structures

Figure 1.2
The Hoover Dam on the Colorado River near Las Vegas, Nevada. (*Photo courtesy of the Bureau of Reclamation.*)

requires knowledge of soil mechanics, hydraulics, strength of materials, concrete engineering, and construction practices. Civil engineers may also be involved in designing smaller structures such as houses, landscapes, and recreational parks. Over the coming decades, civil engineers will play a vital role in revitalizing aging infrastructures worldwide and in dealing with environmental issues such as water resources, air quality, global warming, and refuse disposal. More than any other professional, the civil engineer has to rely heavily on physical scale models, calculations, computer modeling, and past experience to determine the performance of designed structures. This limitation exists because it's seldom possible to build a trial test structure on the scale of most civil engineering products. The civil engineer seldom tests a full-scale, initial prototype, but instead must show via modeling and simulation during the design process that a design will meet its specifications upon final construction. For example, it's not feasible to intentionally collapse a bridge just to verify its weight-bearing capability.

The civil engineer works closely with construction personnel and may spend much time at job sites reviewing the progress of construction tasks. Civil engineers are often employed in the public sector, but may also find work in large or small construction companies and private development firms. One renowned example of a large, public-sector civil engineering effort, shown in Figure 1.3, is the famed "Big Dig" in Boston, Massachusetts. This multibillion-dollar, 10-year effort, the most expensive and extensive single transportation infrastructure project in U.S. history (over $21 billion), is formally known as the Central Artery/Tunnel Project. This

Figure 1.3
Boston's Central Artery/Tunnel Project (the "Big Dig"), one of the largest public works projects in U.S. history. (*Photo courtesy of the Central Artery/Tunnel Project.*)

project has spawned numerous issues of interest to the engineering profession, from structural to ethical.

1.1.6 Computer Engineering

Computer engineering encompasses the broad categories of hardware, software, and digital communication. A computer engineer applies the basic principles of engineering and computer science to the design of computer networks, software systems, communication systems, embedded processors, and computer-controlled devices. The computer engineer also is responsible for designing and building interconnections between computers and their components, including distributed computers, wireless and local area networks (LAN), and Internet servers. For example, a hardware-oriented computer engineer might combine microprocessors, flash memory, disk drives, display devices, LAN cards, and drivers to produce high capacity servers. Graphical-user interfaces and embedded computer systems might be the province of the software-oriented computer engineer. The discipline also includes such areas as sensor networks, crash-resistant hardware and software systems, wireless interfaces, sensor networks, operating systems, and assembly language programming. Computer scientists are traditionally more mathematically oriented than computer engineers, and they have also become involved in the writing of computer software, including Web interfaces, database management systems, and client applications. Unlike the computer scientist, however, the computer engineer is fluent in both the hardware and software aspects of modern computer systems. Examples in which both hardware and software share equally important roles include processor design, network interfaces, desktop and laptop PC design, cell-phone networks, global positioning systems, microcomputer or Internet-controlled appliances, automated manufacturing, and medical instrumentation. Some of the more notable accomplishments of the computer industry include the invention of the microprocessor (Intel, 1971), the explosion of personal computing that began with the first desktops (Apple I, 1976; Apple II, 1978; IBM-PC, 1984; McIntosh, 1984), and the advances in data communication networks that began with the U.S. Department of Defense's Arpanet and grew into the Internet and World Wide Web.

New horizons in computing will present exciting challenges to computer engineers in the 21st century. While not yet realities, quantum computing, nanocomputing, sentient artificial intelligence (e.g., the android Data from *Star Trek: The Next Generation*; numerous machines from *I, Robot*), and direct interfacing between computers and the human brain no longer lie in the realm of pure science fiction.

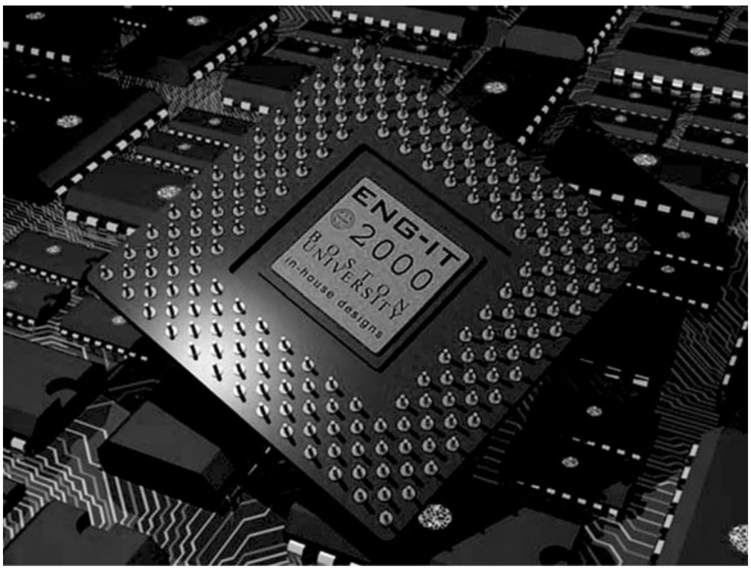
1.1.7 Electrical Engineering

Electrical engineering is an extremely broad discipline that encompasses all forms and uses of electricity. Because information can be expressed in electronic form, the science of information theory often falls within the realm of the electrical engineer. Likewise, because many uses of electricity involve its manipulation and control, the discipline of control theory is often within the province of the electrical engineer. Whether on a large or small scale, electrical engineers are responsible for numerous areas of technology, including microelectronics, data communication, radio, television, lasers, fiber optics, video, audio, computer networks, speech processing, imaging systems, electric power systems, and alternative energy sources such as solar, tidal, and wind power. Many electrical engineers also work in the area of materials science because of the dependence of electronic and photonic devices on advanced semiconductor materials. The electrical engineer also designs transportation systems based on electric power, including mass transit, electric cars, and hybrid vehicles.

The typical electrical engineer has a strong background in the physical sciences, mathematics, and computational methods and also has a knowledge of circuits and electronics, semiconductor devices, analog and digital signal processing, digital systems, electromagnetics, and control systems. The electrical engineer is also fluent in many areas of computer engineering. Some of the more recent accomplishments that have involved electrical engineers include the microelectronic revolution (the microprocessor and large-scale integration on a chip), nano-devices, wireless communication (cellular telephones, data links, iPhones™), photonics (lightwave technology, lasers, and fiber-optic communication), and the so-called laboratory-on-a-chip.

1.1.8 Environmental Engineering

Environmental engineers rely on the principles of biology and chemistry to solve problems related to the environment. A myriad of job opportunities, which are important to communities and society worldwide, await the individual who is proficient in this growing discipline, similar in its core curriculum to civil engineering. In fact, the two programs are housed within the same department at many colleges and universities.



Environmental engineers may be involved in water- and air-pollution control, recycling, waste disposal, and public health issues such as acid rain, global warming, automobile emissions, wildlife protection, and ozone depletion. They may design municipal water supply and industrial wastewater treatment systems, conduct hazardous-waste management studies, or help develop regulations to prevent environmental disasters.

1.1.9 Industrial Engineering

An industrial engineer (sometimes called a manufacturing engineer) is concerned with the total life cycle of a product, from the moment of its inception to its eventual disposal and the recycling of its raw materials. Industrial engineers have the unique challenge of incorporating the latest technological advances in computing and machinery into production and manufacturing facilities. Industrial engineers are intimate with all aspects of the corporate environment, because much of what motivates the field of industrial engineering is the need to maximize output while controlling cost and environmental impact. Skills required for this discipline include knowledge of product development, materials properties, optimization, queuing theory, production techniques, machining, fabrication methods, and engineering economy. Industrial engineers also become fluent in the techniques of computer-aided design (CAD) and computer-aided manufacturing (CAM). Global manufacturing, in which products are developed for a worldwide economy, has become one of the most important aspects of industrial engineering.

A critical area in the province of the industrial engineer is the use of robotics in manufacturing. Building, moving, and controlling robots requires some knowledge of mechanical, electrical, and computer engineering. Most programs in industrial engineering include courses in these additional areas. Another important area of industrial engineering is the field of "green manufacturing," in which an understanding of the environmental impact of a product over its life cycle is considered a central part of the design process.

1.1.10 Materials Engineering

Materials engineering (sometimes called materials science) is one of the oldest engineering disciplines. It concerns the development and use of all forms of physical matter to solve problems on both the macroscopic and microscopic scale. The materials engineer applies knowledge of the basic properties of materials of all types to the solution of engineering problems. In today's high-tech society, an understanding of materials is crucial to almost all engineering endeavors. From such applications as thermal protection of reentering space vehicles to advanced battery concepts for fuel cells, lightweight composite materials for fuel-thrifty vehicles, and even the development of lighter and more efficient laptop computers, the materials engineer plays a key role. An engineer trained in this discipline—one who understands the relationship between materials properties and the performance and durability of ensuing products—is uniquely prepared to contribute to the efforts of a multidisciplinary design team.

Decades ago, the materials engineer dealt almost exclusively in metallurgy and ceramics. The traditional materials engineer was concerned with extracting ores, converting them into useful form, and understanding their properties. Advances in the development of new materials—for example, the proliferation of polymers into society during the latter half of the 20th century—greatly expanded the domain of the materials engineer and led to the creation of new products and entirely new industries. College curricula in the discipline now include elements of chemical, mechanical, civil, and electrical engineering. Modern materials engineering deals with a host of materials, including engineered polymers, high-tech ceramics, composites, liquid/solid state fluids, semiconductors, biomaterials, and nano-materials. The science of *forensics*, concerned with the analysis of materials failure and crime investigation, constitutes an additional application of this field.

1.1.11 Mechanical Engineering

The mechanical engineer is responsible for designing and building physical structures of all kinds. Any device that involves mechanical motion, be it an automobile, bicycle, engine, disk drive, keyboard, fluid valve, jet-engine turbine, wind turbine, or flight structure, requires the expertise of mechanical engineers. Mechanical engineers are fluent in statics, dynamics, materials, structural and solid mechanics, fluid mechanics, thermodynamics, heat transfer, and energy conversion. They apply these principles to a wide variety of engineering problems, including precision machining, environmental engineering, water resources, acoustics, combustion, power sources, robotics, transportation, and manufacturing systems. Mechanical engineers interface most easily with all other types of engineers because their discipline requires such a broad educational background. In addition, our most prevalent interaction with the physical world is via our sense of touch, that is, through mechanical things. The field that best complements a mechanical engineering education is electrical engineering, because so many mechanical things now interface with the world via electrical and electronic interfaces.

One of the newest areas of study related to mechanical engineering is the emerging field of nanotechnology which deals with tiny, microscopic machines fabricated on an atomic scale. "Nanotech" is also closely related to biotechnology. Nano-mechanical systems (NEMS) represents the next great step forward following the micro-electromechanical systems (MEMS) revolution of the late 1990s. The joint fields of MEMS and NEMS have the potential to do for mechanics what the integrated circuit did for electronics, namely, to permit large-scale integration of entire systems on a single semiconductor chip.

1.1.12 Mechatronics Engineering

The mechatronic engineer is fluent in mechanical engineering, electrical engineering, and robotics. As its name implies, the field of mechatronics involves the fusion of mechanical engineering, electronics, and computing toward the design of robotic

Figure 1.4
An engineer simulates nano-particles. (*Photo courtesy of Boston University Photo Services.*)

products and manufacturing systems. Engineers who work in this field require cross-disciplinary training that can best be approached by majoring in either mechanical or electrical engineering and acquiring skills in the other needed disciplines through extra courses or technical electives. Mechatronic engineers are responsible for the innovation, design, and development of machines and systems that can automate production tasks, reduce production costs, reduce plant maintenance costs, improve product flexibility, and increase production performance. The typical mechatronics engineer solves design problems for which solely mechanical or electrical solutions are not possible. Sensing and actuation are important elements of mechatronics.

1.1.13 Naval Engineering

The naval engineer (or naval architect) designs surface watercraft, submarines, barges, and other seagoing vessels, and is also involved in the design of oil platforms, shipping docks, seaports, and coastal navigation facilities. As a rule, naval architects and engineers have a broad background because many branches of engineering are involved in the design of marine vessels. Naval engineers, for example, are fluent in several of the subjects studied by mechanical engineers, including fluid mechanics, materials, structures, statics, dynamics, water propulsion, and heat transfer. In addition, naval engineers take courses on the design of ships and the history of sea travel. Many naval engineers are employed by the armed forces, but some work for companies that design and build large ships. Steeped in tradition and forever at the cutting edge of technology, naval engineering can be a rewarding career to those interested in the sea.

1.1.14 Nuclear Engineering

Nuclear engineers use their knowledge about atomic physics to solve engineering problems. They are concerned with the design and operation of nuclear reactors for use in naval vessels and electric power plants. From the sole point of view of natural resources, atomic-based power represents one alternative to our dwindling supply of fossil fuels. Nuclear engineers understand the physics of radiation and the radioactive atoms produced in nuclear reactions. Most work in private or governmental research and development laboratories. Some work at construction sites for new nuclear power plants. Nuclear engineers also may supervise fuel loading operations or the critical steps related to storage of nuclear waste.

For the second half of the 20th century, the field of nuclear engineering enjoyed widespread growth as part of efforts to find peaceful uses for atomic energy.

(U.S. Navy imagery used in illustration without endorsement expressed or implied.)

Following two severe accidents[3] and mounting concern over hazardous waste disposal, nuclear power found itself in disfavor at the turn of the millennium. As we approach the second decade of the 21st century, severe demands for energy by an ever-increasing population have renewed interest in nuclear power. Despite major global efforts, the demand for power has vastly outstripped the emergence of alternative, renewable energy source. New insights into possible ways for safe waste disposal, and a better understanding of the hazards of nuclear reactions, have fostered a new demand for nuclear engineers.

1.1.15 Petroleum Engineering

Over 70% of the world's current energy needs are derived from petroleum products, and this situation is unlikely to change for at least the next half-century. The principal challenge of the petroleum engineer is to produce oil, gas, and other energy forms from the earth's natural resources. In order to harvest these resources in an economical and environmentally safe way, the petroleum engineer must have a wide knowledge base that includes mathematics, physics, geology, and chemistry, as well as aspects of most other engineering disciplines. Elements of mechanical, chemical, electrical, civil, and industrial engineering are found in most programs in petroleum engineering. Also, because computers are used with ever-increasing frequency in geological exploration, oil-field production, and drilling operations, computer engineering has become an important specialty within petroleum engineering. Many of the world's supercomputers are owned by petroleum companies.

In addition to conventional oil and gas recovery, petroleum engineers apply new technology to the enhanced recovery of hydrocarbons from oil shale, tar sands, offshore oil deposits, and fields of natural gas. They also design new techniques for recovering residual ground oil that has been left by traditional pumping methods. Examples include the use of underground combustion, steam injection, and chemical water treatment to release oil trapped in the pores of rock. These techniques will likely be used in the future for other geological operations, including uranium leaching, geothermal energy production, and coal gasification. Petroleum engineers also work in the related areas of pollution reduction, underground waste disposal, and hydrology. Because many petroleum companies operate on a worldwide scale, the petroleum engineer has the opportunity to work in numerous foreign countries.

1.1.16 Systems Engineering

In the computer industry, the designation "systems engineer" has come to mean someone who deals exclusively with large-scale software systems. The traditional systems engineer, however, can be anyone who designs and implements complex engineering systems. As the complexity of such entities has increased, so has the demand for systems engineers. These professionals understand how complex engineering projects must be designed and managed and deal not only with initial design, but also with logistics, team coordination, and project supervision. Design efforts bearing the stamp of the systems engineer include communication networks, information systems, transportation infrastructure, large-scale manufacturing systems, power distribution networks, and avionics. Other focal areas include automation, robotics and control, computational biology, information science, and

[3]Three Mile Island, PA (1979); Chernobyl, Ukraine (1986)

supply-chain management. Systems engineers also help define the needs and function of consumer products early on in the development cycle. Programs of study in this diverse field include courses in applied mathematics, computer simulation, software, electronics, communications, and automatic control. Because of their broad educational background, systems engineers are comfortable working with most other types of engineers.

1.2 SOME ENGINEERING PROFESSIONAL ORGANIZATIONS

Most branches of engineering are represented by professional societies that bring together members of similar background, training, and professional expertise. These societies operate on a worldwide scale and publish numerous journals for which engineers write papers and articles of interest to the field. Each organization offers its members technical and informational services, post-college training, industry standards, workshops, and conferences. In some cases, other professional services are offered as well, including job networks, advertising, e-mail accounts, product information, web page hosting, and even life and health insurance. All provide student membership at a discount, and student chapters at colleges and universities are common. This section provides information about some of the principal professional organizations. The text provided here has been excerpted from each organization's web page.

1.2.1 American Institute of Aeronautics and Astronautics (*www.aiaa.org*)

> "AIAA advances the state of aerospace science, engineering, and technological leadership. For more than 70 years, AIAA has been the principal society of the aerospace engineer and scientist. In 1963, the American Rocket Society and the Institute of Aerospace Science joined to become AIAA. Both brought long and eventful histories to the relationship – histories that stretched back to 1930 and 1932 respectively, a time when rocketry was the stuff of science fiction and the aviation business was still in its infancy.
>
> "Each society left its distinct mark on AIAA. The merger combined the imaginative, risk-taking, shoot-for-the-moon outlook of Project Mercury-era rocket, missile, and space professionals with the more established, well-recognized, industry-building achievers of the aviation community. The resulting synergy has benefited aerospace ever since.
>
> "Today, with more than 31,000 members, AIAA is the world's largest professional society devoted to the progress of engineering and science in aviation, space, and defense. The Institute continues to be the principal voice, information resource, and publisher for aerospace engineers, scientists, managers, policymakers, students, and educators. AIAA is also the go-to resource for stimulating professional accomplishment and standards-driven excellence in all areas of aerospace for prominent corporations and government organizations worldwide."

Key Publications: *Aerospace America, AIAA Bulletin, Journal of Aircraft, Journal of Spacecraft and Rockets, Journal of Energy, Journal of Aerospace Computing, Information, and Communication.*

1.2.2 Biomedical Engineering Society (*www.bmes.org*)

"In response to a manifest need to provide a society that gave equal status to representatives of both biomedical and engineering interests, the Biomedical Engineering Society was incorporated in Illinois on February 1, 1968. As stated in the Articles of Incorporation, and modified by approval of the Board of Directors in October, 2006, the purpose of the Society is to promote and enhance biomedical engineering knowledge worldwide and its utilization for the health and well being of humankind.

"Initially, the membership of the Society consisted of 171 Founding members and 89 Charter members. With the cooperation of the Federation of American Societies for Experimental Biology, the first Open Meeting of the Biomedical Engineering Society was held at the Ritz-Carlton Hotel in Atlantic City on April 17, 1968.

"The first Annual Meeting of the Biomedical Engineering Society was held in Houston, November 18-20, 1968, in conjunction with the 21st Annual Conference on Engineering in Medicine and Biology."

Key Publications: *BMES Bulletin*, and *Annals of Biomedical Engineering*, *Cellular and Molecular Bioengineering Journal*

1.2.3 American Institute of Chemical Engineers *(www.aiche.org)*

"AIChE is the world's leading organization for chemical engineering professionals, with more than 40,000 members from 93 countries. AIChE has the breadth of resources and expertise you need whether you are in core process industries or emerging areas, such as nanobiotechnology.

"As a member, you can access information on recognized and promising chemical engineering processes and methods. Connect with a global network of intelligent, resourceful colleagues and their shared wisdom. Find learning opportunities from recognized authorities—all of which can help you move forward professionally and enrich the world we live in.

"AIChE's vision is to provide value as the global leader of the chemical engineering profession, the lifetime center for professional and personal growth, and security of chemical engineers, and the foremost catalyst in applying chemical engineering expertise in meeting societal needs."

Key Publications: *Chemical Engineering Progress, AIChE Journal, Environmental Progress, Process Safety Progress*, and *Biotechnology Progress*.

1.2.4 American Society of Civil Engineers *(www.asce.org)*

"Founded in 1852, the American Society of Civil Engineers (ASCE) represents more than 123,000 members of the civil engineering profession worldwide, and is America's oldest national engineering society. ASCE's vision is to position engineers as global leaders building a better quality of life."

"ASCE's mission is to provide essential value to our members, their careers, our partners and the public by developing leadership, advancing technology, advocating lifelong learning and promoting the profession. From the building of the Parthenon in 432 B.C. to the building of the Petronas Towers today, the civil engineering profession has proven its sustainability. Withstanding the passage of time, civil engineers have built cultural landmarks that stand in tribute to the profession's creative spirit and ingenuity."

"Civil engineers are trained to plan, build, and improve the water, sewer, and transportation systems that you depend on everyday. They build dams able to withstand the crushing pressure of a lake full of water. They build bridges able to resist the forces of wind and traffic. They develop environmentally friendly materials and methods, and they build things to last. So skilled is their work that we rarely stop to wonder how they design the mammoth skyscrapers we work in, the tunnels we drive in, and the stadium domes we sit beneath."

Key Publications: *ASCE News, Civil Engineering Magazine*, plus numerous journals on specialized topics in civil engineering.

1.2.5 Association for Computing Machinery *(www.acm.org)*

"The Association for Computing Machinery is an educational and scientific society uniting the world's computing educators, researchers, and professionals to inspire dialogue, share resources, and address the field's challenges. ACM strengthens the profession's collective voice through strong leadership, promotion of the highest standards, and recognition of technical excellence. ACM supports the professional growth of its members by providing opportunities for life-long learning, career development, and professional networking.

"The ACM is widely recognized as the premier membership organization for computing professionals, delivering resources that advance computing as a science and a profession; enable professional development; and promote policies and research that benefit society.

"ACM hosts the computing industry's leading Digital Library and Guide to Computing Literature, and serves its global members and the computing profession with journals and magazines, conferences, workshops, electronic forums, and Online Books and Courses."

Key Publications: *Communications of the ACM*, *The ACM Digital Library* (a collection of online publications), plus numerous technical transactions including *Computer–Human Interaction, Computer Systems, Database Systems, Modeling and Computer Simulation, Networking,* and *Software Engineering and Methodology*.

1.2.6 Institute of Electrical and Electronic Engineers (*www.ieee.org*)

"IEEE's core purpose is to foster technological innovation and excellence for the benefit of humanity. IEEE will be essential to the global technical community and to technical professionals everywhere, and be universally recognized for the contributions of technology and of technical professionals in improving global conditions.

"A nonprofit organization, IEEE is the world's leading professional association for the advancement of technology. The IEEE name was originally an acronym for the Institute of Electrical and Electronics Engineers, Inc. Today, the organization's scope of interest has expanded into so many related fields that it is simply referred to by the letters I-E-E-E (pronounced Eye-triple-E). Through its global membership, IEEE is a leading authority on areas ranging from aerospace systems, computers, and telecommunications to biomedical engineering, electric power, and consumer electronics, among others. Members rely on IEEE as a source of technical and professional information, resources, and services.

"To foster an interest in the engineering profession, IEEE also serves student members in colleges and universities around the world. Other important constituencies include prospective members and organizations that purchase IEEE products and participate in conferences or other IEEE programs."

Key Publications: *IEEE Spectrum, Proceedings of the IEEE,* plus over 40 specialized *IEEE Transactions* from its various societies including: Aerospace and Electronic Systems; Automatic Control; Biomedical Engineering; Circuits and Devices; Communications; Control Systems; Dielectrics and Electrical Insulation; Electromagnetic Compatibility; Energy Conversion; Engineering Management; Image Processing; Industry Applications; Lasers and Electro-Optics; Mechatronics; Micro-Electromechanical Systems; Neural Networks; Parallel and Distributed Systems; Photonics; Power Electronics; Quantum Electronics; Robotics and Automation; Signal Processing; Software Engineering; Solid-State Circuits; Vehicular Technology; and Visualization and Computer Graphics.

1.2.7 IEEE Computer Engineering Society (*www.computer.org*)

The IEEE Computer Engineering Society (CS), a subset of the IEEE, "is the world's leading organization of computing professionals. Founded in 1946, the CS is dedicated to advancing the theory and application of computer and information-processing technology.

"The CS serves the information and career-development needs of today's computing researchers and practitioners with technical journals, magazines, conferences, books, conference publications, and online courses. Its Certified Software Development Professional (CSDP) program for mid-career professionals and Certified Software Development Associate (CSDA) credential for recent college graduates confirm the skill and knowledge of those working in the field. Known worldwide for its computer-standards activities, the CS promotes an active exchange of ideas and technological innovation among its members.

"With about 40 percent of its members living and working outside the United States, the CS fosters international communication, cooperation, and information exchange. It monitors and evaluates curriculum accreditation guidelines through its ties with the US Computing Sciences Accreditation Board and the Accreditation Board for Engineering and Technology."

Key Publications: *Computing in Science and Engineering, IEEE Transactions on Computers, IEEE Transactions on Software Engineering,* plus a host of additional transactions and technical journals.

1.2.8 Institute of Industrial Engineers (*www.iienet.org*)

> "The Institute of Industrial Engineers (IIE) is the world's largest professional society dedicated solely to the support of the industrial engineering profession and individuals involved with improving quality and productivity. Founded in 1948, IIE is an international nonprofit association that provides leadership for the application, education, training, research, and development of industrial engineering.
>
> "With approximately 15,000 members and 280 chapters worldwide, IIE's primary mission is to meet the ever-changing needs of industrial engineers, which includes undergraduate and graduate students, engineering practitioners and consultants in all industries, engineering managers, and engineers in education, research, and government. IIE is recognized internationally as the leading provider of cutting-edge continuing education in industrial engineering, and an association that supports the profession of industrial engineering and promotes an increased awareness of the value of industrial engineers.
>
> "IIE provides leadership in developing industrial engineering; in representing the industrial engineering profession; and in enhancing the capabilities of those who are involved in or manage the application, education, training, research or development of industrial engineering."

Key Publications: *Industrial Engineer, Industrial Management, IIE Transactions, The Engineering Economist.*

1.2.9 American Society of Mechanical Engineers *(www.asme.org)*

> "Founded in 1880 as the American Society of Mechanical Engineers, ASME is a not-for-profit professional organization promoting the art, science, and practice of mechanical and multidisciplinary engineering and allied sciences. ASME develops codes and standards that enhance public safety, and provides lifelong learning and technical exchange opportunities benefiting the global engineering and technology community. ASME has more than 127,000 members worldwide.
>
> "The vision of ASME is to be the premier organization for promoting the art, science and practice of mechanical and multidisciplinary engineering and allied sciences to our diverse communities throughout the world.
>
> "Our mission is to promote and enhance the technical competency and professional well-being of our members, and through quality programs and activities in mechanical engineering, better enable its practitioners to contribute to the well-being of humankind."

Key Publications: *Mechanical Engineering, Journal of Applied Mechanics, Journal of Applied Mechanics Reviews*, plus journals in numerous specialty areas, including applied mechanics, Arctic engineering, biomechanical engineering, computing and information science, dynamic systems, electronic packaging, energy turbines and power engineering, materials technology fluids, heat transfer, manufacturing science, mechanical design, mechatronics, measurement and control, offshore mechanics, pressure vessel technology, solar energy, tribology, turbomachinery, and vibration and acoustics.

1.2.10 Society of Petroleum Engineers (*www.spe.org*)

"The mission of the Society of Petroleum Engineers is to collect, disseminate, and exchange technical knowledge concerning the exploration, development, and production of oil and gas resources, and related technologies for the public benefit; and to provide opportunities for professionals to enhance their technical and professional competence, and to be a society of professional excellence, providing its members the highest quality lifelong learning, and continuous personal and professional growth.

"Total professional and student membership in the Society of Petroleum Engineers grew 8 percent to a record 79,300 members worldwide in 2007, including an increase in members under age 35. SPE membership includes engineers, scientists, technicians, managers, operators, educators and other professionals who work in the global upstream oil and gas industry, as well as students who are studying petroleum engineering or a related field.

Key Publication: *Journal of Petroleum Technology*

1.2.11 American Society of Agricultural and Biological Engineers (*www.asabe.org*)

"The American Society of Agricultural and Biological Engineers is an educational and scientific organization dedicated to the advancement of engineering applicable to agricultural, food, and biological systems. Founded in 1907 and headquartered in St Joseph, Michigan, ASABE comprises 9,000 members in more than 100 countries. Agricultural, food and biological engineers develop efficient and environmentally sensitive methods of producing food, fiber, timber, and renewable energy sources for an ever-increasing world population.

"The ASABE represents technical specialties in areas of biological engineering, education, food and process engineering, information and electrical technologies, power and machinery, soil and water, structures and environment, ergonomics, safety and health, forest engineering, and aquaculture engineering. Society activities are also conducted through geographic sections, affiliated communities, and special programs, including an active preprofessional (student) group for individuals contemplating or preparing for a career in agricultural, food, and biological engineering. ASABE membership is open to all (engineers as well as nonengineers) who are interested in the knowledge and application of engineering in agricultural, food, and biological systems."

Key Publications: *Biological Engineering, Applied Engineering in Agriculture, Transactions of the ASABE, Journal of Agricultural Safety & Health*

1.2.12 American Society of Naval Engineers (*www.navalengineers.org*)

The purpose of the Society of Naval Engineers is, "to advance the knowledge and practice of naval engineering in public and private applications and operations, to enhance the professionalism and well-being of members, and to promote naval engineering as a career field.

Society membership is drawn from a broad spectrum of military and civilian professionals and students, engaged in or associated with the many facets of naval engineering. An ASNE headquarters is maintained in Alexandria, Virginia.

"Naval engineering includes all arts and sciences as applied in the research, development, design, construction, operation, maintenance and logistic support of surface and subsurface ships and marine craft, naval maritime auxiliaries, ship-related aviation and space systems, combat systems, command control, electronics and ordnance systems, ocean structures and fixed and mobile shore facilities which are used by the naval and other military forces and civilian maritime organizations for the defense and well-being of the Nation."

Key Publication: *Naval Engineers Journal*

Professional Success: Choosing A Field of Engineering

If you are a first-year student of engineering, you may already have decided upon a major field. After taking several required courses, however, you may not be sure if you've chosen the right type of engineering. Conversely, you may have entered school without committing yourself to any one field of engineering. If you find yourself in either of these situations, you're probably wondering how to choose a career direction in engineering.

One way to find out more about the different branches of engineering is to attend technical talks and seminars hosted by the engineering departments in your college or university. Such talks are usually aimed at graduate students and faculty, so much of the material will be over your head. Simply *exposing* yourself to these technical talks, however, will give you a feeling for the various branches of engineering and help you find one that most closely matches your skills and interests.

Most schools host workshops on career advising. Be sure to attend one. Talk with the experts in career planning and job placement. Most college campuses host student chapters of professional organizations. These groups often organize tours of engineering companies. Attending such a tour can provide a valuable perspective about the activities of a particular branch of engineering and give you an idea about what life as an engineer will be like.

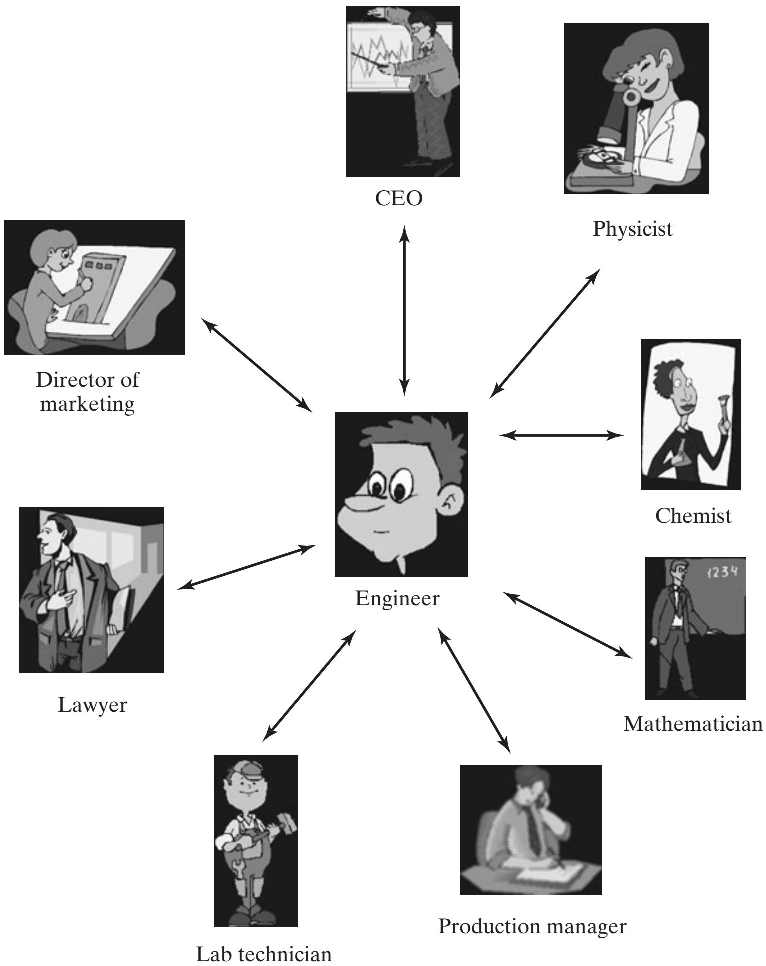
One of the most valuable resources for career advice is your own college faculty. Get advice from your advisor about which major is right for you. Most professors love to talk about their work. Invite a professor to your dormitory or living unit to speak to students about choosing an engineering career. Speak to your department about hosting a career night in which a panel of professors will answer questions about engineering jobs. Learn to make use of all available resources for help in choosing your college major.

1.3 THE ENGINEER: CENTRAL TO PROJECT MANAGEMENT

The word "engineer" may conjure visions of a lone individual sitting in a cubicle at a computer terminal, or perhaps in a workshop, crafting some marvelous piece of technical wizardry. As a student, you may be eager to pursue this notion of the rugged individual—the genius entrepreneur who single-handedly changes the face of technology, perhaps the next Bill Gates or Dean Kamin. You might ask, "Why do I have to take all of these *other* courses? Why can't I just take courses that are of interest to me?" The answer lies in the multidisciplinary nature of engineering. At times, an engineer does work alone, but most of the time engineers must interact with individuals who come from very different educational backgrounds. Engineering projects are often complex undertakings that require teamwork and the coordination of many people possessing different skills and personality traits. An engineer must learn the language of physicists, mathematicians, chemists, managers, fabricators, technicians, lawyers, marketers, and secretaries. It's been said that good engineers are the glue that ties a project together, because they have learned to communicate with specialists from each of these varied fields. Learning to communicate across a variety of occupations requires the engineer to have a broad education and the ability to apply a full range of skills and knowledge to the design process.

To illustrate the breadth of communication skills required of an engineer, imagine that you work for the fictitious company depicted in Figure 1.5. Each person shown in the outer circle possesses a different professional expertise, while you, a design engineer, lie in the center of the organizational circle. Other engineers on

Figure 1.5
The professional circle has the design engineer in the center.



your design team may join you in the center, and each of you can easily communicate with each other due to your similar training. But each of you can also communicate with each of the specialists in the outer ring. As engineers, you've taken courses or have been exposed to each of their various disciplines. This unique feature of your educational background enables you to communicate with anyone in the professional circle and positions you as one of the individuals most likely to act as central coordinator.

The Physicist

The physicist of the company is responsible for understanding the basic physical principles that underlie the company's product line. She spends her time in the laboratory exploring new materials and analyzing their interactions with heat, light, and electromagnetic radiation. She may discover a previously unknown quantum interaction that will lead to a new semiconductor device, or perhaps she will explore the potential for using superconductors in a company product. Or she may simply perform the physical analysis for a new micro-accelerometer. Because you've taken two or more semesters of basic physics and have learned some mechanics, thermodynamics, and electromagnetics, you can easily converse with the physicist and discuss how her basic discoveries relate to the practical interests of the company.

The Chemist

The chemist analyzes materials and substances used in producing company products. She ensures that raw materials used for manufacturing meet purity specifications so that quality control can be maintained. In her laboratory, she directs a team of experimentalists who seek to discover improved materials that are stronger and more durable than those currently being used. She may perform research on complex organic compounds or perhaps work on molecular-based nanotechnology. As an engineer, you've taken one or more courses in chemistry and can speak her language. You understand such concepts as reaction rates, chemical equilibrium, molarity, reduction and oxidation, acids and bases, and electrochemical potential. Perhaps you're a software engineer writing a program that will control a chemical-analysis instrument. Maybe you are a chemical engineer charged with translating a chemical reaction into a manufactured product. Whatever your role, you are an individual very well suited to bringing the contributions of the chemist to the design process.

The Mathematician

The mathematician of the company, who might also be a computer scientist, worries about such things as modeling, statistics, databases, and forecasting. He may be involved in an intriguing new database algorithm or mathematical method for modeling an engineering system. Perhaps he uses mathematics to analyze the company's production line or to forecast trends in marketing. You converse easily with the mathematician, because you have taken numerous math courses as part of your engineering program. Although your emphasis has been on applied, rather than pure, mathematics, you're familiar with calculus, differential equations, linear algebra, statistics, probability, vector algebra, and complex variables. You can easily apply the concepts of mathematics to problems in engineering design.

The Production Manager

Like the army officer in command, the production manager is responsible for mobilizing materials, supplies, and personnel to manufacture company products. He may consider such things as job scheduling, quality control, materials allocation, quality assurance testing, and yield. As the engineer who designs products, you work closely with the production manager to make sure that your design approach is compatible with the company's manufacturing capabilities. Your training as an engineer and your exposure to machining, welding, circuit fabrication, and automation have given you the ability to understand the job of the production manager and have provided you with the vocabulary needed to communicate with him.

The Lab Technician

The lab technician is an indispensable member of the design team. A habitual tinkerer and experimenter, the lab technician helps bring your design product to fruition. He is adept at using tools and has much knowledge about the practical aspects of engineering. The lab technician is masterful at fabricating prototypes and is likely to be the individual who sets up and tests them. The typical lab technician has a degree in engineering technology; hence, you may have taken many of the same courses as he has taken, although your courses probably included more formal theory and mathematics than his. You communicate easily with the lab technician and include him in each phase of your design project.

The Lawyer

The lawyer is concerned with the legal aspects of the company's products. Should we apply for a patent on the XYZ widget? Are we exposing ourselves to a liability suit if we market a particular product? Is our new deal with Apex, Inc. fair to both companies from a legal perspective? To help the lawyer answer these questions, you must be able to communicate with him and share your engineering knowledge. The logical thought that forms the basis of law is similar to the methods you've used to solve countless engineering problems. As an engineer, you easily engage in discourse with the lawyer and can apply his legal concerns about safety, ethics, and liability to the design process.

The Director of Marketing

The director of marketing is a master of imagery and style. She has the job of selling the company's products to the public and convincing people that your products are better than those of your competitors. The marketing manager has excellent communication skills, some knowledge of economics, and an understanding of what makes people want to buy. You interface easily with the marketing manager because you've dealt with all aspects of design as part of your training as an engineer. Through this training, you have focused not only on technical issues, but also on such things as product appearance, the human–machine interface, durability, safety, and ease of use. Your familiarity with these important issues has prepared you to help the director of marketing understand your product and how it works. You are able to respond to her concerns regarding what the public needs from the products that you design.

The President/Chief Executive Officer

The CEO of the company probably has an MBA (Master's of Business Administration) or higher degree and a long history working at corporate financial affairs. The CEO worries about the economy and what future markets the company should pursue or whether to open a new plant in a foreign country. It's the CEO who determines how your current project will be financed, and he needs to be kept up to date about its progress. The CEO also may ask you to assess the feasibility of a new technology or product concept. As an engineer, you have no difficulty conversing with the CEO, because the economic principles of profit and loss, cost derivatives, statistics, and forecasting are closely tied to concepts you learned in calculus, statistics, and economics. You've learned to use spreadsheets in one or more engineering classes and have no trouble interpreting or providing the information that is part of the CEO's world. Likewise, your training as an engineer prepares you to communicate with the CEO about the impact of your projects on the economic health of the company.

1.4 ENGINEERING: A SET OF SKILLS

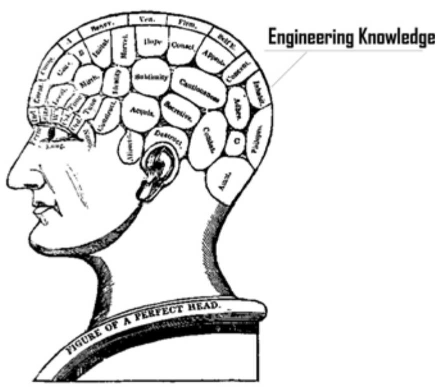
To be successful, an engineer must acquire technical, theoretical, and practical competence and must also be good at organization, communication, and documentation. Three especially important skills that lie at the foundation of engineering are *knowledge, experience*, and *intuition*. These talents do not form an exhaustive set, but they are crucial to the well-rounded engineer.

1.4.1 Knowledge

Knowledge describes the body of facts, scientific principles, and mathematical tools that an engineer uses to form strategies, analyze systems, and predict results. An engineer's acquired knowledge can provide a deeper understanding of how something works. The natural sciences (for example physics, chemistry and biology) help an engineer understand the physical world. Mathematics provides a universal technical language that bridges different disciplines and can be understood by anyone regardless of spoken language or cultural background. Each field of engineering has its own traditional body of knowledge, but an engineer in one field also learns subjects from other fields. Areas of knowledge that are common to all engineers include mechanics, circuits, materials science, and computer programming.

As a student of engineering, you may ask why you are required to take subjects that seem irrelevant to your career aspirations. Any experienced engineer will tell you the answer: Engineers work in a multidisciplinary world where a basic knowledge of many different subject areas is an absolute necessity. Examples abound: mechanical and computer engineers use electrical circuits. Electrical engineers build physical structures design biomedical electronics. Aeronautical engineers rely on software systems and need to know about materials. Software engineers design civil infrastructure systems. Understanding the field of another engineer is critical to cross-disciplinary communication and design proficiency.

Although formal education is an important part of any engineer's training, the prudent engineer also acquires knowledge through on-the-job training and a lifetime of study and exploration. Tinkering, fixing, experimenting, and taking things



Knowledge is an important part of engineering. (graphic courtesy of Fermi National Laboratory) apart to see how they work also are important sources of engineering knowledge. As a young person, did you disassemble your toys, put together models, write your own computer games, create Web pages, or play with building sets, jewelry construction kits, hammers, nails, glue guns, picture hangers, radios, bicycles, or cars? Without knowing it, you began the path toward acquiring engineering knowledge. The professional engineer engages in these same practices. By becoming involved in all aspects of a design project, by keeping up to date with the latest technology, by taking professional development courses and solving real world problems, the practicing engineer remains current and competent.

1.4.2 Experience

Experience refers to the body of methods, procedures, techniques, and rules of thumb that an engineer uses to solve problems. For the engineer, accumulating experience is just as important as acquiring knowledge. As a student, you will have several opportunities to gain engineering experience. Cooperative assignments, assistantships in labs, capstone design projects, summer jobs, and research work in a professor's laboratory provide important sources of engineering experience. On-the-job training is also a good way to gain valuable professional experience. Many engineering companies recognize this need and provide entry-level engineers with initial training as a way of infusing additional experience not acquired in college. Developing experience requires "seasoning," the process by which a novice engineer gradually learns the "tricks of the trade" from other, more experienced engineers. Company lore about methods, procedures, and history is often passed orally, from one engineer to another, and a new engineer learns this information by working with other engineers. The history of what *hasn't* worked in the past is an important part of this oral tradition.

An engineer also gains valuable experience by enduring design *failure*. When the first attempt at a project fails in the testing phase, the wise engineer views it as a learning experience and uses the information to make needed changes and alterations. Experience is acquired by testing prototypes, studying failures, and observing the results of design decisions.

Engineers also must consider the issues of reliability, cost, manufacturability, ergonomics, and marketability when making design decisions. Only by confronting these constraints in real-world situations can an engineer truly gain experience.

Photo courtesy of NASA

1.4.3 Intuition

Intuition is a characteristic normally associated with fortune-tellers, stockbrokers, and baseball players. Successful engineers, however, also employ intuition from time to time. To the engineer, intuition refers to a basic instinct about what will or will not work as a problem solution. In the age of the calculator, it's easy to let the results of key punching (*the calculated volume of my cup is 1.7694 cubic meters*) assume the role of a correct answer over an intuitive feeling for what might actually be reasonable (*a cup can't be as big as my desk*!). Although intuition can never replace careful analysis and meticulous design work, it can help an engineer decide which approach to follow when faced with many choices and no obvious answer. An intuitive feeling for what will work, as well as what will *not* work, grounded in extensive experience and knowledge, can save time by helping an engineer choose the path that will eventually lead to success rather than failure. When intuition is at work, you may hear an engineer using such phrases as "That seems reasonable" or "That answer is plausible."

Intuition is a direct byproduct of design experience and is acquired only through practice, practice, and more practice. In the information age, where much of engineering focuses on the computer, engineers are tempted to solve everything by simulation and computer modeling. While computers have dramatically accelerated the design cycle and have changed the practice of engineering, they make it easy to forget that a product ultimately must obey the idiosyncrasies of the real physical world. Developing intuition about that world is an important part of your engineering education. The difference between a good engineer and an excellent one is often just an instinct for how the laws of nature will manifest themselves in the design process. Will too much power overheat that circuit? Will friction rob that engine of too much power? How much oil can we reliably extract from that shale? How big should the vessel be for a production run of that new cosmetic? Will this ship float? Will this spacecraft fly? Developing intuition should be a key goal of your engineering education.

Examine your own experiences to date to see if you have already acquired some intuition. Do you alter computer settings just to see what happens? Have you opened the hood of the family car just to see what lies beneath it? Have you adjusted the gears on your bicycle? Have you put together a kit or built your science project from raw materials? Have you built a birdhouse? Each of these tasks helps you acquire intuition. Observing the way in which other engineers have laid out the boards of a computer will acquaint you with the techniques of hardware design. Adjusting the gear and brake settings of your bicycle will help you to understand design tradeoffs, such as the conflict between strength and durability versus lightweight construction. Building a birdhouse will acquaint you with the geometrical principles that lie at the core many fields of structural engineering. Becoming knowledgeable in the use of tools will help you to better understand the impact of

your design decisions on manufacturing. Repetition, testing, careful attention to detail, working with more experienced engineers, and dedication to your discipline are the keys to developing design intuition. Design intuition is best acquired by "doing design," that is, by playing with real things.

Professional Success: How to Gain Experience as a Student

This chapter stresses the importance of experience in the life of an engineer. You can begin to acquire design experience even while you are a student. A cooperative education program, if your school has one, is an excellent way to gain experience as an engineer. The typical program places you as an intern in an engineering company for six to twelve months. You'll typically be assigned to a senior engineer to assist in such tasks as computer-aided design, software development, product prototyping, testing, laboratory evaluation, or other work. You'll get to see how the company works, and the company will get to evaluate you as a possible future hire. In addition, you'll be paid for the time you spend at the company.

Students can also gain valuable experience by working in research labs at school. Most professors are delighted to take eager undergraduates into their research laboratories. Most schools list the research interests of the faculty on departmental Web pages. Learn about the research activities of a professor whose class you have enjoyed. Don't be afraid to simply ask if the professor needs help in the lab. Many professors receive industry or government funding for their research, so you may even be paid an hourly wage or a small stipend for your time. You'll be assigned such tasks as fabricating experiments, wiring circuits, writing programs, taking data, preparing test samples, or assisting graduate students.

KEY TERMS

Career	Intuition	Management
Engineering	Knowledge	Profession

CHAPTER 2

What Is Design?

Objectives

In this chapter, you will learn about:

- The engineering design process
- The difference between design, analysis, and replication
- The difference between good and bad design
- The elements of the design cycle
- How to generate ideas through brainstorming

Engineers have made tremendous contributions to the quality of life since the dawn of the industrial age. Automobiles, bicycles, airplanes, space exploration, digital communication, Internet, lifesaving medical devices, all forms of entertainment, global shipping networks, international transportation systems, fuel infrastructure, the national power grid, cellular-telephone networks, fax machines, and the global positioning system all began with one common feature: engineering *design*. One way to define design is that it's any activity whose objective is to meet a need. The object of design might be a physical device, such as a machine or building. Alternatively, the objective might be something less tangible, such as a software program, operating system, web infrastructure, manufacturing method, or process control. In the engineering profession, the word "design" simply answers the question, "What do engineers do?"

2.1 THE USE OF THE WORD "DESIGN"

The common dictionary definition of the word "design" may be found, for example, in Merriam-Webster's online dictionary[1]:

> *design:* to create, fashion, execute, or construct according to plan.

In this book, however, the word "design" will be assigned specific meanings appropriate to the engineering profession. It may be used as a verb (*design a widget that can slice a pizza into five even pieces*), or it might be used as a noun that defines the creation process itself (*learning design is an important part of engineering education*). Alternatively, the word "design" may be used as a noun that describes the end product of an engineer's efforts (*the design was a success and met the customer's specifications*). The word also may be used as an adjective (*this book will help you learn the design process*).

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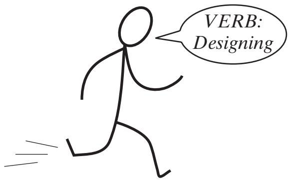
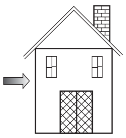
[1]Merriam-Webster Online (*www.m-w.com*)



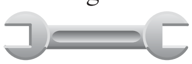
Sometimes, we'll need another word to describe the end goal of a particular design process. For this purpose, we may use the word "product" in its generic sense, even if the item being designed is not a product for sale. Similarly, the word "device" may be used to describe the results of a design effort, even if the entity is not a physical apparatus. Thus, the words *product* and *device* may refer not only to tangible objects, but also to systems, procedures, processes, and software.

2.2. THE DIFFERENCE BETWEEN ANALYSIS, DESIGN, AND REPLICATION

Noun:
THE DESIGN



Adjective:
"The Design Product"



Students of engineering are often confused by the distinction between *analysis*, *design*, and *replication*. In science classes, such as chemistry and physics, students are asked to take and evaluate data and then report the results. This process is known as *analysis*. The word "analysis" can also be applied whenever mathematics is used to predict or confirm the results of an experiment. In contrast, students of engineering are often asked to engage in *design*. Design is an open-ended process where more than one feasible solution may exist. The goal of design is to converge on the best possible solution. In this context, "best" encompasses many factors, including cost, accuracy, robustness, safety, and feasibility. The engineer seeks to meet a set of predetermined specifications, rather than to uncover the secrets behind some physical phenomenon. The difference between analysis and design might be defined in the following way: If the answer can be found by putting together the pieces of a puzzle, then the activity is probably analysis. For example, processing data and using it to test a theory is analysis. On the other hand, if more than one solution exists, and if deciding upon a suitable path demands creativity, choice, testing, iterating, and evaluating, then the activity is most certainly design. Design often includes analysis as one of its component steps, but it always involves creativity and choice as key ingredients.

One example of the difference between analysis and design can be found in the weather monitoring buoys shown in Figure 2.1. These remote-controlled stations, maintained by the National Oceanic and Atmospheric Administration over all U.S. coastlines and waterways, provide vital data to mariners. Processing data from these buoys and using them to forecast the weather are examples of analysis. Deciding how to *build* the buoys so that they meet the specifications of NOAA is an example of design.

Figure 2.1
Building NOAA weather buoys requires engineering design. Interpreting the data from them involves analysis. (*Photo courtesy of the National Oceanic and Atmospheric Admisnistration.*)

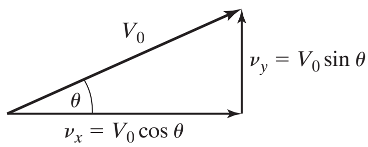
Figure 2.2
The Lyle gun was used to launch rescue lines to vessels that ran aground along the rocky coasts of the Atlantic.

Another example that illustrates the difference between analysis and design can be found in the apparatus of Figure 2.2. The Lyle gun was invented at the behest of the U.S. government by an engineer named David A. Lyle in the late 1800s. This device was used to launch rescue lines to vessels that ran aground along the rocky coasts of the Atlantic. A crude cannon of sorts, the *Lyle gun* saved numerous lives at a time when ships sailed without the benefit of modern navigational aids. The Lyle gun worked by launching a tethered rescue buoy toward a stricken ship. The tether was then used to string a strong rescue cable from ship to shore. Sailors were pulled ashore in a basket hanging from the breeching cable. Of paramount importance was ensuring that the launched buoy projectile successfully reached its target.

Analysis

The development of the Lyle gun no doubt involved much engineering design. Determining the x–y trajectory of its launched, tethered projectile—a critical part of the effort—is an analysis problem.

The Lyle gun exerts an impulse force on the buoy only at the moment of launch, imparting to the buoy initial x and y velocity components v_x and v_y. Thereafter, the buoy follows a free trajectory, subject only to the forces of gravity, air resistance, and drag of the trailing tether. To help get a feeling for the problem, let's simplify it by ignoring air resistance and tether drag in the analysis to follow. (In a real engineering project, one would never ignore these secondary forces without firmly establishing their effects to be negligible.) With these secondary forces ignored, it's a fact of physics that after initial launch, the buoy will feel no x-directed forces, but only the y-directed force of gravity. Hence, the x-component of the buoy's velocity will remain unchanged. Conversely, the y-component of its velocity will be altered by the effect of gravity.



If the initial velocity components of the projectile upon exit from the Lyle gun are designated V_{x0} and V_{y0}, the situation for $t > 0$, after the launch at $t = 0$, can be described by the equations

$$\mathbf{F} = m\mathbf{a} \tag{2.1}$$

$$v_x = V_{x0} \tag{2.2}$$

and

$$v_y = V_{y0} - gt \tag{2.3}$$

If you've had some calculus already, you know that Eq. (2.3) may be found by integrating Newton's Law of Motion: $\mathbf{F} = \mathrm{m}\mathbf{a}$. (If you've not yet had calculus, don't worry. Our analysis will proceed directly from Eqs. 2.2 and 2.3).

Here, g is the gravitational constant ($9.8\ \mathrm{m/s^2}$), and t is in seconds. In a practical situation, the capabilities of the Lyle gun are known; hence, it is possible to adjust the buoy's total initial velocity V_0 as well as its launch angle θ relative to the horizontal. These values can be used to find the x and y components of the initial launch velocity:

$$V_{x0} = V_0 \cos\theta \tag{2.4}$$

and

$$V_{y0} = V_0 \sin\theta, \tag{2.5}$$

where V_{x0} and V_{y0} at $t = 0$ are related to V_0 by the equation:

$$V_0^2 = V_{x0}^2 + V_{y0}^2 \tag{2.6}$$

With this information, it's possible to fully analyze the buoy's trajectory and predict its landing point. The launch speed V_0 and the launch angle θ of the buoy are set by the user of the Lyle gun by adjusting the amount of explosive charge and cannon inclination, respectively. As suggested by Figure 2.3, the user must first choose

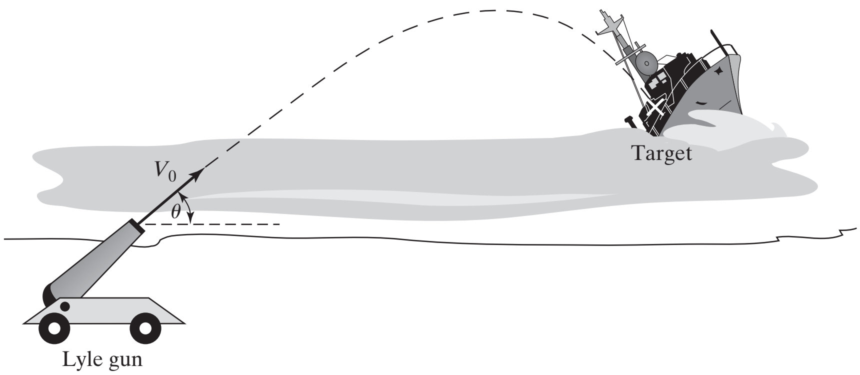


Figure 2.3
A Lyle gun sends a projectile along a trajectory toward a target. Computing the parameters needed to hit the target is an example of analysis. Determining how to best build the device is an example of design.

the target point (presumably a waiting recipient on the stricken ship), then adjust V_0 and θ so that the rescue buoy hits the desired target. Although this process involves making decisions (*for which target point shall I aim?*) and setting parameters (*which* V_0 *and* θ *shall I choose?*), and although the problem has more than one possible solution, it requires analysis only and involves no design.

Design

In contrast to the problem of analyzing the projectile's trajectory, determining *how to build* the buoy catapult system most certainly involves design. Such a system can be built in more than one way, and the designer must decide which method is best. Should the carriage of the cannon be made from wood or metal? The former will be lighter and easier for the rescue brigade to bring to the closest shore, but the latter will be stronger and less likely to fail. Wood can rot, but steel can rust. Should the support for the breeching cable be H-shaped or X-shaped? How large should they buoy be? Should the cannon rest on wheels or skids? Answering these questions requires experimentation, analysis, testing, evaluation, revision—and of course, creativity—all of which are elements of the design process.

Replication

The preceding example illustrates the difference between analysis and design. Specifically, analysis embodies the mathematics needed to determine the buoy's trajectory, while design involves the creation of the Lyle gun itself to meet the user's needs and specifications. In contrast, the word *replication* refers to the process of re-creating something that has already been designed. Replication may involve an exact reproduction, or it may involve minor revisions whose consequences have already been determined. For instance, assembling the laptop computer of Figure 2.4 from premade, constituent components—a circuit board, disk drive, memory module, and display screen—may involve some choices, but the bulk of the design work has been previously performed by other engineers. The task is principally a form of replication. Similarly, building a bird house from a set of purchased plans involves replication, but no design. Replication is an important part of engineering and lies at the core of manufacturing, but it does not require the same set of skills and tools as does true design.

Figure 2.4
Engineered devices, such as this laptop, are mass produced using the process of replication.

EXAMPLE 2.1

Trajectory Analysis[2]

Equations (2.2) and (2.3) describe the motion of the Lyle gun buoy after its initial launch. Given an initial velocity V_0 and launch angle θ, these equations can be solved for the buoy's position coordinates $x(t)$ and $y(t)$ as functions of time. The techniques for obtaining an analytical solution to the problem involve the use of calculus wherein the projectile coordinates $x(t)$ and $y(t)$ are related to the velocities by the derivatives

$$v_x(t) = \frac{dx}{dt} \tag{2.7}$$

and

$$v_y(t) = \frac{dy}{dt} \tag{2.8}$$

Equations of this sort are covered in the math courses taken by most students of engineering; however, many first-year students do not yet have the math skills

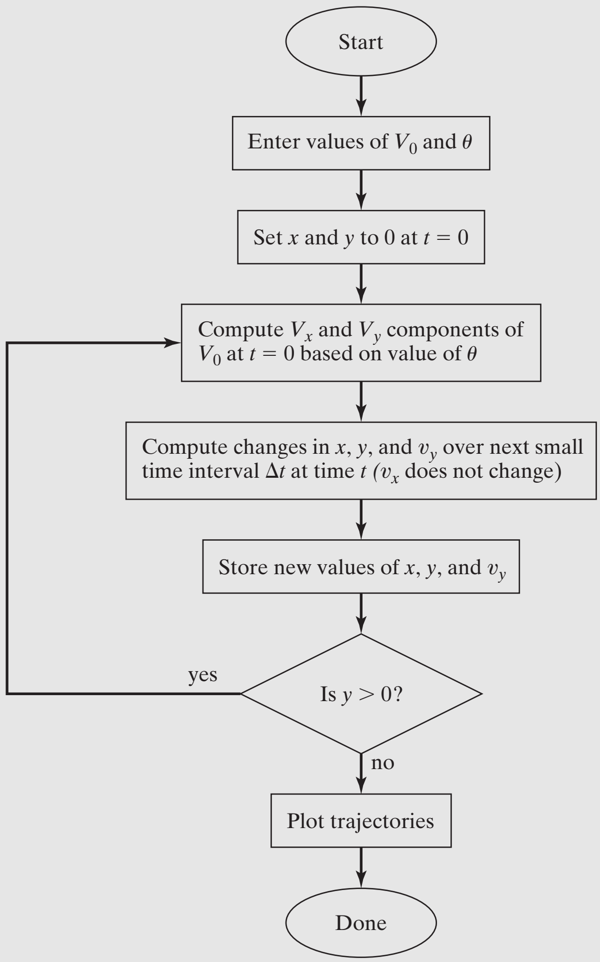


Figure 2.5
Flowchart for the iterative solutions of Equations (2.7) and (2.8). The solution requires that the initial velocity V_0 and launch angle θ be known ahead of time.

[2] If you've not yet had calculus, you can skip this example without loss of continuity.

needed to solve them. Hence, the integral solutions for $x(t)$ and $y(t)$ are simply stated here:

$$x(t) = V_{x0}\,t \tag{2.9}$$

and

$$y(t) = V_{y0}\,t - \frac{1}{2}gt^2 \tag{2.10}$$

Another method by which solutions for the projectile coordinates $x(t)$ and $y(t)$ can be found without differential calculus is to solve for them iteratively by computer. This second method is illustrated in this example. The flowchart of Figure 2.5 illustrates the basic roadmap for writing such a program.

	A	**B**	**C**	**D**	**E**	**F**
1	Buoy Trajectory Calculations					
2	V_0	15	launch velocity (m/s)			
3	theta	60	launch angle (degrees)			
4	dt	0.1	time increment in ms			
5	V_{x0}	7.51	m/s			
6	V_{y0}	12.99	m/s			
7	g	−9.8	gravitational constant			
8	pi	3.14	π			
9					**Cell Contents**	
10	time (ms)	x-position	y-position		x-position	y-position
11	0.00	0.00	0.00		V_{x0}*A11	V_{y0}*A11 + 0.5*g*A11^2
12	0.10	0.75	1.25		V_{x0}*A12	V_{y0}*A12 + 0.5*g*A12^2
13	0.20	1.50	2.40		V_{x0}*A13	V_{y0}*A13 + 0.5*g*A13^2
14	0.30	2.25	3.45			
15	0.40	3.00	4.41		:	:
16	0.50	3.75	5.27			
17	0.60	4.50	6.03			
18	0.70	5.25	6.69			
19	0.80	6.01	7.25			
20	0.90	6.76	7.72			
21	1.00	7.51	8.09			
22	1.10	8.26	8.36			
23	1.20	9.01	8.53			
24	1.30	9.76	8.60			
25	1.40	10.51	8.58			
26	1.50	11.26	8.45			
27	1.60	12.01	8.23			
28	1.70	12.76	7.92			
29	1.80	13.51	7.50			
30	1.90	14.26	6.99			
31	2.00	15.01	6.37			
32	2.10	15.76	5.66			
33	2.20	16.52	4.85			
34	2.30	17.27	3.95			
35	2.40	18.02	2.94		:	:
36	2.50	18.77	1.84		V_{x0}*A36	V_{y0}*A36 + 0.5*g*A36^2
37	2.60	19.52	0.64		V_{x0}*A37	V_{y0}*A37 + 0.5*g*A37^2
	2.70	20.27	−0.66			

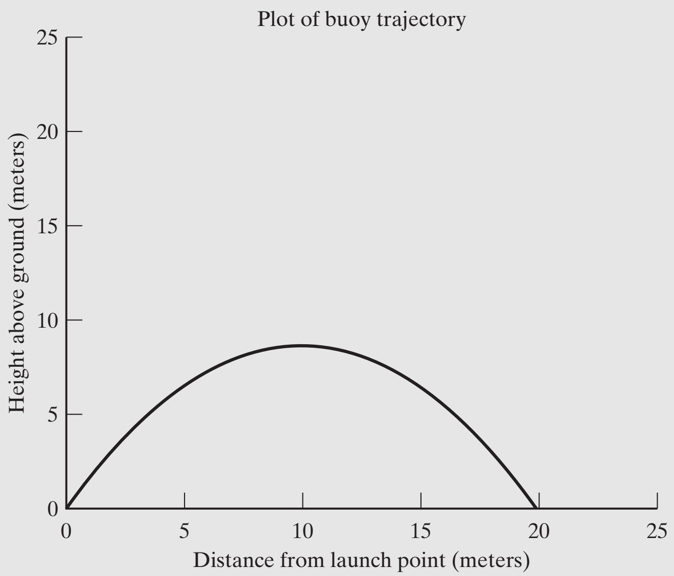


Figure 2.6
Result of the computation of Figure 2.5 for the case $V_0 = 15$ m/s and $\theta = 60°$.

A code listing that implements the flowchart of Figure 2.5 can be constructed using a spreadsheet such as Excel. The problem could also be solved using any of a number of programming languages such as MATLAB, Mathematica, or C^{++}. One possible approach using a spreadsheet is shown below. The value of the cell contents of columns B and C are shown in columns E and F. Each row of the spreadsheet represents a calculation based on the iterated value of time in column A. A plot of the trajectory, based on the x- and y-position values, is shown in Figure 2.6.

Practice!

For Exercises 1 to 25, determine whether the indicated task involves analysis, design, or replication.

1. Find the best land travel route between two cities.
2. Find the shape of soda bottle that will be able to withstand the highest pressure from carbonation.
3. Find a way to prevent people from cutting their hands while slicing a bagel.
4. Find the best dimensions of a 16-ounce soup can so that a packing box for 24 cans has the smallest volume.
5. Find a way to mount a cell phone on a bicycle to permit safe hands-free operation.
6. Find a way to produce individualized bar-coded badges that can be distributed to the attendees of a technical conference.
7. Find a way to seat passengers on an airplane so as to minimize loading time.

8. Find a way to distribute meals on a transcontinental airplane that does not rolling carts.
9. Find a way to store the information for a building directory so that it can be easily retrieved from a touch screen located in the lobby.
10. Find a hack-proof method for counting and tallying votes in a national election.
11. Find a way to use a global positioning system (GPS) receiver to automatically navigate street sweeping machine around city streets.
12. Find a way to automate the oil-changing operation at a drive-in car-service facility.
13. Find a way to automatically label blood samples taken from a hospital patient wearing an identification wrist band.
14. Find a way to monitor the temperature of an unoccupied vacation home via telephone.
15. Develop a children's toy that teaches counting.
16. Develop a system that can make customized shirts for individual customers based on a database of previously acquired body measurements.
17. Develop a system for optimizing a newspaper delivery route for minimum time.
18. Develop a system for loading folded newspapers into protective plastic bags for daily home delivery.
19. Find a way to spread grass seed evenly over an area of lawn.
20. Develop a system for downloading and updating the contact list in a cell phone from a wireless laptop.
21. Develop a system for a telemarketing system that automatically deletes entries from the National Do Not Call Registry (*www.donotcall.gov*).
22. Find a way to assess the condition of the shingles or tiles on a pitched roof without requiring that a person climb on the roof.
23. Develop a system for fulfilling drive-up orders at a fast food establishment.
24. Find a way to determine the height of trees in need of trimming without requiring that the trees be scaled.
25. Find a way to produce custom-printed books that allow a customer to select various available chapters for an individualized text.
26. *Challenge Exercise*. Show by direct solution that Equations (2.2) and (2.3) yield a parabolic trajectory.
27. *Challenge Exercise*. Why does the mass of the projectile not affect the parabolic trajectory of Figure 2.6?
28. *Challenge Exercise*. For a given initial velocity V_0, find the launch angle θ that will yield the furthest target distance x.
29. *Challenge Exercise*. A projectile-buoy target lies 100 m away. Determine at least one possible set of values for V_0 and θ in Figure 2.3 such that a 5-kg projectile hits the target. How much energy must the Lyle

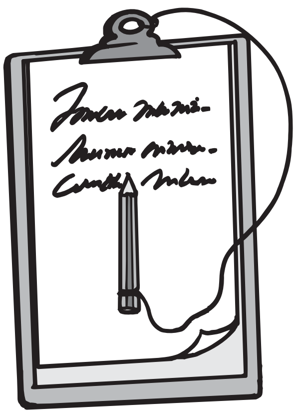
gun impart to the projectile in order to meet this objective? (Hint: When the buoy first leaves the muzzle, its kinetic energy is $mV_0^2/2$.)

30. *Challenge Exercise*. Modify the spreadsheet of Example 2.1 so that a program based in its pathways will plot a) the height of the projectile as a function of time, and b) the angle of the total projectile velocity relative to the horizontal as a function of time.

2.3 GOOD DESIGN VERSUS BAD DESIGN

Anyone who has taken a car in for repair recognizes the difference between a good mechanic and a bad mechanic. A good mechanic diagnoses the problem in a timely manner and makes repairs that last. A bad mechanic fails to find the real problem and masks the symptoms with expensive, unnecessary repairs. Engineers are a bit like auto mechanics in this respect. The world is full of both good engineers and bad engineers. Just because an engineer has produced something does not mean it has been designed well. Just because the product works initially doesn't mean that it will last over time. Although the criteria by which a product is judged varies with the nature of the product, the success of most design efforts can be judged by the characteristics summarized in Table 2.1.

The contrast between good and bad design is readily illustrated in the context of a product made to help rescue individuals from ships run aground. Built in the days before helicopters, the device worked by shooting a tether-carrying projectile out of a small cannon toward the stricken ship, and then using the tether to run a "breeches buoy" line and basket from ship to shore. Imagine that you work for the Apex Rescue Catapult Corporation (ARCC) which has been asked to produce this device for a shoreline rescue brigade. The buyers will judge the worthiness of the apparatus based on the considerations of good and bad design, as illustrated by the following discussion.



1. Does the product meet technical requirements?

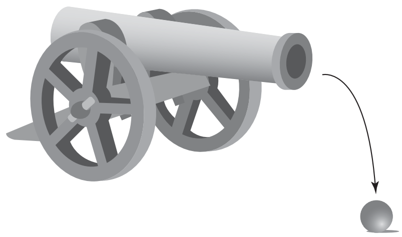
It might seem simple to decide whether a buoy launcher meets its technical requirements. Either the tethered buoy hits its target, or it does not. But success can be judged in many ways. A launcher that is well designed will accommodate a wide range of buoy weights, sizes, and shapes. It will require the efforts of only one or two people to operate and will repeatedly hit its target, even in strong wind or rain. A poorly designed launching system may work under ideal conditions but may accommodate buoys of only a single weight or shape. It may fail in strong winds, or it may not produce repeatable trajectories. The launcher might work fine in clear weather, only to fail in a storm.

Table 2.1 Characteristics of Good Design versus Bad Design

Good design	Bad design
1. Meets all technical requirements	1. Meets only some technical requirements
2. Works all the time	2. Works initially, but stops working after a short time
3. Meets cost requirements	3. Costs more than it should
4. Requires little or no maintenance	4. Requires frequent maintenance
5. Is safe	5. Poses a hazard to users
6. Creates no ethical dilemma	6. Raises ethical questions

2. Does the product work?

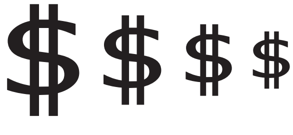
During the development stage, the product cannot be expected to work flawlessly the very first time it is tested. However, it *must* work perfectly before it can be delivered to the customer. It must be durable, and it must not fail in the field. The buoy launcher example provides an excellent illustration of this second principle. Even a bad designer could produce a launcher capable of meeting its specifications upon initial delivery to the customer. The Apex Company could make the a cheap cannon from inexpensive aluminum and construct a simple carriage from wood and nails. A bad designer would also build the launcher in an ad hoc fashion, adding new features on top of old ones without examining how each feature interacts with those before it. Such a launcher might pass inspection upon delivery and be able to launch projectiles during practice, only to fray a line, crack a cannon barrel, or break its trigger mechanism during an actual rescue. After a short period of use, the ill-designed frame might weaken, causing the device to fail during a particularly difficult rescue. Such shortcomings could prove disastrous to a ship's crew awaiting rescue.



A good designer would develop a robust launcher capable of many long hours of service even under the most adverse weather conditions. This conscientious engineer would test different building materials, carriage constructions, trigger mechanisms, and launch devices before choosing materials and design strategies. The good engineer would design the launcher as a whole, carefully considering how its various parts interact. The resulting product might require stronger and more expensive materials and perhaps more assembly parts, but it would prove more reliable and allow the user to hit the target repeatedly under the stress of the most severe rescue operations.

3. Does the product meet cost requirements?

Some design problems can be approached without regard to cost, but in most cases, cost is a major factor that affects design decisions. Often a tradeoff exists between adding features and adding cost. A cannon carriage made from iron will be much less expensive than one made from stronger stainless steel. Will the consumer be willing to pay the higher price? Durable titanium will last even longer and be much lighter in weight, but the monetary cost might be exhorbitant. Will the consumer absorb the cost of the more durable material? Painting the launcher might make it visually more attractive and longer lasting, but will not enhance performance. Will the customer want an attractive piece of machinery at a higher price? Will an attractive appearance make the rescue brigade feel more professional? An engineer must face questions such as these as part of the design process.



4. Will the product need extensive maintenance?

A durable product will provide many years of flawless service. Durability is something that must be considered as part of the design process, even when the cost of the final product is of concern. At each step, in the design process, the designer must decide whether cutting corners to save money will lead to component failure in the future. A good designer will eliminate as many latent weaknesses as possible. A bad designer will ignore them as long as the product can pass its initial inspection tests. If the ARCC wishes to make a long-lasting rescue device worthy of its company's name, it must design durability into its product from the very start.

5. Is the product safe?

Safety is a quality measured in relative terms. No product can be made completely hazard free, so a "safe" product simply has a significantly smaller probability of causing injury than does an "unsafe" product. Assigning a safety value to a product is one of the harder aspects of engineering design because adding safety features usually requires adding cost. Also, accidents are subject to chance, and it can be difficult to identify a potential hazard until an accident occurs. An unsafe product might never cause harm to a particular user, but statistically, it would be more likely to cause injury to some fraction of a large group of users. The cannon-based buoy launching system provides an example of the tradeoff between safety versus cost. Can a launcher be designed to facilitate rescue without endangering people? When a buoy is launched at a stricken vessel, there is a small probability that it will hit a person instead. Perhaps designing a buoy that disperses its mass during flight will reduce the potential for human injury, but such an approach may add to the cost of designing and producing a more complex projectile. Features also could be added to the cannon system to protect its primary users. Guards, safety shields, and interlocks could prevent accidental misfirings, but they would increase the cost and inconvenience of the finished product.

6. Does the product create an ethical dilemma?

Designing a device that can save lives seems like an unquestionably altruistic goal. Yet even such a task raises ethical questions. Although one of its primary goals is to help people, ARCC must ultimately make money if it is to stay in business. Imagine yourself as an employee of this company. If your boss asked you to use cheaper materials but not tell the customer, would you comply with these instructions or defy your employer? If you discovered a serious safety flaw in the system that might lead to human injury, would you insist on costly revisions that would reduce the profitability of the product? Or would you say nothing and hope for the best? Even the very use of the product raises questions of societal ethics. Some communities might be better able to afford a rescue system than would others. Will you advocate more expensive pricing to service affluent communities, or keep the price low so that everyone can afford it? These questions are never simple, but engineers face similar questions all the time. As part of your training as an engineer, you must learn to apply your own ethical standards to problems that you encounter on the job. This aspect of design will be one of the hardest to learn, but is it one that you must master if you wish to be an engineer.

Professional Success: Choose a Good Engineer to be Your Mentor

Will you become a good engineer or a bad engineer? Practicing engineers of both types can be found in the profession, and you must learn to distinguish between the two. As you make the transition from student to professional engineer, you are likely to seek a mentor at some point in your career. Be certain that the individual you choose practices good engineering. Seek an engineer who has an intrinsic feeling for why and how things work. Find someone who adheres to ethical standards that are consistent with your own. Avoid "formula pluggers" who memorize equations and blindly plug in numbers to arrive at design decisions but have little feeling for what the formulas actually mean. Avoid engineers who lack vision and creativity. Likewise, shun engineers who take irresponsible shortcuts, ignore safety concerns, or choose design solutions without thorough testing. In contrast, emulate engineers who are well respected, experienced, and practiced in the art of design. A mentor who excels in explaining things to you is a big plus.

2.4 THE DESIGN CYCLE

Design is an iterative process. Seldom does a finished product emerge from the design process without undergoing changes along the way. Sometimes, an entire design approach must be abandoned, and the product must be redesigned from the ground up. The sequence of events leading from idea to finished product is called the *design cycle*. Although the specific steps of the design cycle may vary with the product and field of engineering, as well as with the instructor of any given undergraduate design course, most cycles resemble the sequence depicted in Figure 2.7. The following section explores this diagram in more detail.

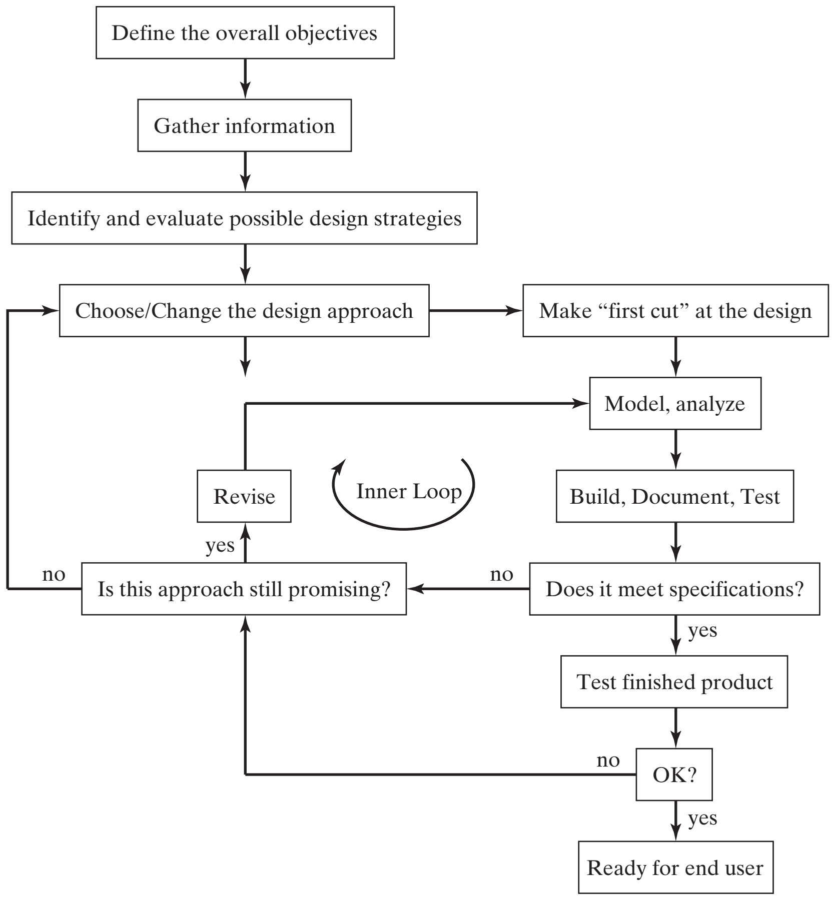


Figure 2.7
One version of the design cycle. Successful design often requires many cycles around the inner loop. Sometimes, the cycle must be reentered when the finished product does not meet design goals.

2.4.1 Define the Overall Objectives

A design team should begin any new project by defining the overall objectives. This step may seem like a nuisance to the student eager to build and test, but it is one of the most important steps in the process. Only by viewing the requirements from a broad perspective can an engineer determine all factors relevant to the design effort. Good design involves more than just making technical choices. Consider, for example, a marine engineer who must design a new sailboat. In addition to technical constraints, the designer must consider the aesthetic, safety, and cost factors that go into a successful design. The engineer must thus ask the following questions: Who will use the product? Will it be a seasoned mariner or a first-time boater? What are the needs of the end user? Will it be used, for example, for business or recreation? What are the cost factors? Which features are critical, and which are only desirable? For example, should the boat have power winches, GPS navigation, and a stereo sound system, or are these needless, expensive frivolities? What are the manufacturing constraints? Must the boat be made of fiberglass, or are other materials acceptable? What are the safety factors? How much risk is acceptable? Answering these questions at the outset will help at each subsequent stage of the design process.

2.4.2 Gather Information

In the early stages of a new project, a large amount of time should be devoted to gathering information. Learn as much as possible about the relevant technology. Do similar solutions already exist? What can you learn from them? Can you identify off-the-shelf modules or components that can be incorporated directly into your design, so that you don't have to "reinvent the wheel?" Look for product descriptions, data sheets, and application notes on the Web. Keep this information in a file folder (either as a hard copy or on a computer) where you'll be able find it easily. Also look for reports or project descriptions in the same general area as your own project. Detailed specifications about most component parts and devices are available on company websites. Such electronic databases have largely supplanted printed catalogs as the primary source of information for design engineers.

Perusing advertisements in trade magazines and journals can be a good way to learn about commercial products that might be relevant to your project. Each field of engineering has many such publications, but the list in Table 2.2 provides a

Table 2.2 Some Engineering Trade Publications

Bioscience Technology	Hydraulics and Pneumatics	Miscellaneous Publications
Compliance Engineering	*Machine Design*	*Advanced Manufacturing*
Computer Technology Review	*Medical Design Technology*	*Aviation Week and Space Technology*
Design News	*Plastics Technology*	*Chemical Engineering/Progress*
EDN (Electronic Design News)		*Environmental Science and Technology*
Electronic Design		*Industrial Engineer Magazine*
		Medical Electronics Magazine

representative set. A more comprehensive directory of technical magazines can be found at *www.techexpo.com*.

2.4.3 Identify and Evaluate Possible Design Strategies

When working with the design cycle, the next step is to identify possible strategies for meeting your design objectives. At this stage, the design team will typically run a brainstorming session to help identify them. Other decisions, such as whether preexisting components will be incorporated into the product, or whether the product will be designed from the ground up, are often made at this time. The team then evaluates the merits of each possible solution, choosing one or more for detailed investigation. The chosen approach is the one deemed most likely to succeed. This choice may change later on, depending on the outcome of each step of the design process.

2.4.4 Make a First Cut at the Design

Once the team has identified a likely design strategy, it's time to make a "first cut" (initial attempt) at the design. This step typically involves rough approximations and estimates. If the product is to be a physical entity, tentative choices are made for dimensions, weight, user controls, construction materials, part numbers, and component values—whatever parameters might be relevant. If the objective is a software product, its outer shell, modular pathways, and user interface are laid out as part of the first-cut attempt. If the design involves a system—for example, a manufacturing procedure—then the overall flowchart might be specified at this time.

If the system is complex, it should be divided into smaller pieces that can be designed by subdivisions of the team and later combined to form the complete product. These subsections, or modules, should be designed so that they can be tested individually before the entire system is assembled. Dividing a large job into several more manageable tasks simplifies synthesis, testing, and evaluation. In a team design effort, the modular approach is essential. For example, the various components of the automobile in Figure 2.8—the engine, cooling system, electrical

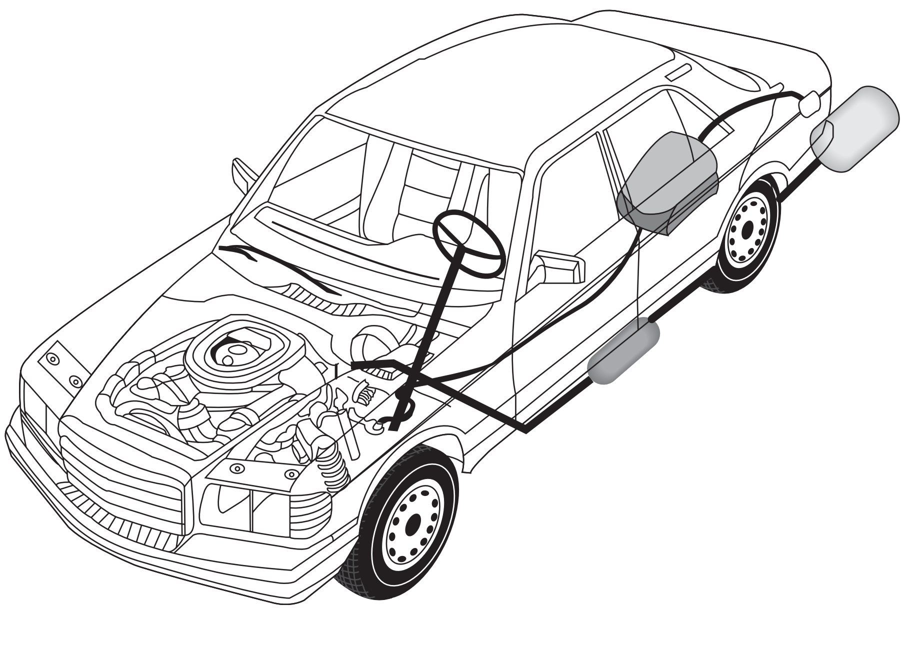


Figure 2.8
Component systems of a typical automobile are designed as interacting modules.

system, suspension, braking system, chassis, and drive train—are each designed and tested individually before the entire automobile is assembled. Constant communication between individuals is vital to ensuring that the automobile's constituent components work together in harmony. The final integrated product will be more than the sum of its individual parts. This same modular strategy applies to large software systems, where each section should be designed as an independently testable module.

The design strategy should also consider similar efforts that may have been attempted in the past. Does a new technology exist that will improve upon an existing design? Perhaps a partial solution is already available in commercial form. For example, suppose that your design for a talking clock includes the amplification of voice or music. You could design your own sound amplifier. Alternatively, many inexpensive off-the-shelf kits exist for constructing board-level amplifiers (see, for example, *www.rainbowkits.com*), so designing your own amplifier would be an unnecessary duplication of effort. The wise engineer uses existing products and components to simplify the design task. There is no shame in using off-the-shelf ingredients if they can help you achieve your design objectives more quickly and inexpensively. Typically, labor is the most expensive part of any development effort, so it's often cheaper (and sometimes more reliable) to buy something ready made and previously debugged than it is to design it from scratch. Imagine how needlessly complex it would be to design a house without using prefabricated windows, doors, electrical panels, insulation, radiators, and air conditioners that are available from other vendors. Be certain, however, that using another company's product does not create patent infringement problems if your product is destined for commercial sale.

2.4.5 Model and Analyze

This activity goes hand in hand with making the first design cut. In some design situations, it could even precede the latter. In the modeling phase of the cycle, a combination of mathematics and/or software modeling tools is used to fine-tune design parameters to shorten the path to the finished product. Modeling and analysis is usually much less expensive (in terms of person-hours of labor) than building an actual prototype for testing.

During the modeling phase of design, commercially available computer simulation tools (such as AutoCAD, ProENGINEER, Solidworks, MATLAB, Orcad, and Simulink) can save time and expense by allowing the designer to predict performance before the actual construction of the prototype. These software packages can help identify hidden flaws before the product is built and provide some indication as to the success of the design approach. Whenever practical, however, computer simulations should never be used as a substitute for actual physical testing unless the product is very similar to one that you have previously designed. "Glitches," "bugs," and other anomalies caused by physical effects not modeled by the simulator have a nasty habit of appearing when a new product undergoes actual testing. Despite the usefulness of computer-aided design tools and simulators, there is simply no substitute for testing a real physical prototype. The use of scale models—for example, an aircraft model made one-tenth of actual size inside a wind tunnel—can be useful for testing large products.

2.4.6 Build, Document, and Test

After the design team has reached a consensus on a first cut, its next goal is to build a working prototype. In some situations, the cost of fabrication is so high that an initial

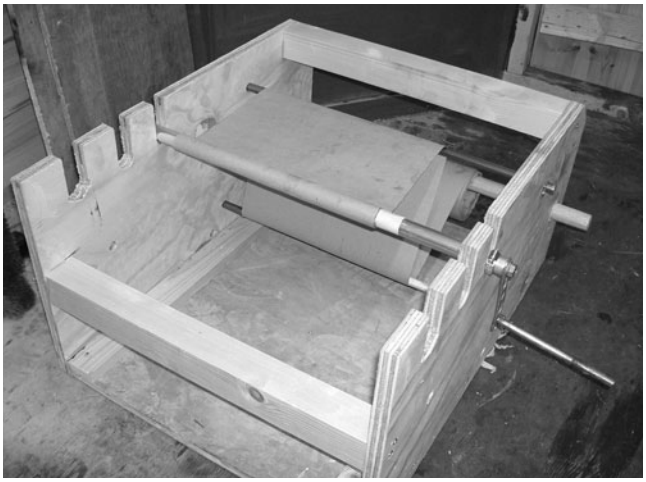


Figure 2.9
A prototype of the finished product made from wood and other easy-to-fabricate materials.

prototype may not be practical. An oil platform or space station, for example, would fall into this category. In such cases, modeling and analysis can help close the loop between the design concept and the final product.

The typical first prototype is destined to be revised many times before the design cycle has been completed. This first prototype should be functional, but it does not need to be visually attractive. Its primary purpose is to provide a starting point for evaluation and testing. If the product is mechanical, for example, it can be built as a mock-up from easy-to-modify materials, such as wood or pre-punched metal, as shown in Figure 2.9. For instance, a prototype for a new self-standing ATM machine might be built inside an open wooden box made from plywood. Such a structure would permit easy access to the inner machinery during testing, but obviously would never be used in a commercial installation. If the product is electrical, its prototype might be wired on a temporary circuit breadboard, such as the one shown in Figure 2.10. If the product is software, the prototype might consist of the main calculation sections without the fancy graphical interfaces that the user will expect in the final version.

Documentation

Note that documentation is part of the inner loop of the design cycle of Figure 2.7. The typical engineer faces considerable temptation to leave documentation to the very end of the design process. Pressed with deadlines and project milestones, many inexperienced engineers think of documentation as an annoying intrusion rather than an integral part of the design process. After working diligently on a design project, the unseasoned engineer may panic at the reality of documentation. ("*Now I have to write all this up*?") Documentation added as an afterthought is often incomplete or

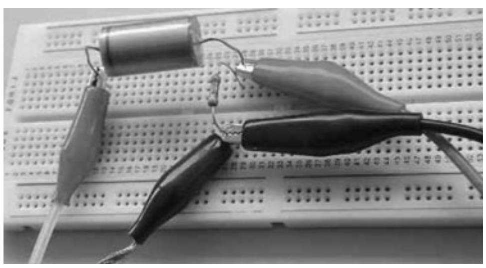
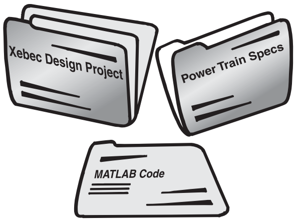


Figure 2.10
Temporary circuit breadboard for electronic prototyping.



Project Documentation is an important part of engineering design.

substandard, because most of the relevant facts and steps have been forgotten by the time the writing takes place. Haphazard, after-the-fact documentation is the province of the bad design engineer. Many a product, developed at great cost but delivered with grossly inadequate documentation, has found its way to the trash heap of engineering failures because no one could figure out how to use or repair the product. Poor documentation also leads to a duplication of effort and reinvention of the wheel, because no one can remember the results of previous work.

A good engineer recognizes that documentation is absolutely critical to every step of the design process. The good engineer will plan for documentation from the very beginning, keeping careful records of everything from initial feasibility studies to final manufacturing specifications. As the design progresses, it's a good idea to write everything down, even if it seems unimportant at the time. Information should be written in such a way that another engineer with the same technical background could continue your work at any time by simply reading your documentation. Careful documentation will also aid in writing product literature and technical manuals should the product be destined for commercial sale. Good documentation provides the engineer with a running record of the design history and the answers to key questions that were addressed as part of the design process. It provides vital background information for patent applications, product revisions, and redesign efforts, and it serves as insurance in cases of product liability. Above all, documentation is part of an engineer's professional responsibility. Its importance to engineering design cannot be overemphasized.

2.4.7 Revise and Revise Again

One of the characteristics that distinguishes design from replication is that the finished product may be totally different from what was envisioned at the beginning of the design cycle. Elements of the system may fail during testing, forcing the engineer to rethink the design strategy. The design process may lead the engineer down an unexpected path or into new territory. A good engineer will review the status of a product many times, proceeding through numerous revisions until the product meets its specifications. In truth, this revision process constitutes the principal work of the engineer. An experienced engineer recognizes it as a normal part of the design process and does not become discouraged when some aspect of the product fails on the first or second try. The revision cycle may require many iterations before success is achieved.

2.4.8 Test the Product Thoroughly

As the design process converges on a probable solution, the product should be thoroughly tested and retested. Performance should be assessed from many points of view; the design should be modified, then tested again, whenever problems are identified. If, at any stage, the product does not meet design requirements, the designer should reenter the iterative loop once again.

Sometimes, though the end may seem near, it is unreachable due to an unforeseen late-breaking but fatal flaw in the design. The product may thus be deemed a failure, even if it seems ready for use. In such cases, the design loop must be reentered with an alternative solution as its basis.

If the product is a physical entity, it should be tested—if relevant—for the effects of temperature, humidity, loading, and other environmental factors, as well as the effects of repeated and prolonged use. Physical products, such as each one of the instruments in Figure 2.11, should be subjected to a "burn-in" (extended use) period

Figure 2.11
Mass-produced electronic instruments for sale undergo a "burn-in" period prior to final shipment.

to help identify latent defects that might cause the product to fail in the field. The human response to the product should also be assessed, because no two people are exactly alike. Exposing the product to many different individuals will help identify problems that may not have been apparent during the development phase, when the product was examined only by the design team. Only after a comprehensive test period is the product ready to be put into actual service. Nothing will discourage consumers faster than a new product that malfunctions in the field.

Like their physical counterparts, software products should also be tested by a variety of different users who can discover hidden bugs. Different individuals will exercise a software product in very different ways; hence, extensive testing by a multitude of users is essential if all software bugs are to be discovered. One way to discover hidden bugs is to release the software program to a control group of customers before widespread distribution. This control group understands that bugs may exist in the preliminary version, and the group is usually given incentives (e.g., a reduced cost or a jump on competitors) to serve as real-world testers. This type of trial is sometimes called a *beta test*.

Professional Success: Being Realistic About the Design Cycle

The design loop shown in Figure 2.7 is typical of what an engineering design team might follow, but it is not inclusive of all situations. Sometimes, steps may be omitted, while others might be added. For example, if the problem is so well defined and its goals immediate, one might pass over the information gathering steps without detriment. Similarly, the analysis step might be so trivial as to be unnecessary. A good structural engineer, for example, would know by rote the rules of thumb for the strengths of commonly used beams. An electrical designer would be familiar with the ampacity of commonly available wire gauges.

In some cases, the prototype step inherit to the "first cut" might be impractical, or not feasible at all. This latter scenario typically applies to large public works projects, for example. The key thing to remember in studying the design cycle is its test and retest loop – an essential element of good design, whether it be by perfecting a physical prototype, or constantly reiterating over a simulation or paper design.

Practice!

1. Consider the questions posed under "Define the Overall Objectives" in Section 2.4.1. Answer these questions in the context of designing a recreational sailboat.
2. Consider the questions posed under "Define the Overall Objectives" in Section 2.4.1. Answer these questions in the context of designing a high-performance bicycle.
3. Suppose that you are asked to build a recumbent bicycle (a low-profile bicycle in which the pedals are in front of the seat.) Make a list of the various ways in which you might gather information as part of the design cycle.
4. Draw a modified design cycle, similar to Figure 2.7, that includes feedback from a test group of individual users (i.e., a "beta" test group).
5. Define the design strategy that might have been used to invent the first personal computer. Imagine yourself before the days of hard disk drives, graphical user interfaces, color monitors, compact disks, USB ports, and inexpensive memory chips. (In the early days of computers, random-access memory chips were one of the most expensive components of the PC.)
6. Describe the various stages of the design cycle for the development of the ballpoint pen.
7. Write a chronology of the design cycle for a paper clip.
8. Specify the steps in Figure 2.7 as they might apply to the design of a microwave oven.
9. Discuss the elements of the design cycle that might apply to a heart rate monitor to be used as part of a medical diagnostic system.
10. Imagine that you were the American engineer who first invented the pinball machine. Write a short essay on your experience, trials, and errors in developing this widely used entertainment device.
11. In-flight refueling is a technique that makes most military air operations possible. Prepare a chronological table that shows how the design cycle may have proceeded when the technique was developed. Label each event in your table with the corresponding step in Figure 2.7.
12. The automobile airbag has become an indispensable safety device, but its history is rather short compared with the evolution of the automobile. Describe what you imagine to have been the first airbag prototype, and then document each of the changes that led to today's airbag design.
13. Imagine that your design team has developed a personal human rocket transportation device. List the design changes that helped you converge on a successful product.
14. Research the history of invention; identify one product that did not require design revisions before becoming successful. (Hint: some inventions that *did* undergo extensive, iterative revisions during the design process include the airplane, the automobile, the sewing machine, and the ballpoint pen.)

15. Write a short essay that describes the evolution of the sewing machine. This product underwent numerous design changes from its inception to the first commercially viable machine.
16. Research the history of the modern dishwasher; draw a detailed design cycle that chronicles the development of this device by its inventor, Josephine Cochran.
17. How do the design steps for a production process differ from those of a physical product? List several examples.
18. Compare the design cycle of a commercial aircraft with the design cycle of a radio-controlled model airplane. How might the various elements differ?
19. The design of a large-scale solvent ore extraction plant will differ markedly from the design of a similar system that classifies ores on a laboratory scale. List several ways in which the design process will differ for these two products.
20. What differences might exist between the design of a reading lamp and the design of a light tower for a football stadium?
21. Consider the issues involved in interfacing a large solar-cell plant that produces hydrogen for fuel cells with the national power grid. What design issues would be of paramount importance
22. Consider the design of a large-scale wind turbine farm. What project-specific elements do you imagine filling the boxes of the design cycle of Figure. 2.7?
23. Consider the design of a tethered buoy for harnessing ocean energy. What project-specific elements do you imagine filling the boxes of the design cycle of Figure. 2.7?

2.5 GENERATING IDEAS

The element of creativity is one of the more salient characteristics that distinguishes design from analysis or replication. Creativity is quintessential to the human experience, particularly for engineers. Without it, the requisite iterations versions of the design cycle would not be possible.

When engineers gather to solve design problems, they can arrive at ideas through a variety of methods. One of these techniques is *brainstorming*. Brainstorming helps engineers channel their creative energies by requiring a spontaneous mode of thinking that frees the mind from traditional boundaries. All too often, we limit our problem-solving approach to obvious solutions that have worked in the past, or perhaps to the first thing we think of. Responsible engineering often requires the consideration of other design alternatives. A good engineer will never settle on a solution just because it's the first one to come to mind. Brainstorming provides one good method for generating a plethora of ideas.

In the early stages of the design process, creativity should proceed spontaneously, unfettered by concerns that any proposed ideas are "way out," "ridiculous," or otherwise impractical. When the constraints of traditional paradigms are removed, new solutions often emerge. Hearing the ideas of others can tap ideas in the subconscious mind. Promising, but different, ideas can eventually be discarded as unfeasible, but only after study, analysis, and comparison with competing ideas.

Brainstorming allows engineers to consider as many options as possible before choosing a design path.

Brainstorming follows many forms. It can be done informally, or it can follow one of several time-tested formal methods. The latter are appropriate for large group settings where organization is needed to avoid chaos. Less formal brainstorming methods are reserved for groups of, say, one to four people who wish to generate ideas. Although they differ in execution, formal and informal brainstorming methods share the same set of core principles. The primary goal is to foster the uninhibited free exchange of ideas by creating a friendly, nonjudgmental environment. Brainstorming is an art. It requires practice, but any team member who has an open mind and imagination can learn this important skill.

2.5.1 Ground Rules for Brainstorming

When a team decides to brainstorm, member should agree ahead of time on a set of rules of behavior. These ground rules should be chosen to create a friendly, nonthreatening environment that encourages the free flow of ideas. Although the specific rules depend on the version of brainstorming, the following list can serve as a guideline:

1. No holding back. Any idea may be brought to the floor at any time.
2. No boundaries. An idea is never too outrageous or "way out" to mention.
3. No criticizing. An idea may not be criticized until the final discussion phase.
4. No dismissing. An idea may not be discounted until after group discussion.
5. No limit. Another idea is never one too many.
6. No restrictions. Participants may generate ideas from any field of expertise.
7. No shame. A team participant should never be made to feel embarrassed for contributing an idea.

2.5.2 Formal Brainstorming Method

When a large group gets together to brainstorm, formal method can be helpful. Without such structure, a flood of competing ideas, all brought to the floor simultaneously, can create chaos. Instead of thinking creatively, participants can become confrontational as they strive to gain a voice in the conversation. With so many randomly competing opinions, each person's creative process is inhibited, and the brainstorming session becomes unproductive. This effect is sometimes called *idea chaos*. Adding formal structure to a brainstorming session restricts the flow of ideas to a manageable rate without restricting the number of ideas generated. In fact, adding formal structure to large group settings can enhance the brain's creative process by preventing aggressive individuals from dominating the conversation and by providing time for people to think.

When a brainstorming session is in progress, one person should act as the facilitator, and another should record everyone's ideas. It's also possible to use video or audio tape in lieu of a human secretary.

Many formal brainstorming techniques exist, but the *idea trigger* method has been well tested and acknowledged to be an effective way to generate ideas in large groups. The idea trigger method enhances the brain's creativity via a process of alternating tension and relaxation to tap the brain's inner resources. By listening to other people's ideas and being forced to respond with counter ideas, a participant's behavioral patterns, personality constraints, and narrow modes of thinking can be broken momentarily. This allows ideas hidden in the recesses of the brain to come to the foreground. A shy participant who is reluctant to offer seemingly silly ideas, for example, may be more willing to speak under the alternating tension and relaxation of the purge-trigger sequence.

The idea trigger method requires a leader, at least four participants, and a piece of paper divided into four or five columns.

A group of students holding a brainstorming session.

Phase 1: Idea Generation Phase

The problem or design issue is summarized by the leader. Without talking, participants each rapidly write down as many ideas or solutions as possible under the first column on their papers. Key words suffice; whole sentences are not necessary. During the idea-generation phase, participants open their minds, consider many alternatives, and do not worry if ideas seem too trivial or ridiculous. "Pie in the sky," radical, or impossible ideas should definitely be included. In short, participants write down any relevant ideas that come to mind. Since the ideas are written down silently, the element of intimidation is removed from the idea generation process.

After the first 2 minutes of the session, the group takes a break and then attempts to write additional ideas under Column 1 for another 1 minute. This *tension and relaxation* sequence has been shown to enhance creativity. It helps to extract all ideas from the brain's subconscious memory, much like squeezing and releasing a sponge several times to extract all the water.

Phase 2: Idea Trigger Phase

After the idea generation phase, participants take turns reading their entries from Column 1. As people recite their Column 1 entries, others silently cross out the duplicates on their own lists. Hearing other ideas will trigger new ideas, which should be immediately written under Column 2. This process is called *idea triggering*. Listening to others causes hidden thoughts stored in the subconscious to surface. The purpose of the idea trigger phase is not to discount the ideas from Column 1, but rather to amplify them, modify them, and add to them.

After all members have read their Column 1 entries and have completed their Column 2 entries, the idea trigger process is repeated. This time, entries from Column 2 are read, and any new ideas are entered under Column 3. The process is repeated, with entries added to Columns 4, 5, and so on, until all ideas are exhausted. Complex problems may require as many as five rounds of the idea trigger phase.

The entries that appear under the second and third columns (and the fourth and fifth columns if the problem is complex) are usually the most creative. Such richness results from several factors. Often participants are secretly angry because their ideas were stolen by others. This simple competitive pressure can propel a person toward new unexplored territory. Conversely, when ideas have not been duplicated by others, participants can receive positive reinforcement, which helps them create even better ideas. Some individuals may respond to their own unduplicated entries with a desire to produce more as a way of hoarding the good ideas. Yet others may subconsciously think that augmenting previously discussed ideas fosters group cooperation.

Phase 3: Compilation Phase

When the idea trigger phase has been completed, the leader compiles everyone's sheets and makes one master list of all the ideas that have been generated. The group then proceeds to discuss all ideas, discarding the ones that probably will not work, and deciding which of the remaining ideas are appropriate for further consideration and development.

EXAMPLE 2.2

A Formal Brainstorming Session

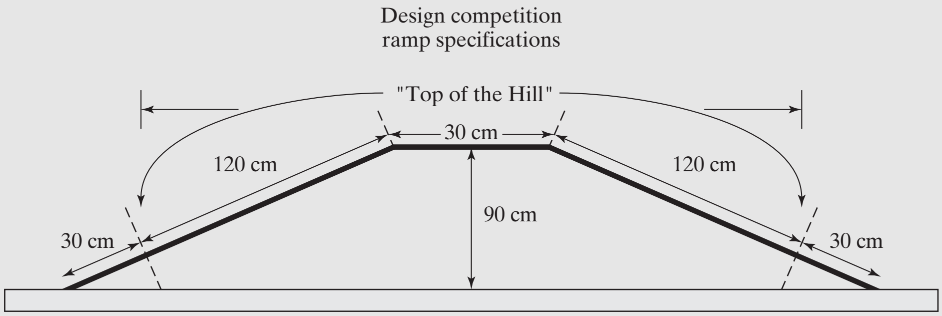
Let's illustrate the formal idea trigger method with an example. Four engineers, Morris, Lawrence, Cindy, and Shana are designing an entry for a design competition. The overall objective is to design a self-propelled vehicle that can climb one side of a trapezoidal, carpet-covered ramp, stop at the top, and prevail over an opposing vehicle that is climbing up the ramp from the other side. The basic elements of the challenge are as follows:

1. The vehicle must be self-contained. No wires or tethers are permitted.
2. The vehicle must fit inside a $25 \times 25 \times 25$-cm cube.
3. The vehicle can be powered in only one of the following ways: a single 9-V battery, any number of rubber bands, or a mousetrap that measures 3 cm $\times$ 6 cm or less.
4. The vehicle's weight may not exceed 2 kg.

The specifications of the competition's ramp are shown in Figure 2.12.

The team recently held a brainstorming session using the idea trigger method. They addressed all elements of the design, including the issues of propulsion, offensive and defensive strategies, and a stopping mechanism. The following discussion chronicles their brainstorming session. Moe acted as the leader and timed the first 2 minutes, the break, and the subsequent 60-second idea generation phase. At the end of the phase, Larry's page showed the following ideas:

Figure 2.12
Ramp specifications for the vehicle design competition.



Larry	Idea Generation Phase Column 1 (2 Minutes)
	Support structure = wood (easy to make)
	Use angle irons from Meccano™
	Plastic body for lighter weight
	Zinc air batteries (lightweight)
	Wheels taken from my radio-controlled car
	Rubber band for chain drive
	Small car will be harder for opponent to deflect
	1 Minute
	Ramming device
	Wedge-shaped body

Larry read his entries. As Cindy listened, she crossed out her own duplicate entries. When Larry was finished, Cindy's first column, including cross outs, showed the following ideas:

Cindy	Idea Generation Phase Column 1 (2 Minutes)
	~~No heavy batteries (use zinc air~~)
	Larger wheels for slower turning speed
	Gear box
	Higher torque (harder for opponent to push backwards)
	~~Use plastic for body~~
	Electronic timer for stopping mechanism
	Rechargeable batteries
	~~Wedge-shaped design~~
	1 Minute
	~~Buy wheels from hobby shop for radio controlled car~~
	Sense speed, determine distance traveled
	Aluminum frame

Next Shana read her entries that had not been duplicated by Larry. As Cindy listened, an idea flashed into her head: *we can make the drive shaft from a threaded rod*. Cindy reasoned that the threaded rod could screw a sliding nut toward a cut-off switch. The method would not be foolproof, because slipping wheels could ruin the system's ability to track distance. It seemed worth discussing, though, so she wrote "threaded rod" under her Column 2 entries.

When Shana heard Larry read his "ramming device" entry, it made her think about using an ejected object as part of an offensive strategy. She wrote the words "ejected device" under her Column 2 entries. Moe reacted similarly to Larry's idea and wrote the words, "lob something on the track ahead of opposing car" under his Column 2 entries. The spoken trigger phase made its way around the group. When everyone had finished, Moe, acting as leader, started the process again. This time, everyone read their Column 2 entries and wrote new ideas under Column 3. As Shana read her entry about ejected devices from Column 2, Moe had a fleeting image of a Lyle gun breech buoy that he'd read about in an engineering design book. He imagined a flying arrow with a barbed tip shot ahead of the vehicle over the top of the hill. *After hitting the carpet in* *front of the opposing vehicle,* he thought, *the barbed tip will dig into the carpet, blocking the other car. This spear will be very difficult to dislodge*. Moe wrote "harpoon" under his Column 3 entries.

The second idea trigger round progressed, and Moe started a third. After about 45 minutes, the entire Phase 2 session was finished. Moe suggested a break so that he could compile everyone's lists of ideas. His combined list of entries from everyone's three columns showed the following ideas:

Shape

Small car = harder for opponent to deflect
Wedge-shaped vehicle having same width as track
Rolling can design
Snowplow-shaped wedge

Structure

Support structure = wood (easy to make)
Aluminum frame
Plastic body for light weight
Use angle irons
Hot-melt glue balsa wood

Power

Zinc air batteries (lightweight)
Rechargeable batteries
Change batteries after every run
Electronic timer for stopping mechanism
Microprocessor-controlled car with onboard sensors
Microprocessor speed determines distance traveled

Propulsion

Wheels from radio-controlled car purchased at hobby shop
Large wheels
Rubber band for chain drive
Plastic-linked chain from junked radio-controlled car chassis
Single large mousetrap with mechanical links
Wind up large rubber band

Strategies

Ramming device
Flying barbed harpoon
Pickup arm
Throw jacks in front of oncoming opponent
Roll over opponent with large roller

After the break, Moe reconvened the team to discuss the list of ideas. They weeded out the ones that did not seem feasible and compared ideas that looked promising. Finally, they combined multiple ideas and converged on the concept of a slow-moving, wedge-shaped vehicle for the prototype stage. They also decided to try Moe's flying harpoon strategy, where the harpoon is designed to dig into the carpet and block the path of the opposing vehicle. This strategy constituted their "first cut" entry into the inner loop of the design cycle.

2.5.3 Informal Brainstorming

As discussed in the previous section, the formal brainstorming method requires organization and planning. In contrast, informal brainstorming can be done anywhere. As a technique for engineering design, informal brainstorming in a round table format is appropriate for small groups of people. Ideas can be contributed in random order by any participant. The lack of tension inherent in large groups is absent, and the randomness of interjection can be tolerated if the group is small. The flow of ideas need not be logical, and new proposals can be offered whenever they come to mind. The ground rules introduced in Section 2.5.1 should still be enforced during an informal brainstorming session.

EXAMPLE 2.3

Informal Brainstorming

The following example of an informal brainstorming session describes a hypothetical conversation between two structural engineers who were asked to design a crossbeam for a renovated building. The renovation involves gutting the building interior and tearing out existing internal walls. However, after the initial demolition, the designers discover a support column hidden inside a wall in the middle of a large room. The architectural plans require that the vertical column be removed to create open space, as illustrated in Figure. 2.13. This column holds up the mid-span of a wooden crossbeam that had previously been hidden inside the ceiling. The engineers must find some new way to support the crossbeam and the upper floor it sustains, so that the column can be removed permanently. In its present form, the wooden crossbeam is too weak to be supported only at its two ends. If left unsupported in the middle of its span, it will surely break and cause the floor above it to fall. The engineers,

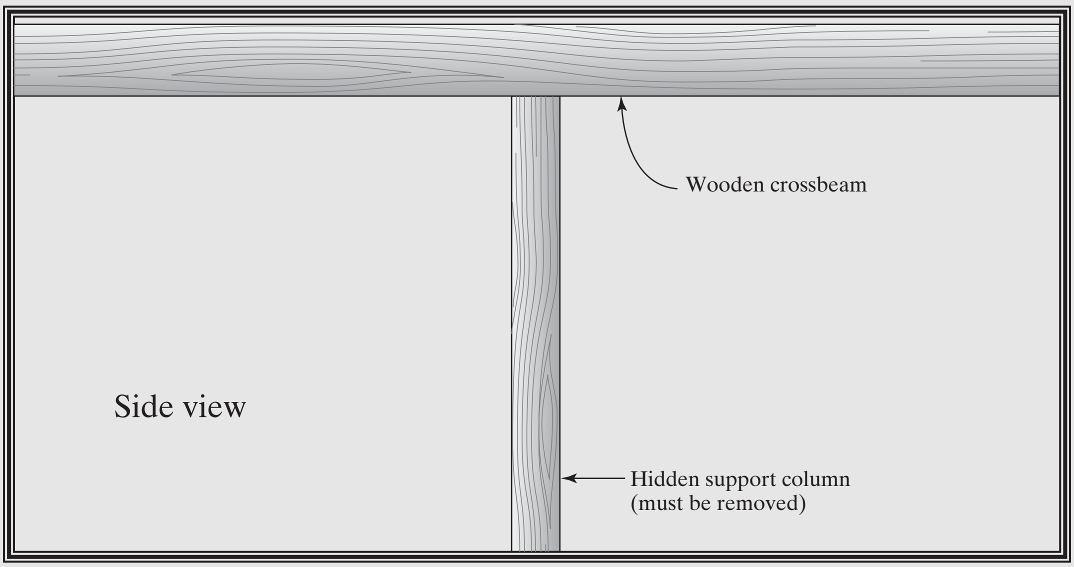


Figure 2.13
Demolition plan showing a previously hidden vertical support column and crossbeam (side view).

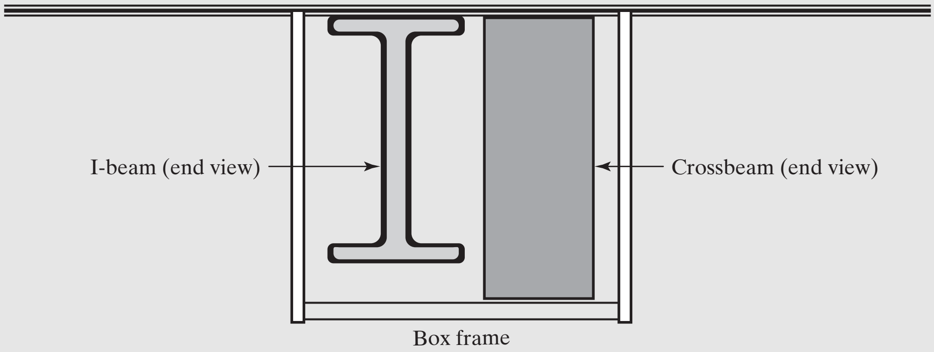


Figure 2.14
I-beam and wooden cross-beam side by side. The box encasing the two beams is very wide and ugly.

Robert and Ernest, discuss the problem using the informal brainstorming method. Note the ebb and flow of ideas between the two engineers. They do not immediately fixate on the first idea that comes to mind; instead, they allow the flow of ideas to lead them to a feasible solution.

Bert: "Let's just install a new steel I-beam under the upper floor, running it side-by-side next to the existing wooden one. A steel beam is much stronger than a wooden beam, so we could remove the supporting column without worry."

Ernie: "OK, we could." *He thought for a while.* "But we'll have to enclose the existing beam in a box casing when we finish the ceiling. Adding another beam side-by-side will make this box *very* wide." *He drew the sketch shown in Figure 2.14*. "This wider-than-expected box will compromise the artistic interior design of the building and will also interfere with the planned layout of the hanging light fixtures.

"What if we *take out* the existing wooden beam and replace it with a steel I-beam? Thus, we can minimize the impact of the box casing."

Bert: "That might work, but we would need to make a temporary beam to support the upper floor while we remove the old beam; that would require a temporary column as well. We'd need to build a false wall in the basement to support the temporary column. It would take lots of time and lots of money. It may not be worth it." *Bert showed Ernie the sketch in Figure 2.15*.

Ernie: "Yeah, it would cost a lot. But the client will understand that we have no choice."

Bert: "But she would not be very happy about it. We need a better solution." *Bert thought for a while*. "I've got it. We can drill holes through the existing beam, and then create thin steel plates with holes in the same places. Then we can bolt the plates on either side of the wooden beam with these huge bolts." *He made a sizing gesture with his hands*. "The composite beam would be strong enough to support the upper floor without the column." *Bert drew the sketch of Figure 2.16 to illustrate his idea*.

Ernie: "I have a better idea. Let's have the plates made up first with the holes. We'll clamp the plates in place, and *then* drill the holes in the wooden beam, using the steel-plate sandwich as a template."

Bert: "Yeah! Good idea. The beam sandwich will be nice and strong and only a little bit wider than the wooden beam alone." *He thought a moment more.* "But we should do some analysis to be sure that the reinforced beam will be

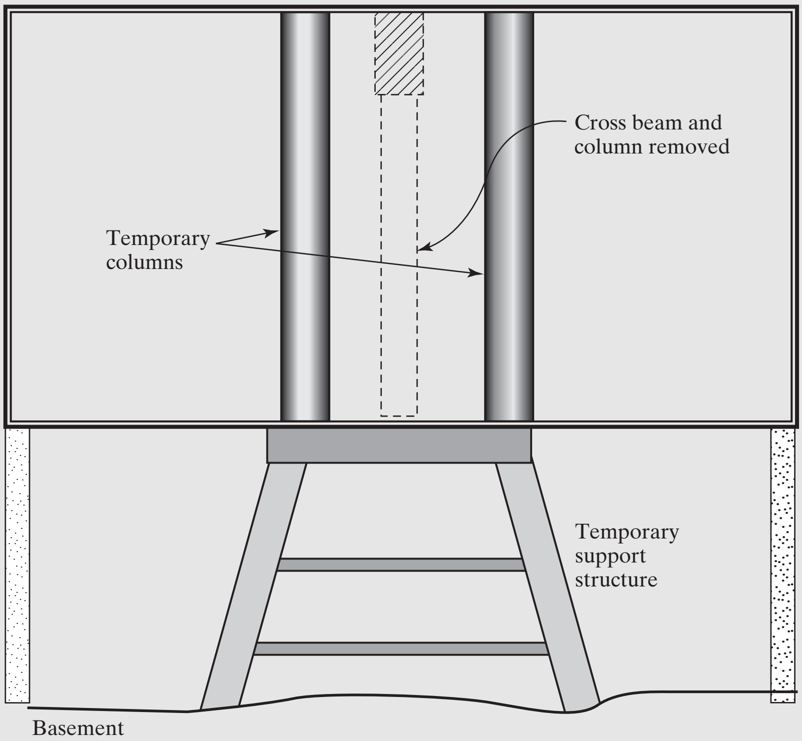


Figure 2.15
Replacing the existing wooden beam requires building a temporary structure in the basement so that the upper floor can be supported while the column and beam are removed.

strong enough. I'll do some rough calculations to figure out how thin the plates can be, and then do some more accurate computer modeling."

Ernie: "Good. In the long run, it will be cheaper to do it this way. I like this idea much better than the first two. It's a good compromise. "

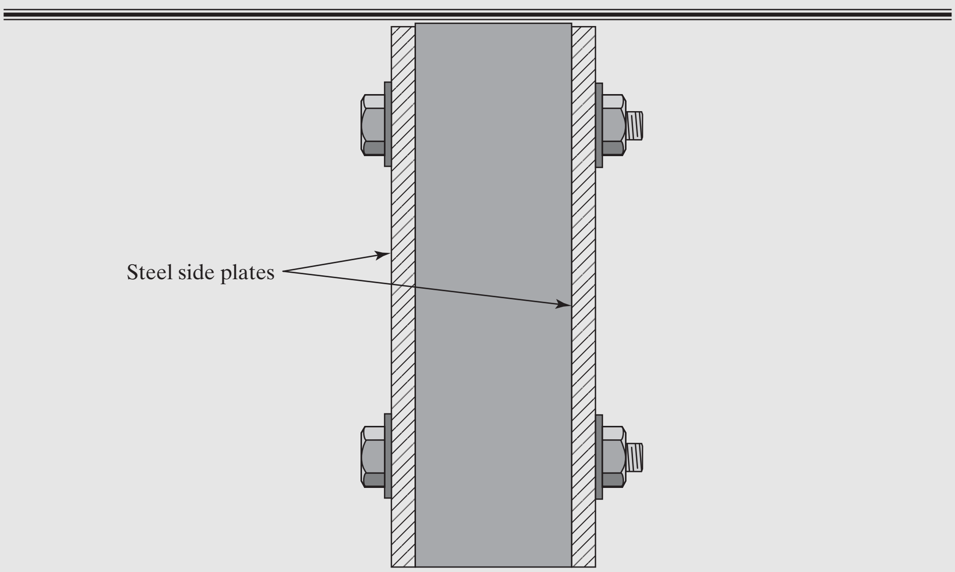
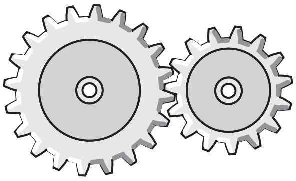


Figure 2.16
Bert's idea for two side plates to strengthen the existing wooden beam.



Professional Success: What to do When One Individual Dominates a Brainstorming Session

Suppose that you are the leader of a brainstorming session, and one member of your team dominates the conversation. That person may criticize participants, dismiss unconventional ideas, cut off speakers, or otherwise break the rules. When this situation occurs, it's your responsibility to keep the offender in line. You might say to the group, "Hey, we need to stick to the formal rules of brainstorming. Let's institute a don't-speak-until-called-upon rule." This approach will tactfully short-circuit the behavior of the dominant person and maintain harmony among team members.

Practice!

1. Examine the final list of ideas compiled by Morris and his group during their idea trigger session. Conduct a one-person "mini-brainstorming session" and add as many ideas as you can. Allow yourself 4 minutes to compile your ideas.
2. A non-engineering friend complains about a pair of ear-bud headphones that keep falling out. Give yourself 5 minutes of brainstorming time, and compile a large list of ideas to solve your friend's problem. After the 5 minutes are over, take a short break, then sort your list, categorizing each idea with a "feasibility" rating of 1 to 5, with 5 being the most feasible.
3. In 2 minutes, write down as many ways as you can for safely confining a dog to a yard. Then rate your ideas in rank order, from least costly to most costly.
4. In 2 minutes, write down as many ideas as you can for designing a hands-free water faucet.
5. To save energy, you'd like to devise a method for reminding people to turn off lights. Devise as many methods as you can to achieve this objective. Allow yourself 2 minutes of brainstorming time.
6. Form a team of three to five colleagues. Using brainstorming method of your choice, come up with as many methods as you can for alerting city officials that parking meters are full and need to be emptied of coins (e.g., emptied "on demand", rather than on a schedule.
7. Form a team of three to five colleagues. Using brainstorming method of your choice, come up with as many concepts as you can for a system that will automatically feed pellets to a pet hamster. Allow yourself 3 minutes of brainstorming time. If possible, work with a group of up to four people.
8. Get together with a teammate to conduct an informal brainstorming session. Take turns contributing a single new idea, one after the other, until one of you has run out of ideas. Then the other should declare all remaining ideas. Each of you should write down ideas as soon as they come to mind. Use this method to develop a concept for designing an automatic bagel-slicing machine.

9. Imagine that you are part of design team that is developing a method to synchronize an MP3 personal music player with a companion program on a desktop computer. Compose the idea trigger session sheets that four teammates might contribute to such a session. These sheets should have the form shown in Figure 2.12. Also, compile a composite sheet that summarizes the session.
10. In two time spans of 2 minutes each, with a 1 minute break in between, think of as many ways as possible to determine the depth and breadth of a newly discovered underground oil deposit.
11. The following exercise involves a futuristic problem. Meet with one or more classmates for a brainstorming session (either formal or informal). Write multiple ways to transfer information from a human into a computer without a keyboard or mouse. Provide details of each possible method.
12. Imagine that you have a toy rocket, a baseball, and a helium balloon. Get together with three to five fellow students, and run a brainstorming session to determine different ways of using these items, and these items only, to determining the height of Mount Washington in New Hampshire, USA.
13. Run a brainstorming session to determine how one might use a barometer, stopwatch, and tape measure to determine the height of the Washington Monument in Washington, DC?
14. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 as it might evolve during a session to develop a sensing mechanism for measuring the speed of a bicycle.
15. Suppose that your design team has been given an egg, some tape, and several plastic drinking straws. Run a brainstorming session to devise a system to prevent the egg from breaking when dropped from a height of 6 ft (2 m). You are to use only the aforementioned materials.
16. Get together with one classmate. Run an informal brainstorming session to devise as many different methods as you can for using your desktop computer as a stop watch to time a road race.
17. Think about a large aquarium (the kind the public visits to see large sea creatures). Suppose that your team has been given the task of designing a system for washing the inside surfaces of the windows from the outside. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 as it might evolve during a brainstorming session.
18. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design a system to help a quadriplegic turn the pages of a book.
19. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design of a system for automatically raising and lowering the flag at dawn and dusk each day.
20. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design of a system that will automatically turn on a car's windshield wipers when needed.

21. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design of a device that can alert a blind person when a pot of water has boiled.
22. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design of a system to line up screws on an assembly-line conveyor belt. All screws must point in the same direction.
23. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design of a method for detecting pinhole leaks in latex surgical gloves during the manufacturing process.
24. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design of a method for deriving an electrical signal from a magnetic compass. The compass must interface with a computer running navigational software.
25. Imagine that you have been given a coil of rope and eight poles. Run an informal brainstorming session to devise a method for building a temporary emergency shelter in the wilderness.
26. Run an informal brainstorming session to devise an alarm system to prevent a thief from stealing memory chips from inside a personal computer.
27. Imagine custodial workers who are in the habit of yanking on the electrical cords of vacuum cleaners to unplug them from the wall. Run an informal brainstorming session to devise a system or device to prevent damage to the plugs on the ends of the cords.
28. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design of a system for automatically dispensing medication to an elderly person who has difficulty keeping track of schedules.
29. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design of a system that will agitate and circulate the water in an outdoor swimming pool so that a chlorine additive will be evenly distributed. Assume that a ground-fault protected (GFCI) electrical outlet is available at the pool site.
30. Reconstruct a brainstorming sheet of the type discussed in Example 2.2 related to the design of a system that will allow truck drivers to check their tires' air pressure without getting out of the vehicle.
31. Can brainstorming be used to solve math problems? Why or why not?

2.6 DESIGN EXAMPLES

In this section, the principles of engineering design are illustrated by three specific examples. The approach in each case emulates key elements of the design process.

2.6.1 Model Vehicle Design Competition

Imagine that you've entered a vehicle design competition in which the sponsor, your engineering college alumni association, offers textbook gift certificates to the college bookstore to the winners. Given the high cost of textbooks, you're eager to win.

The goal of the competition, as previously shown in Figure 2.12, is to design and construct a vehicle that can climb a ramp under its own power, stop at the top of the ramp, and sustain its position against an opposing vehicle coming up the other side of the ramp. The vehicle deemed "on top of the hill" is the one closest to the centerline after a 15-second time interval. Multiple runs against different pairs of competitors will determine the final winner.

The rules state that the vehicle can be powered by just one of the following energy sources:

- A battery of up to 9 volts
- A rubber band (4 mm × 10 cm maximum size in its unstretched state)
- A mousetrap (3 cm × 6 cm maximum spring size).

Imagine that you have entered this design competition and wish to design a competitive vehicle. Let's examine the problem using the design cycle of Figure 2.7. Remember that the problem can be addressed in many different ways. The solution presented here is but one of many.

1. Gather Information

The rules for the competition comprise a self-evident source of information about the design objectives. At this stage, it would be a good idea to gather information about battery life and power output, rubber band statistics, commercially available mousetraps, and, of course, easily obtainable electric motors. Only after compiling a comprehensive set of such information can you proceed with confidence to the next step of choosing a design strategy.

Choose a Design Strategy. Many different design strategies will lead to a vehicle capable of competing. Building a *winning* design, however, requires careful consideration of several key issues. How can you know ahead of time what the right choices will be? In truth, you can't, especially if you've never built such a vehicle before. You can only start by making educated guesses based on your experience and intuition, plus the information you've gathered in the previous step. You then can rely on the iterative nature of the design process to help you converge on a workable solution. The following list defines some possible design strategies that you might adopt:

1. *Design for speed*. The vehicle with the fastest speed will not necessarily win, but one strategy could be to race to the top as fast as possible, then defend against a slower opponent by blocking access to the top of the ramp using a proper defensive strategy.
2. *Design for strength*. Alternatively, you could design a strong, steady, slower-moving vehicle capable of pushing away the opposing car as it "bulldozes" its way to the center of the ramp.
3. *Design for easy changes*. The rules state that modifications to the vehicle are permitted between runs. Adopting an easy-to-change construction strategy will facilitate "on-the-fly" changes to your vehicle.
4. *Design for durability*. During the competition, your vehicle must endure many trips up the contest ramp. Opposing vehicles and accidents can damage a fragile design. You must weigh the issue of durability against your desire to produce a vehicle that's flexible and easy to modify.

Note that strategies (3) and (4) are not independent of one another. For example, designing for easy changes may conflict with building a durable vehicle. Engineers typically face such tradeoffs when making design decisions. Deciding which pathway to take requires experience and practice, but making any decision at all means that you've begun the design process.

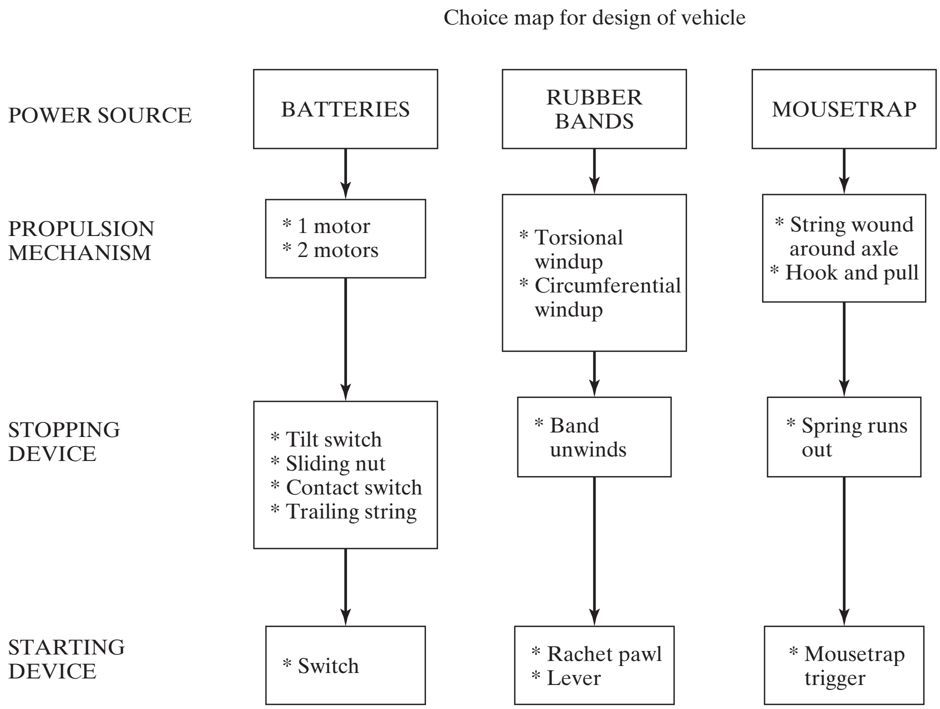


Figure 2.17
Choice map that outlines the decision tree for the first phase of the design process in the vehicle design competition.

The rules of this particular competition provide for many alternatives in vehicle design. Regardless of the details, however, all vehicles will require the same basic components: an *energy source*, a *propulsion mechanism*, a *stopping method*, and a *starting device*. After some discussion with your teammate, you develop the *choice map* shown in Figure 2.17.

Although the choice map does not provide an exhaustive list, it serves as an excellent starting point for your design effort. The following paragraphs outline some of the thought processes that might accompany your design choices.

Energy Source. Batteries are attractive as an energy source because they require no winding or preparation. They will need frequent replacement, however, and will thus be more expensive than the mechanical alternatives. Rubber bands will require much less frequent replacement, but will store the smallest amount of energy among the three choices. Like a rubber band, a mousetrap does not need frequent replacing. It stores more energy than a rubber band, but because of its physical form, it offers the fewest options for harnessing its stored energy.

Propulsion Mechanism. Your choice of the propulsion device, or *energy converter*, will depend on your choice of an energy source. If you decide to use batteries, an electric motor will be the obvious choice for turning the vehicle's wheels. Rubber bands can be stretched to provide linear motion or twisted for torsional energy storage to turn an axle or power shaft. Alternatively, a rubber band can be stretched around a shaft or spool like a fishing reel and used to propel the vehicle's wheels. A mousetrap can provide only one kind of motion. When released, its bale will retract in an arc, as depicted in Figure 2.18. In principle, this motion can be harnessed and used to propel the vehicle.

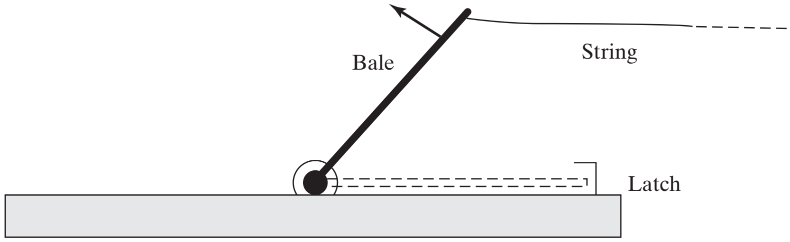


Figure 2.18
Harnessing the stored mechanical energy of a mousetrap. The bale retracts in an arc when the mousetrap is released.

Stopping Method. According to the competition rules, your vehicle must stop when it arrives at the top of the ramp. This requirement can be met by interrupting propulsion power precisely at the right moment and relying on a combination of gravity and friction to stop the vehicle. A braking device to augment these forces might also be considered. If the vehicle is powered by batteries, there are many ways to interrupt power flow to the vehicle. A simple tilt switch can disconnect the battery when the vehicle is level, but connect the battery when the vehicle is on a slope. A metal ball that rolls inside a small cage and makes contact with two electrodes, as illustrated in Figure 2.19, might serve as a suitable tilt switch. Other choices include a spring-loaded contact switch, such as the one shown in Figure 2.20, or a system that cuts off power to the wheels after the car has traveled a preset distance as measured by wheel rotations. This latter scheme will work well only if the wheels do not lose traction and slip on the track.

One interesting alternative to a mechanical switch would be to use an electronic timer circuit that shuts off power from the battery after a precise time interval. Through trial and error, you could set the elapsed time so that the vehicle stops precisely at the top of the ramp. One problem inherent to this open-loop timing system is that the vehicle does not actually sense its own arrival at the top of the

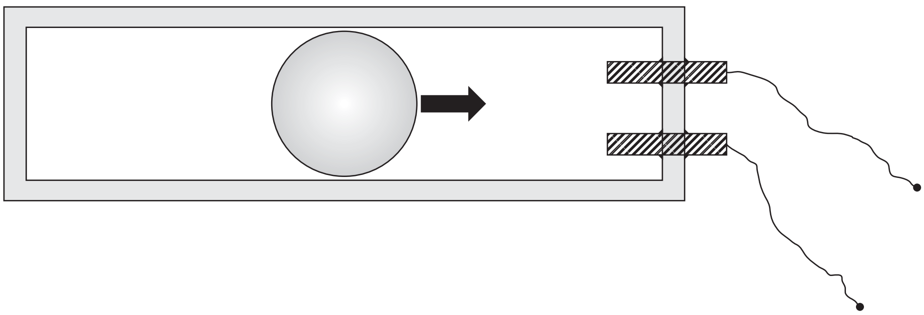


Figure 2.19
Tilt switch made from a small enclosure, a metal ball bearing, and two contact points.

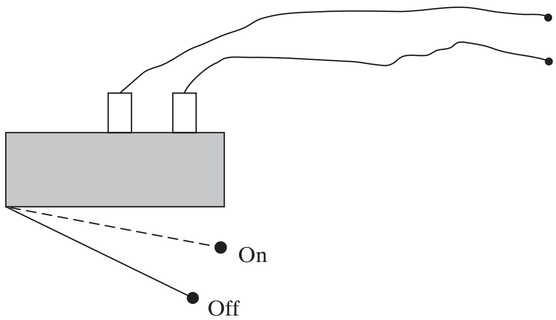


Figure 2.20
Spring-loaded contact switch.

ramp, but rather infers it by interval timing. Because the speed of the vehicle may decrease with each successive run as battery energy is depleted, this timing scheme might cause problems. The method will also fail if the wheels slip on the track. On the other hand, it is likely to be more reliable than solutions that involve mechanical parts.

If a rubber band or mousetrap is chosen as the power source, then stopping the vehicle will require something other than an electrical switch. One way of stopping a vehicle propelled by mechanical energy storage is simply to allow the primary energy source to run out (e.g., allow the rubber band to completely unwind). While this method is crude, it is reliable, because power input to the vehicle will *always* cease when the source of stored energy has been depleted.

Starting Device. If the vehicle is powered by a battery, then an electrical switch becomes the most feasible starting device. You could, however, design the vehicle so that the motor is brought up to speed prior to the start, then mechanically engaged at the starting time. This latter approach might enable a strategy involving rapid ascent up the ramp. A rubber-band power source will require a mechanical device such as a trip lever to initiate power flow to the wheels. A mousetrap can use its built-in trigger mechanism or any other starting mechanism that you might devise.

2. Make a First Cut at the Design

The first design iteration begins with rough estimations of the dimensions, parameters, and components of the vehicle to make sure that the design is technically feasible. After discussing the long list of design choices, you and your teammate decide to use a battery-powered vehicle. This decision allows many choices for a stopping device. You feel that the flexibility inherent to this design choice far outweighs the advantages of mechanical propulsion schemes. You decide upon a defensive strategy and agree to build a slower-moving, wedge-shaped vehicle powered by a small electric motor. The advantage of this design approach is that the motor can be connected to the wheels using a large gear ratio, thereby providing higher torque at the wheels and a mechanical advantage that would be unavailable to a very fast vehicle. Because your vehicle will be slower than the others, it may not reach the top of the ramp first, but its wedge-shaped design will help to dislodge any opposing vehicle that does arrive first at the top of the ramp. On the other hand, if your vehicle arrives first, its defensive wedge shape will cause your opponent's car to ride over your car's body, allowing you to maintain your position at the top.

A rough preliminary sketch of your car is shown in Figure 2.21. You've entered this sketch into a notebook that contains all information relevant to the project, including design calculations, parts lists, and sketches of various pieces of the car. Shown in Figure 2.21 are the car's wedge-shaped design; a single drive shaft driven by a motor, belt, and pulleys; and a single switch to turn off the motor when the vehicle arrives at the top of the ramp.

3. Build, Document, Test, and Revise

The sketch of Figure 2.21 represents a beginning, but it is not the finished product. You still have many hurdles to overcome and tests to run before your vehicle will be ready to compete. The next step in the design process should probably be the building and testing of a "first-cut" prototype. To help you in this phase of the design process, you've built a test ramp that mimics one side of the official test ramp. You begin by constructing a chassis shell in the form of a wedge, but without a motor drive or stopping mechanism.

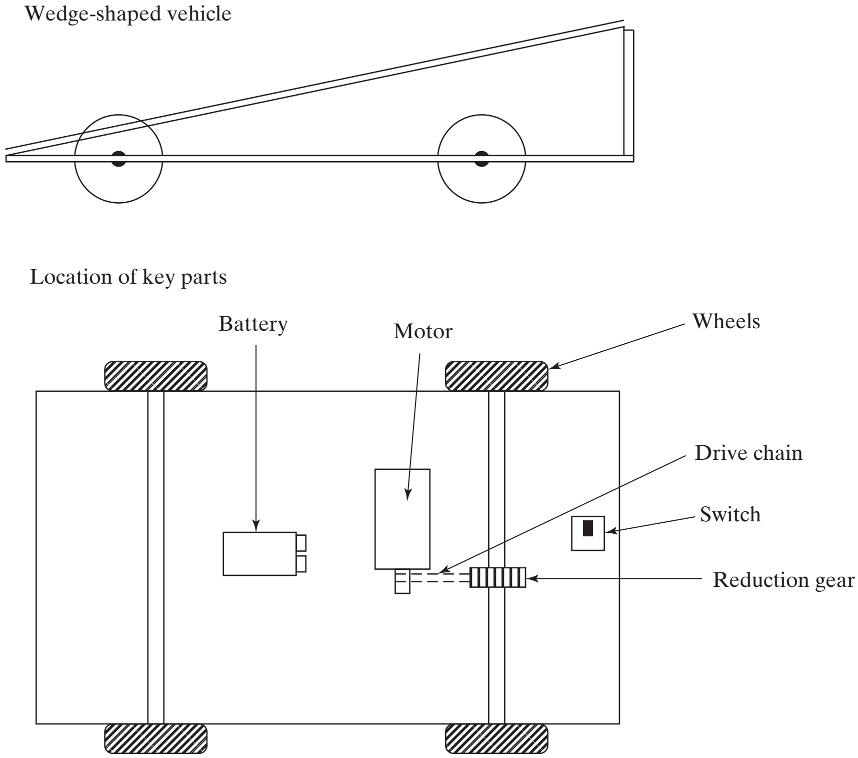


Figure 2.21
Rough, preliminary sketch of a car for the vehicle design competition.

You run your wedge-shaped vehicle up the ramp slope by hand. You soon discover that the bottom of the vehicle hits the ramp at the top of the hill, as depicted in Figure 2.22(a). The change in the angle of the ramp is large, and all four wheels do not always maintain contact with the track surface. You discuss several solutions to this problem with your teammate. One solution would be to increase the diameter of the wheels, as shown in Figure 2.22(b). This change would decrease the mechanical advantage between the motor and the wheels, requiring you to recalculate the torque required from the motor. Another solution would be to make the vehicle shorter, as in Figure 2.22(c), but you realize that this solution would lead to a more acute angle of your wedge shape and reduce its effectiveness as a defensive strategy. (The thinner the wedge, the more capable the car of wedging itself under opposing vehicles. However, the rear of the wedge must be the same thickness to leave space for the motor and gear box.)

4. Revise Again

Your teammate suggests keeping the wheels and shape of the wedge the same and moving the rear wheels forward, as depicted in Figure 2.23. You rebuild the vehicle by moving the rear shaft mount forward, and you test your vehicle again. The redesigned vehicle no longer bottoms out on the track, and you claim success. Your professor sees your design changes and suggests that you test your vehicle under more realistic conditions. For example, what will happen when another vehicle rides over the top of your wedge-shaped body? You proceed to simulate such an event by placing a weight at various positions on the top of the car. The results of these additional tests suggest that moving the wheel locations may not be the best solution to your problem. When you move the rear wheels forward, you change the base of

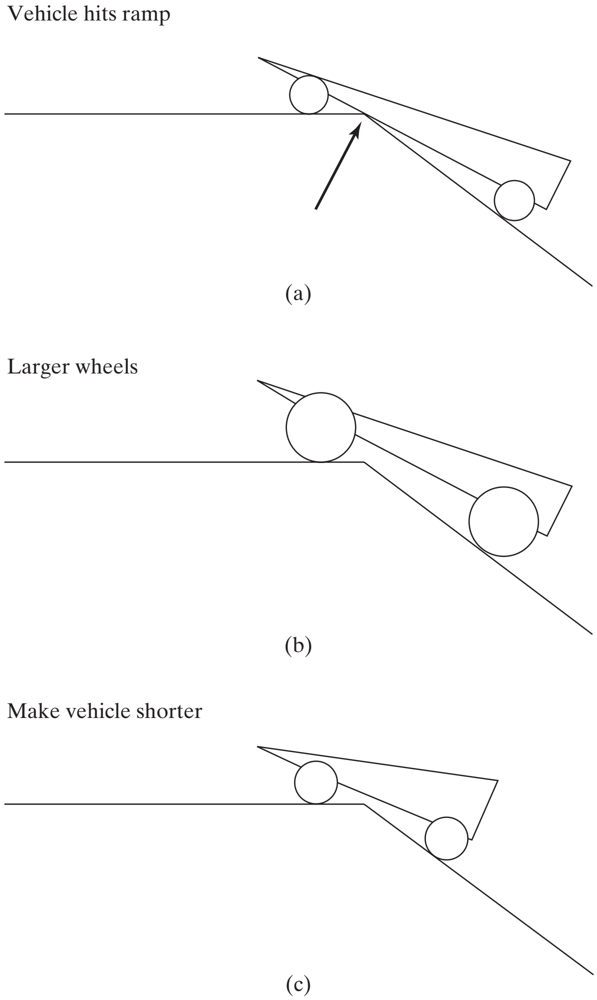


Figure 2.22
Vehicle at the top of the ramp. (a) Bottom of vehicle hits the ramp; (b) vehicle with larger wheels; (c) a shorter vehicle.

support for the car's center of gravity. You discover that if an opposing vehicle rides over the top of your car, the net center of gravity moves toward the rear, eventually causing your car to topple backwards, as depicted in Figure 2.24.

5. Reality Check

This latest discovery may seem like a setback, but it's a normal part of the iterative design process. Some things work the first time, while others do not. By observing

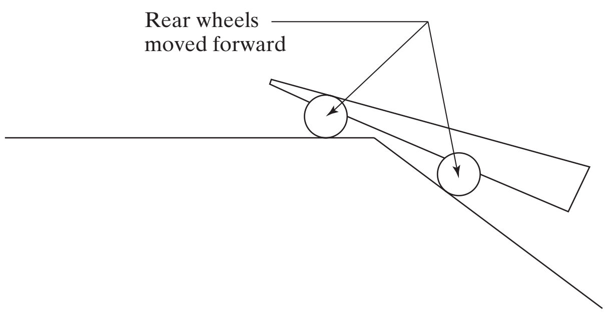


Figure 2.23
Moving the rear wheels forward.

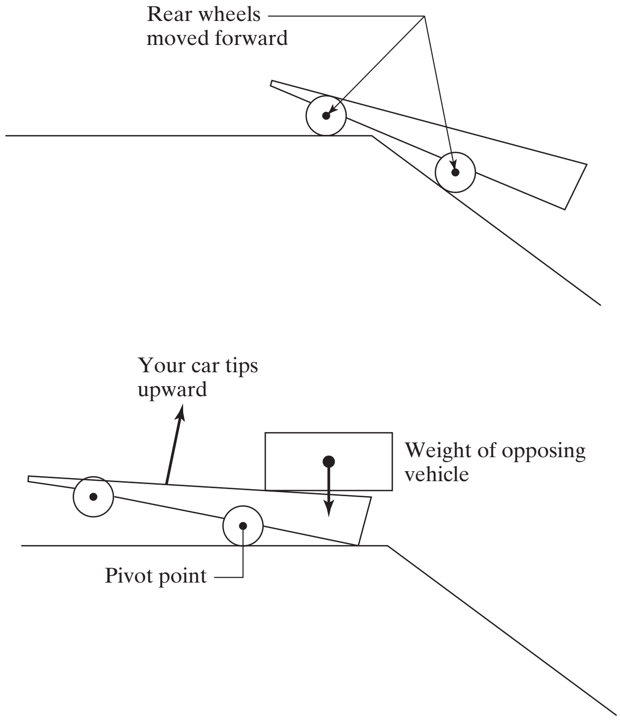


Figure 2.24
Weight of opposing vehicle on top of rear end causes car to topple backwards.

and learning from failure and by building, testing, revising, and retesting, you will be able to converge on the best solution to the problem.

6. More Revisions

After some thought, you decide that increasing the diameter of the wheels may be the best option after all. Your teammate points out that you can simply change the ratio of the gear box to preserve the net mechanical advantage between the motor and the wheels. This change will allow you to accommodate larger wheels. You buy some new wheels and try them with success. With the rear axle moved to its original location and the larger wheels in place, your car no longer bottoms out on the ramp.

Practice!

1. Make a two-column list that outlines the advantages of the various power sources for traveling up the ramp of Figure 2.12 in the vehicle design competition.
2. Make a list of additional propulsion mechanisms that could be used to drive a design competition vehicle.
3. Make a two-column list that outlines the advantages of using gravity and friction versus an applied brake as a stopping mechanism for a design competition vehicle.
4. Determine the minimum energy needed to drive a 2-kg vehicle from the bottom of a ramp to the top, a net vertical distance of 1 meter.

5. How much electrical energy (in joules) is needed to exert one newton of force over a distance of 1 meter (m)?
6. How much electrical power (in watts) is needed to exert one newton of force on a body over a distance of 1 m for 10 seconds?
7. Determine the number of turns per centimeter (cm) of wheel diameter that will be required to move a vehicle from the bottom to the top of a 1-m ramp in a vehicle design competition.
8. For a 1-m design competition ramp, determine the wheel diameter needed to move a vehicle from the bottom of the ramp to the top with 50 turns of the drive axle.

Professional Success: Parallel Paths to Different Design Solutions

One of the interesting features of the design process is that more than one perfectly acceptable solution may exist to the same engineering problem. The endpoint of your design efforts may be affected more by arbitrary design decisions than by the intrinsic worth of one solution over another. This scenario is not unlike that found in any of several science fiction stories involving time travel, in which parallel time travel paths, each originating at the same point event, lead to drastically different outcomes. In the classic movie *Back to the Future*, for example, Marty McFly (played by Michael J. Fox) inadvertently travels back in time to his parents' 1955 high school. With the help of his scientist companion, Dr. Emmett Brown (played by Christopher Lloyd), he repeatedly travels back to the present, each time returning to a different reality based on small changes he made in his parents' past. The parallel time pathways depicted in the story all lead to valid, believable, but very different outcomes.

This same scenario exists in the world of engineering design. Small changes in a design approach can lead to very different, but equally valid, design solutions. If you find yourself in such a situation, know that the decision may be left to your whim and fancy—provided that each outcome will truly meet design objectives. In any given situation, take heed that the latter is really true. Sometimes, hidden factors (such as the availability of raw materials, public reaction to a particular style, or the ability to market one design over another) may, in fact, make the choice far from arbitrary.

2.6.2 DVD Production Facility

In this example, we'll examine the design cycle for the case where the product is a manufacturing process, rather than a tangible physical entity. Although the means of execution of the various stages of the cycle may differ, the basic principles will be identical to those used in the previous example.

The case involves a software interface that must be written for a company that makes digital video disks (DVDs). The disks are sold online by several vendors, including Amonia.com, BestVids.com, CircuitTown.com, and WebFlix.com. Each of these vendors wishes to minimize its physical inventory while maximizing its ability to fulfill orders quickly. A machine that can mass produce plastic DVDs from etched metal master disks is very expensive—on the order of a few million dollars—and none of the DVD vendors alone can afford that sort of capital investment. They each would like a subcontractor who can manufacture DVDs on demand as they are ordered from each vendor's individual website. In recognition of this need, your company, Disk Stamper Inc., has raised money from venture capitalists, purchased a stamping machine, and has contracted with each of the four vendors separately to fulfill their orders on demand. The job of your design team is to determine a manufacturing system than can accomplish this task. Let's discuss this design problem in the context of the design cycle of Figure 2.7.

1. Define the Overall Objectives

The overall objectives of this design problem are clear. First, you desire to keep your clients happy. You must stamp and ship their DVD orders as quickly as possible and strive for 100% accuracy. You must provide for contingencies should your machine (or machines) be out of service for repairs, and you must regularly back up data. In addition, you need to fulfill your prime directive as a small company: you must make money. This last objective is neither whimsical nor callous. If your company does not make money, you will not be able to sustain your operations, and you and your employees will be out of jobs.

2. Gather Information

Your first step should be to interview your clients to determine their requirements. If you're lucky, their needs will coincide, and your design task will be simplified. In practice, however, their needs are apt to differ somewhat. One element of your information-gathering goal will be to seek common threads among your customers' aggregate needs. Perhaps it will be possible to persuade them to alter their stated requirements so that you can converge on a workable solution.

You should also investigate the operations of other companies involved in the order fulfillment business. You'll find that some, like you, actually manufacture the products they ship, while others simply act as wholesale distributors for other manufacturers—in essence, they act as the interface between the manufacturing company and online sales vendor. Some online bookstores, for example, work in this latter way, sending their orders to central distributors, called *fulfillment* companies, who in turn order the books from publishers and ship them.

3. Choose a Design Strategy

At this stage of the design cycle, you outline one or more approaches to the overall problem. In one plan, you would allot a daily manufacturing time slot to each DVD seller. During each vendor's allocated time slot (6 hours total, for around-the-clock operations), its accumulated online orders would be fulfilled, and DVDs of the same title would be processed together. This approach, illustrated graphically in Figure 2.25, would require that you change the master stamping disk several times during the vendor's time window, but it would enable you to group together each vendor's orders for shipment. An alternative strategy, shown in Figure 2.26, would collect DVD orders by title regardless of vendor and then stamp all the DVDs of the same title together, as a single batch. This approach would reduce the need to change stamp masters frequently, but it would require that you sort orders by seller at periodic intervals. After some discussion, you decide to investigate the latter approach: You will collect orders for all the vendors, sort them by DVD title, and then stamp single titles as a batch, changing masters only when it's time to change the DVD title. There is some motivation for this approach, because it's faster and

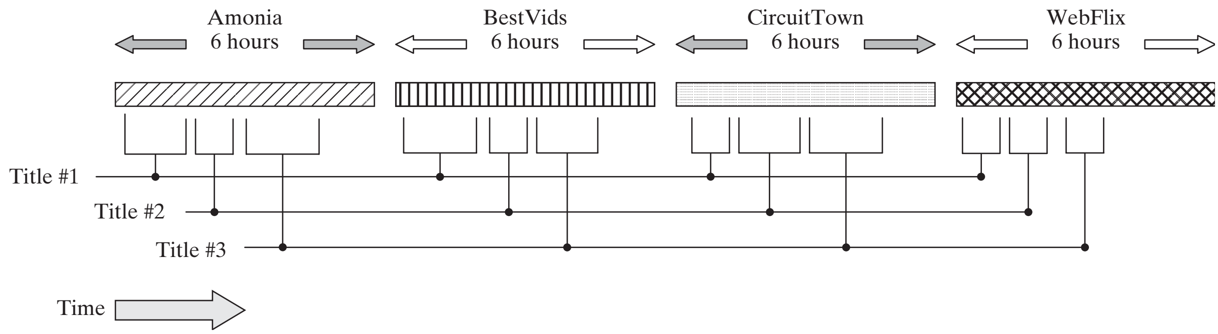


Figure 2.25
One possible implementation of the DVD order fulfillment process. Each of the four vendors is allocated one 6-hour time slot, and individual orders for the same DVD title are processed as a batch within each vendor's time slot.

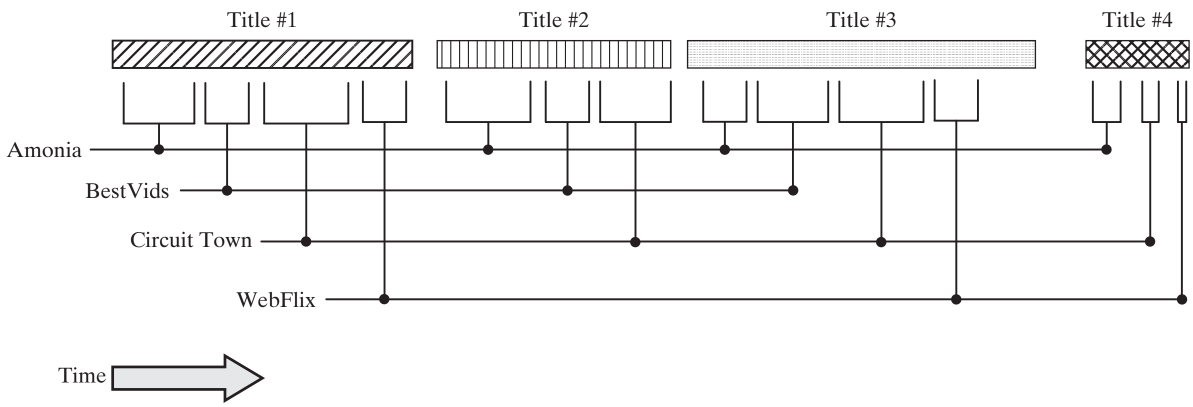


Figure 2.26
Another possible implementation of the DVD order fulfillment process. In this scheme, DVD titles are processed in batches independent of vendor.

will reduce labor costs. Once your business becomes operational, you'll need to pay machine operators by the hour. Given the low profit margin for DVDs (most of the profit in the movie industry goes to the movie production company), reducing labor costs seems like a good idea.

4. Make a First Cut at the Design

A block diagram of your proposed system is shown in Figure 2.27. At the present time, the only definite piece of hardware is the actual stamping machine; all other components will ultimately have to be designed and integrated into the system. Incoming data from the vendors is stored in an "orders" database, and the master disks are stored in a digitally controlled carousel. When the stamping machine becomes free for stamping, the controller retrieves a packet of orders from the input queue, then sends a signal to the carousel to load the correct master into the stamping machine. As each fabricated DVD exits the machine, it is labeled, then, its carrier vessel is tagged with a bar code that links that specific disk to the shipping information stored in the orders database. Packaging occurs down the production line, where the shipping information is printed on the outside of the package.

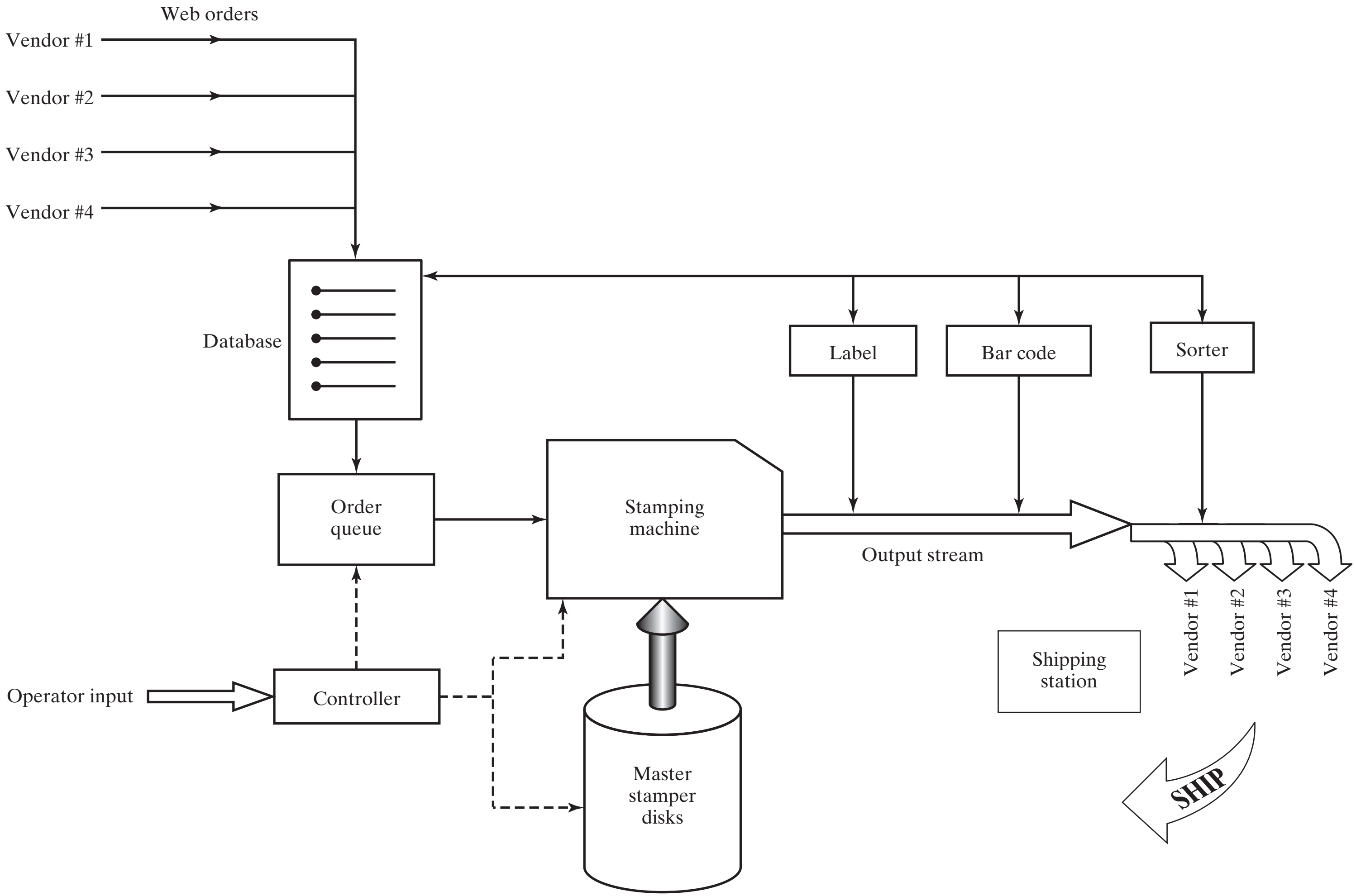


Figure 2.27
Block diagram of a system that can implement the production scheme of Figure 2.26.

5. Model and Analyze

In order to ensure that the system will work as expected, some engineering analysis is appropriate. Each physical transition of a disk from one station to another will require some time delay. If the system is to operate efficiently and provide the fastest overall throughput, proper coordination of events is necessary. Thus, several questions arise. For example, is it better to wait until the disk has been tagged with a bar code before loading the next blank disk in the stamping machine? Or should the blank disk be loaded immediately after its predecessor has left the machine, without regard for the tagging operation? Similarly, what steps must be taken to ensure that incoming orders do not arrive simultaneously, thereby confusing the system? Alternatively, if they do, what techniques can be incorporated into the system to deal with the conflict? A systems-level analysis, in which the dynamics of the queuing process are examined in detail, will help to optimize the system. Answering questions of this sort falls in the domain of *systems engineering,* usually included under the umbrella of *manufacturing* or *industrial engineering* in most college curricula.

6. Build, Document, and Test

Full-scale construction of your proposed system will be costly; hence, you decide (wisely) to attempt the build-and-document phase of the design cycle using simulation. Specifically, you choose to model the entire system using a commercial systems-analysis software package. Several excellent sources of such programs exist; you decide upon Simulink,™ a toolbox in the MATLAB software suite.

Your simulation and testing reveal no debilitating problems, but a major bottleneck develops at the packaging stage. Your vendors have specified different shipping methods (e.g., United Parcel Service, FedEx Ground, and the U.S. Postal Service). These different shipping methods require that you change shipping labels from order to order. Given that you have decided to process orders by DVD title, rather than by vendor, changing labels must occur often, possibly causing unneeded delays.

7. Revise and Revise Again

You solve the labeling problem by adding a package sorting station to the system downstream of the stamping operation. This feature will identify each packaged DVD by its bar code, then divert it to one of three shipping stations (one for each method of shipping). This addition to the system will increase capital costs—you will need to purchase and install the components of the additional sorting station—but the overall improvement in efficiency will more than pay for the added startup cost. Your systems-level analysis estimates the payback period for the additional feature to be about 4 months at a 100% production level. Your team decides to adopt this design revision.

8. Thoroughly Test the Finished Product

After extensive testing of your simulated system, you will then build the actual devices and connect them together on the factory floor. You will be able to approach this high-cost portion of the project with some confidence, having analyzed and revised the system prior to construction. Full-scale testing using a simulated order queue will be the next step before you open your company for business. Limited trials of actual orders will be next, followed by ramp-up to full-scale production. Even in this final phase of implementation, you should expect to uncover previously hidden problems and be prepared to return to the design cycle for revisions and further tests.

2.6.3 Automatic Pipette Machine

In this example, we examine a real-world design problem from the combined fields of biomedical, mechanical, and electrical engineering. It provides a good example of a multidisciplinary problem. Our discussion will highlight the various design choices that the engineers faced during the "Choose a Design Strategy" step of the design cycle of Figure 2.7.

In the typical biomedical engineering laboratory, one may find one or more versions of the calibrated pipette dispenser. This essential tool delivers a precisely calibrated volume of liquid ranging from microliters to hundreds of milliliters. Often these calibrated liquid doses are dispensed into the cells of a standardized 96-well microplate such as the one shown in Figure 2.28. The user sets the dials of the pipette to the desired volume, then picks up a disposable tip. Examples of single-tip, manually operated pipettes are shown in Figure 2.29. Samples of disposable tips that fit in the ends of the pipettes are shown in Figure 2.30.

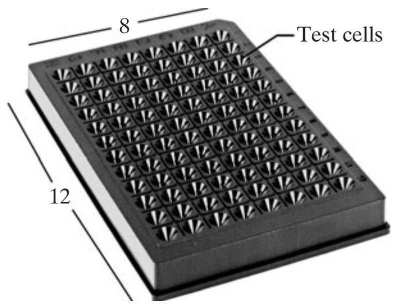


Figure 2.28
Standard 96-well microplate. The volume of each cell is about 100 microliters.

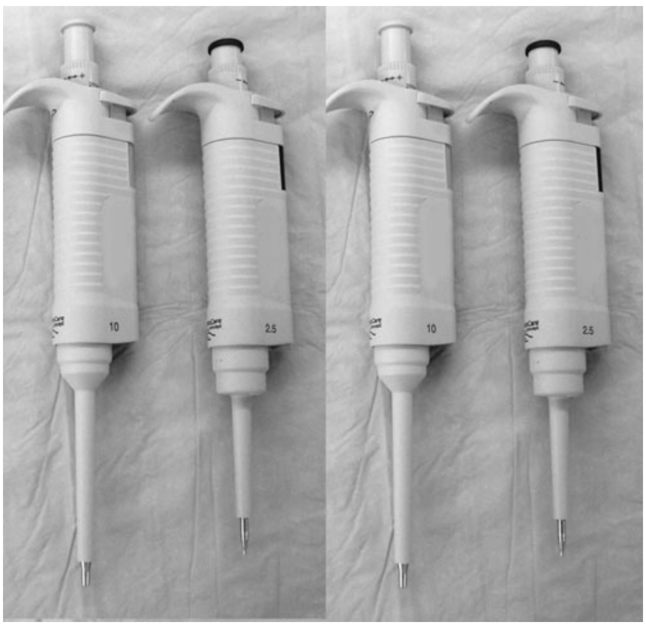


Figure 2.29
Variety of hand-held single-tip micropipettes (disposable tips not attached)

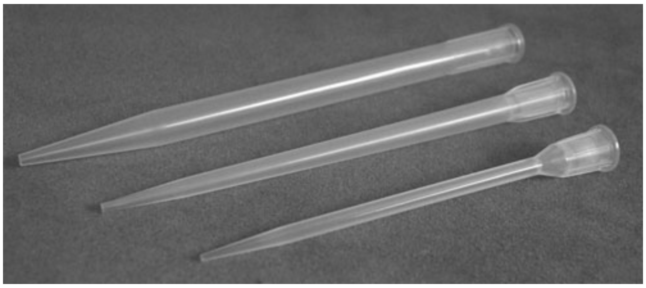


Figure 2.30
Examples of disposable pipette tips.

To use a pipette, the user picks up a disposable tip which is replaced each time the pipette contacts a new liquid or cell culture. The tip is dipped into the liquid to be dispensed. The user pushes, then withdraws a thumb activated plunger to draw up the designated liquid volume into the pipette's tip. The liquid can then be dispensed into any cell of the target microplate by pressing the plunger again. The latter operation causes the liquid to be expelled from the tip. The disposable tip can be changed at any time (for example, to avoid cell-to-cell contamination) by pushing a tip ejection lever.

The application in question involves a Public Health professor who needs to assess the effect of multiple chemical compounds on living cell cultures. Both the compounds and target cultures reside in the cells of 96-well microplates. Because thousands of different chemicals must be tested, the professor has asked a colleague in mechanical engineering to build a robotic machine to perform the tests automatically.

The following table lists the requirements of the system:

- Accommodate standard 96-well microplates (12 rows of 8 cells each spaced 9 mm apart).
- Pick up 10 μL of solvent from reservoir.
- Dispense solvent to each of 96 wells in a target microplate carrying the different compounds, then mix.
- Pick up 3 μL of chemical-laden solvent, then dispense 1 μL into each of the 96 wells in three adjacent microplates. Each well carries 100 μL of cell culture.
- Eject used tips between dispense operations into a disposal bin.

Designing this machine presents the engineer with a myriad of choices that must be resolved as part of the design process. The depth of design choices is illustrated in the following discussions.

Decision: Manual or Electronic Pipette?

Issue. Pipettes are available from several manufacturers in either manual or electronic form. In the former, all operations are fully mechanical and are operated by hand

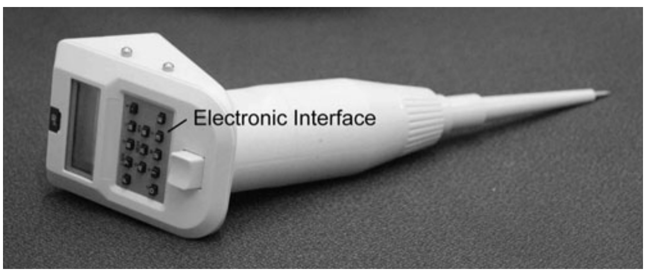


Figure 2.31
Electronic pipette

manipulation. In the latter, the pipette's dispensing syringe is operated by an internal motor and servo control system; the user interface consists of buttons and a display on the pipette's small operating panel. One such pipette is shown in Figure 2.31. Some electronic pipettes can be interfaced to a computer via a cable.

Pipette Comparison		
	Manual Pipette	**Electronic Pipette**
Cost	Inexpensive	Very expensive
Reliability	Simple; no circuitry or motors to malfunction	Complicated electronics and internal motor must function consistently
Design of Interface	Must design complicated mechanical holders, pistons, and actuators for operation in an automated robot system.	Can be interfaced with computer via a single data wire using a standard connector.
Accuracy	Adequate	Marginally better than manual

Decision: Single or Multi-Channel Pipette?

Issue. All pipettes, whether manual or electronic, are available with a single tip or in multi-channel versions having four, eight or twelve parallel tips each tied to the same dispensing mechanism. All volumes must be set to the same value, and all syringes are operated simultaneously, whether drawing up liquid or dispensing it. An example of a multi-channel pipette is shown in Figure 2.32.

Figure 2.32
Multi-channel pipette

Number of Channels Comparison		
	Single Channel	**Multi-Channel**
Mechanical Complexity	Requires two-axis (X-Y) motion to reach all cells of the microplate	Only one direction of motion (x-axis) is needed. Can dose an entire microplate row simultaneously if a 8- or 12-channel pipette is chosen.
Overall Speed	Slower	Faster; Can dispense all the cells in microplate row at the same time.
Cost	Least Expensive	Cost rises with number of channels.
Tip Pickup	Easy; requires pressure at only a single point.	Difficult; requires that pressure be applied evenly across an entire row of tips.
Accuracy	Same as multi-channel	Same as single channel
Small droplet pickup	Feasible; requires contact of only one tip with the droplet	Difficult; requires precise alignment of 4 to 12 tips with their respective droplets.

Decision: Aluminum, Plain Steel, or Stainless-Steel Frame?

Issue. The material for constructing the basic support frame must be chosen in consideration of strength, cost, ease of fabrication, and ease of "on-the-fly" design changes. The material chosen for the prototype may differ from that used in the finished product.

Materials Comparison			
	Aluminum	**Plain Steel**	**Stainless Steel**
Ease of fabrication and revision	Easy to machine	Harder to machine	Hardest to machine
Biocompatibility	Can interact with some chemicals; oxides readily	Rusts; can interact with some chemicals	More resistant to corrosion.
Weight	Lightest of feasible metals	Heaviest of feasible metals	Relatively heavy
Cost	Least expensive	Fairly inexpensive	Most expensive of feasible metals
Strength	Weakest	Strong	Strong

Decision: Types of Motion Required to Move Pipette Horizontally and Vertically, and also to Activate its Eject Button

Issue #1. The pipette must be clamped in a secure holder, and the latter must be mounted on a "carriage" capable of motion along one or two axes. The number of axes depends on whether a multi-channel or single channel pipette is chosen. The carriage must be positioned so that the tip (or tips) of the pipette align with the centers of the wells of the microplate. Moving from cell to cell, and also from microplate to microplate, requires long-distance linear motion.

Issue #2. Prior to accessing any microplate well, the pipette syringes must be fitted with disposable tips from a carrier. The spacing between tips in the carrier is identical to that of the inter-well spacing on the microplate.

Issue #3. In order to pick up tips that will reliably remain on the pipette, extra force must be applied during tip pickup. The amount of force required may be large, because a good seal must be achieved between tip and syringe.

Issue #4. Once the pipette has been positioned above a given microplate cell, it must be lowered so that its tip(s) can make contact with the contents of the cell(s). This action requires short distance linear motion.

Issue #5. When a given dosing sequence is completed, the apparatus must push the tip-eject lever. This action requires very short (1 cm) linear motion, but the force required can be large, depending on how forcefully the tips have been picked up previously.

General considerations regarding motion

Type of Actuation. Electric power is readily available almost everywhere via standard wall plugs. Electrically derived forces, however, are generally weaker per unit device volume than those derived from compressed air. Sources of the latter are less ubiquitous than electricity, but compressed air outlets can generally be found in most well equipped scientific laboratories. A stand-alone compressor also can be used to supply compressed air, but this is a generally costly and noisy alternative. The strongest of all actuators are those operated by hydraulic fluids. These types of devices are generally found in the realm of heavy machinery and are probably not well matched to the design requirements of the pipette robot.

Rotary motion versus Linear Motion. The natural role of an electric motor is to provide rotary motion. Many different types and sizes of commercial off-the-shelf (COTS) motors are available from numerous vendors. Common types include stepper, servo, and synchronous motors. Linear electric motors are available but tend to be specialty devices.

Deriving linear motion from an electric motor requires the use of a screw-gear apparatus. A small number of electric motors capable of direct linear motion may be found, but these tend to be large specialty devices. Linear motion may be easily derived from compressed air or hydraulic fluid using simple, inexpensive piston devices.

Deriving rotary motion from compressed air requires an expensive and noisy air turbine. Simple air pistons, on the other hand, are compact, cheap, and easy to locate. Figure 2.33 illustrates some of these common types of motors and actuators. The various functions in the pipette robot may involve one, some, or all of these types of devices.

Design Choice: Relative or Absolute Position Sensing

Issue. Regardless of whether one-axis or two-axis motion is chosen, the location of the pipette must be controlled to a tolerance of about 0.5 mm (the approximate diameter of the tip orifice). Many robotic systems utilize a relative registration system in which all positions are determined by the distance traveled from a known home location (e.g., the x-y coordinate 0,0). Position increments are measured by devices such as the rotary encoders shown in Figure 2.34. Each of these devices produces an electronic pulse for each 2.5 degrees of shaft rotation. The designer can set the relationship between this angular increment and a distance increment by appropriate gear ratios.

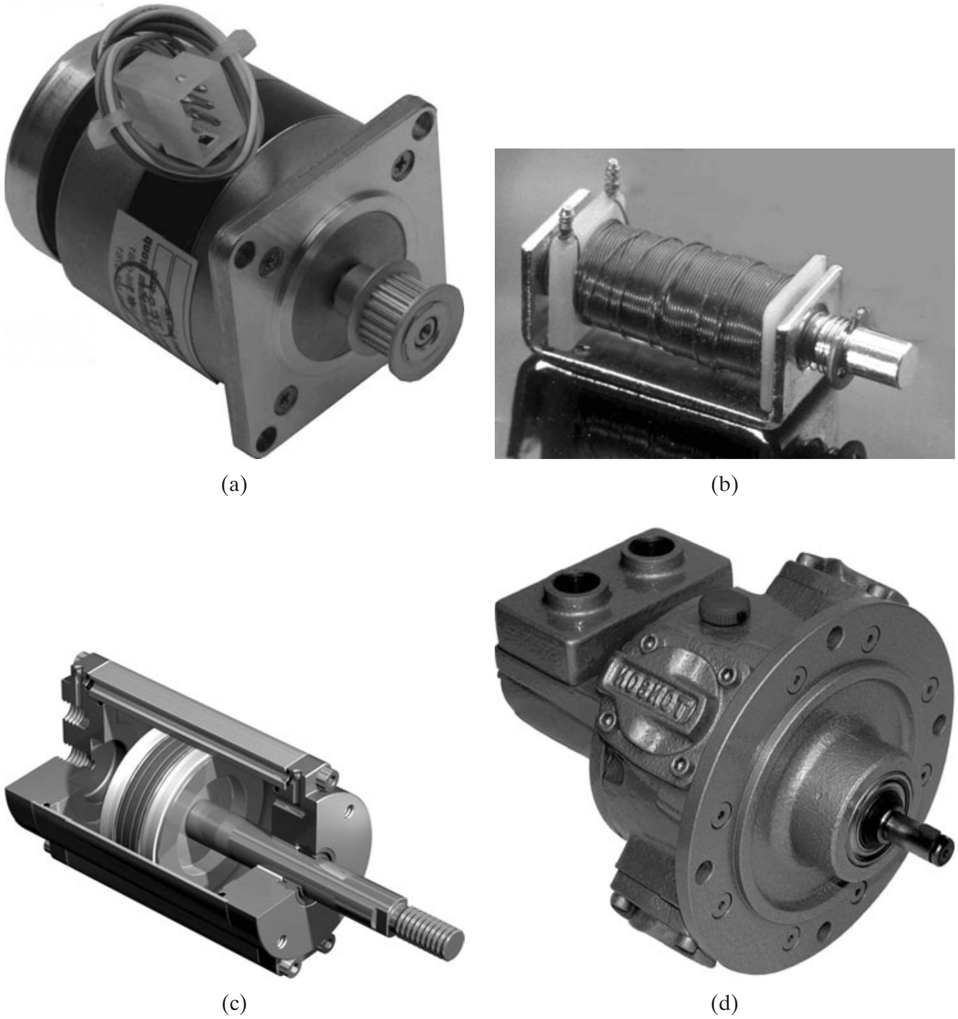


Figure 2.33
Various types of actuators: a) stepper motor with belt pulley; b) magnetic solenoid; c) pneumatic cylinder; d) air turbine motor.

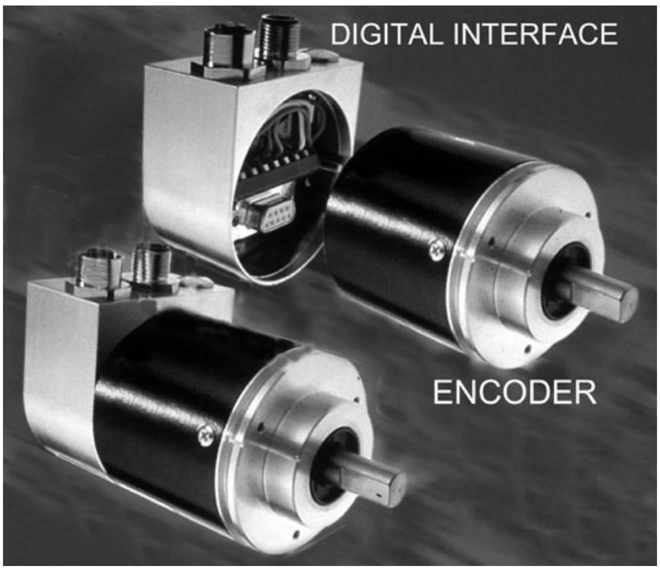


Figure 2.34
Examples of rotary shaft encoders.

Other robotic systems use absolute positioning systems in which a location is determined by the arrival of the moving member at a fixed sensor. With this method, a sensor is required at each location at which stopping is desired.

Position Sensing Comparison		
	Relative	**Absolute**
Cost	Only one shaft encoder required	Many position sensors required
Design Flexibility	Critical stopping positions are easily changed in software.	Changing stopping positions requires movable sensors, hence more mechanical complexity
Decoding	Entirely a software solution	Requires data acquisition hardware with an input for each sensor.
Reliability	One gear slip throws off position tracking.	Any slippage in system irrelevant. Position sensors are fixed.

Epilogue. The above problem actually emerged at a major research university. The design effort for the automatic pipette system took place over the span of approximately two years. It involved numerous iterations around the design loop. The first design, based on a single-channel pipette and all electrical actuation, had to be abandoned at a stage of near completion for two reasons. First, the *x-y* motion designed to move the pipette between cell and microplates resulted in a system that required four hours for each experimental run. This duration exceeded the viability time of the living cells in the microplate wells. Second, electric actuation of the pipette in the downward direction proved insufficient to reliably pick up tips between dispense operations. Ultimately, a multi-channel, one-axis design was employed. The final iteration of the design is shown in Figure 2.35. It uses a stepper motor with low pitch drive screw to move the pipette between well plates, a two-way pneumatic piston to move the pipette vertically, and a short-stroke air piston to push the tip-eject button. The electronic pipette is tethered to a laptop computer which controls all functions via a MATLAB program and digital interface board.

EXAMPLE 2.4

Sailboat Autopilot

Homer S. has decided to embark on a solo sailing voyage across the Atlantic. He plans to leave from his home town of Springfed, arriving in Brest, France sometime thereafter. For this purpose, he has built his own wooden sailboat complete with watertight sleeping quarters. As he prepares for the trip, he realizes that it will definitely take longer than one day, hence he needs some arrangement by which he can sleep while the boat is underway. It would not be proper to simply let the boat drift while he sleeps.

Not being very mechanically inclined, he has asked you, his engineering pal, to convene a team to design an autopilot for the boat. You graciously accept, hoping that the story will someday be featured in a television episode or major animated movie chronicling Homer's journey. Let's once again analyze the problem in the context of the design cycle of Figure 2.7.

Several commercial solutions to this problem exist, so the analysis to follow simply highlights some of the choices that one might make in addressing Homer's navigational needs.

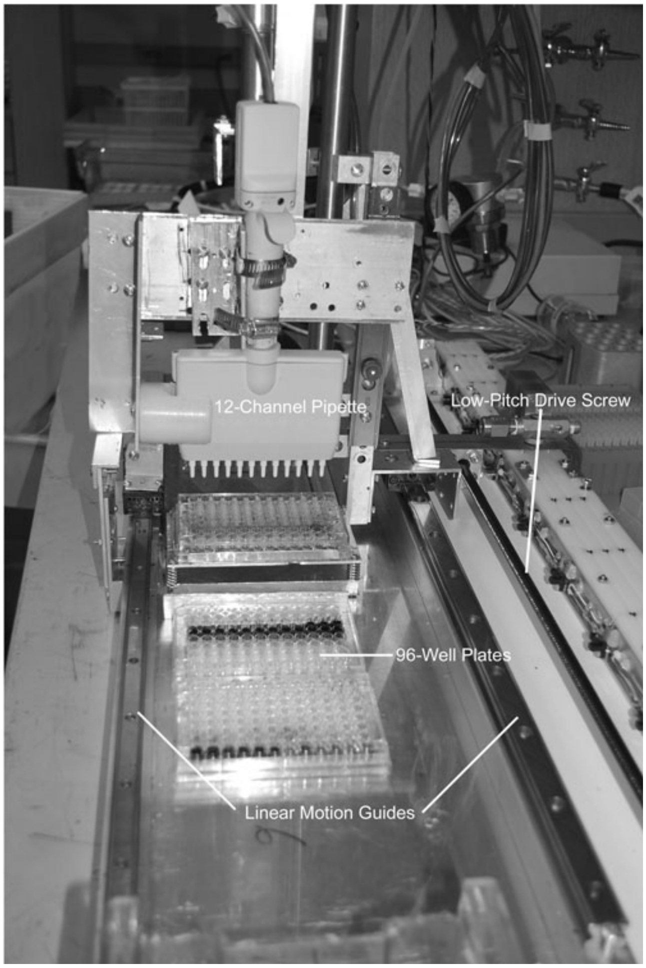


Figure 2.35
Final iteration of the pipette robot design.

Gather Information

You quickly confirm the obvious: a sailboat is propelled by the force of the wind on its sails. When a sail is properly set, its cross section resembles that of an airplane wing pointing up toward the sky. The "lift" in this case is applied horizontally. A small component of the lift extends toward the front of the boat and moves the boat forward. The remaining lift force is balanced by the hydrodynamic and gravitational forces of the boat's keel. The complete balance of forces acting on a moving sailboat is complicated, but it works quite well. A vector diagram illustrating the various forces on a sailboat is shown in Figure 2.36.

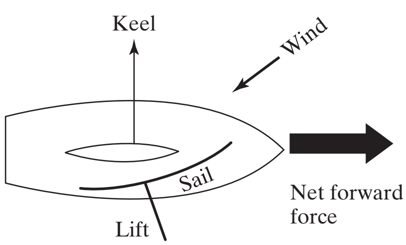


Figure 2.36
Vector forces acting on a sailboat. The net force is in the forward direction.

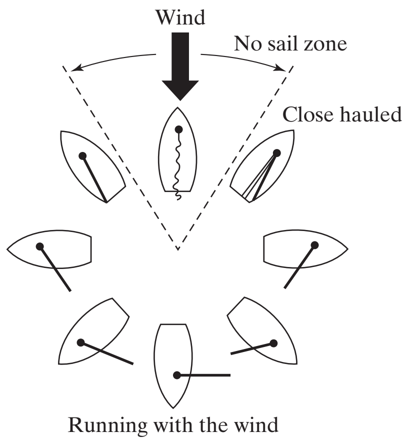


Figure 2.37
The points of sail. Inside the "no sail" zone, the sail cannot fill with wind.

You also learn that a sailboat cannot travel directly into the wind. Rather, its forward motion is confined to the region outside an arc of approximately 90° centered about the wind direction, as shown in Figure 2.37. If one tries to steer a sailboat inside this arc, the sail cannot fill with wind, the delicate balance of forces is disturbed, and the boat ceases to progress. The 90° arc is sometimes called the "no-sail" zone. When a sailboat is directed as close as possible to the wind direction, its sailing position is called "close hauled." A boat traveling in the same direction as the wind is called "running free" or "running with the wind." It seems counterintuitive, but a sailboat on a close-hauled course moves faster than one running free.

The direction of a sailboat is determined by its rudder which extends into the water at the rear of the boat. Turning the rudder to the right or left causes the rear of the boat to swing in the same direction, in turn altering the direction of travel. The rudder is controlled by either a long steering pole called the "tiller," or, if the boat is large, by a mechanically linked steering wheel similar to that found in a car. Homer has chosen the much simpler tiller method of steering for his boat.

Choose a Design Strategy

There are three possibilities for keeping the sailboat on course. One would be to measure the prevailing wind direction, then maintain the angle between it and the desired course direction. A simple wind vane is ideal for this purpose. As long as the chosen direction does not extend into the no-sail zone, the boat will move forward. This method has the advantage that the steering system will always choose a direction in which the boat can actually move. Its principal disadvantage is that the wind direction may change as the boat travels along. If the boat's travel direction is oriented to the wind direction, it will veer off course when the wind changes.

Another possibility is to orient the boat relative to the Earth's magnetic north. A compass must be employed for this purpose. The main advantage of this method is that the boat will always be pointed in the desired course direction. It is possible, however, for the autopilot to point the boat into the no-sail zone, in which case it will not move at all.

Most sailboat compasses are simple in design, consisting of a magnetized disk floating on a pin joint. The disk is marked with the points of the compass (e.g., North, South, East, West). If the compass orientation method for the autopilot is chosen, however, then a more expensive electronic compass will be the obvious choice. Interfacing with the delicate floating magnet of a conventional compass is a very difficult task and not one easily accomplished. Electric power on a sailboat is usually derived from solar cells, or sometimes from a small windmill mounted on the rear of the boat. In either case, the availability of electric power can be unpredictable and assured only if the helmsman is diligent about harvesting the energy from sunlight or wind.

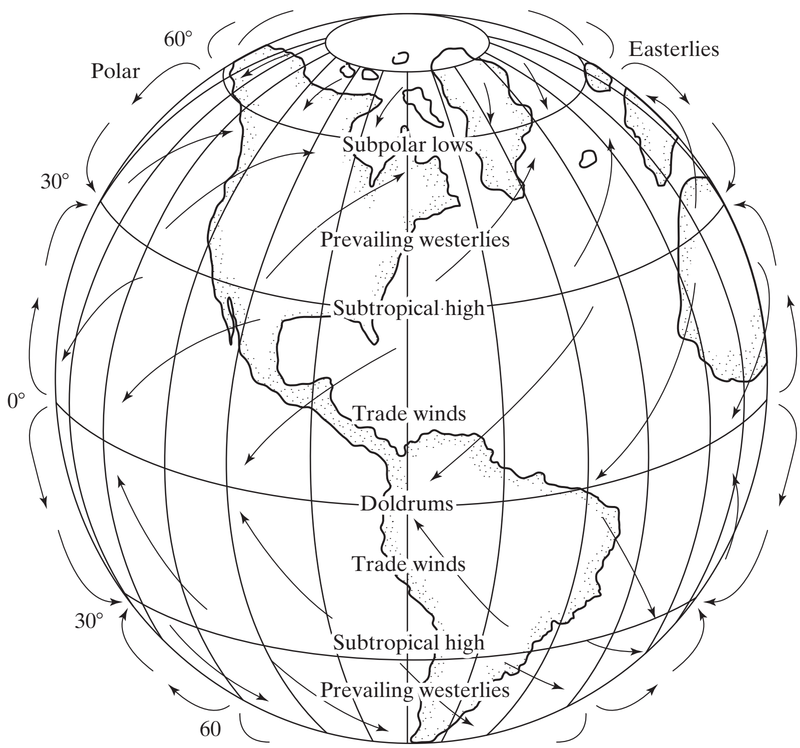
A third possibility is to use the global positioning system (GPS) to determine the boats course. This approach has the same advantages and disadvantages as the compass method, except that it would be possible to keep a record of the boat's actual course while on autopilot.

Gather More Information

At this point, you realize that it's impossible to choose between the wind and compass methods of orientation without knowing more about the nature of the wind along Homer's projected path. It is likely to depend on his ports of embarkation and arrival, and possibly the season in which the trip is planned. (Given that Springfed lies somewhere in Indiana, you highly recommend to Homer that he choose a more convenient embarkation point; you suggest Montauk Point, an isolated peninsula at the tip of Long Island, NY. Leaving from this state park location will allow access to whatever curious spectators may wish to endure the long car ride to see him off.)

Your research leads you to the National Ocean Data Center maintained by the US National Oceanic and Atmospheric Administration (NOAA). Your data compilation, summarized by the global map of Figure 2.38, reveals the that in the months of October through December, the prevailing winds from Montauk to Brest

Figure 2.38
Global wind vector map.



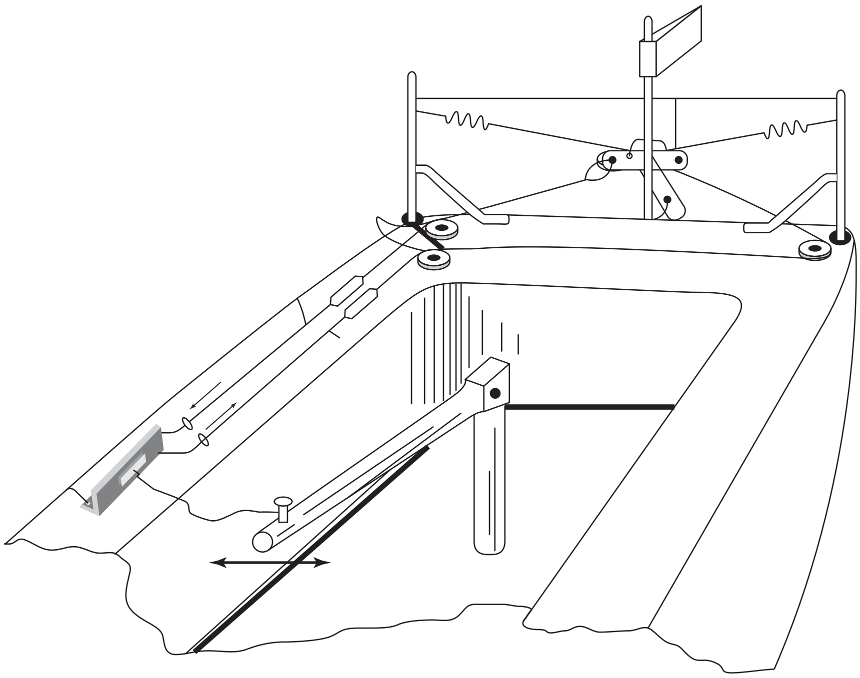


Figure 2.39
Possible solution to Homer's autopilot requirement.[3]

should be westerly and steady. Thus Homer's boat will not likely have to deal with the no-sail zone inherent to sailing close-hauled.

Make a First Cut at the Design

From the additional information you have gathered, you decide that an orientation system tied to wind direction is probably the best choice. This decision is based, in part, on human factors. Homer is insistent on making the trip in the colder fall months, when sunlight will be less prevalent. You also realize that he may forget to charge his boat batteries when sunlight is available. Additionally, if the boat is going to be traveling in the same direction as the prevalent west-to-east wind, then the apparent wind it will feel (the difference between the actual wind and the boat's velocity) may be small. You realize that if a system based on wind direction is chosen, then a fully mechanical steering system could be built, thus eliminating entirely the need for electricity. This feature would not be true of a compass oriented system, which would require constant electric power.

Based on the above considerations, you sketch the system shown in Figure. 2.39[3]. A wind vane sitting atop a pole mounted on the back of the boat moves cables through pulleys to make slight course correction adjustments to the tiller, thus keeping the boat moving at a selected angle relative to the wind.

Build, Document, Test, Revise

Testing must take place once Homer has towed his boat from Springfed to Montauk. He must first figure out how to get the boat through the much smaller garage door.

[3]Figure derived from U.S. Patent No. 4,366,767.

SUMMARY

In this chapter, the essential elements of the design process have been outlined at a very basic level. As an engineering endeavor, design differs from analysis and replication because it involves multiple paths to solution, plus decision making, evaluation, revision, testing, and retesting. The *design cycle* is an important part of engineering problem solving, as are knowledge, experience, and intuition. *Documentation* is critical to the success of a product and should be an integral part of the design cycle.

KEY TERMS

Analysis	Evaluation	Simulation
Decision making	Iteration	Testing
Design	Replication	Brainstorming
Design cycle	Revision	Idea Generation

Professional Success: How to Tell a Good Engineer from a Bad Engineer

If you pursue engineering as a career, you will encounter many colleagues along the way. Some will be good engineers, and others will be bad engineers. In your quest to identify and emulate only good engineers, you should learn the differences between the two. The following list highlights the traits of both types of engineers:

A Good Engineer	A Bad Engineer
• Listens to new ideas with an open mind. • Considers a variety of solution methodologies before choosing a design approach. • Does not consider a project complete at the first sign of success, but insists on testing and retesting. • Is never content to arrive at a set of design parameters solely by trial and error. • Uses phrases such as "I need to understand why" and "Let's consider several possibilities."	• Seldom listens to the ideas of others. • Has tunnel vision and only pursues the first design approach that comes to mind. • Ships the product without thorough testing. • Uses phrases such as "Good enough" and "I don't understand why it won't work. So-and-so did it this way." • Equates pure trial and error with engineering design.

PROBLEMS

The following problem statements can be used to practice problem-solving skills and idea generation. Some of them involve paper designs, while others are suitable for actual fabrication and testing.

2.1 Develop a design concept for a mechanical device that will allow hands-free operation of a standard wired telephone. Outline its basic form, key features, proposed method of construction, and prototyping plan. Consider size, weight, shape, safety factors, and ease of use.

2.2 Develop a concept for a device that will allow hands-free use of a cellular telephone without the addition of accessories such as an earphone, or microphone, or Blue-Tooth® headset. Your design should be based solely on a mechanical solution.

2.3 Design a device for recording design ideas that enter your mind while you are riding your bicycle. Your contraption should enable the rider to record notes while holding onto the handlebars with both hands.

2.4 Design a device for securing a cell phone near the driver's seat of an automobile. It should be universally adaptable to a wide variety of vehicles. Address safety and liability issues as part of your design.

2.5 Develop at least three design concepts for a non-lethal mousetrap. Your device should be cost-competitive with an ordinary, spring-bale mousetrap.

2.6 Devise a concept for a powered device that can dig holes in the ground for the installation of fence posts. Sketch a prototype and outline a test plan for your design concept.

2.7 Design a device that will allow the inside and outside surfaces of windows to be cleaned from the inside only. Compare the projected cost with that of a simple, handheld, squeegee-type window cleaner.

2.8 Design a system for feeding a pet lizard automatically when the owner is out of town.

2.9 Develop a design concept for a spill-proof table candle. Such an item is required by some fire departments for use at banquets, etc. If knocked over, it should right itself without spilling any wax or extinguishing its flame.

2.10 Develop a design concept for a warning system that monitors the inside temperature of a food storage freezer.

2.11 Design a device for conveying bricks to the top of a house for chimney repair. (The alternative is to carry them up a ladder by hand.)

2.12 Design at least three different methods for measuring the height of a tall building.

2.13 Design a system that will enable a self-propelled, unattended lawn mower to cut the grass in a yard.

2.14 Design a system for minimizing the number of red lights encountered by cars traveling east and west through a major city. The system should not unduly impede north–south traffic flow.

2.15 Devise a method for managing the flow of two-way railroad traffic on a one-track system. The track may have parallel spur tracks at regular intervals. These parallel sections of track allow one train to wait as another passes in the opposite direction. Note, however, that each parallel section adds cost to the system.

2.16 Develop a concept for a public transportation system in which every traveler can ride a private vehicle on demand from any one station to any other.

2.17 Design a transportation system based on situating free-use bicycles at strategic points around a large city.

2.18 Design a transportation system based on keeping fee-for-use, electric automobiles at strategic points around a large city. Your system must include a means for recharging the vehicles

2.19 Most large airports provide carts for travelers to transport luggage from baggage claim areas to taxi stands, transit stations, and parking lots. Develop a system for locating and reclaiming carts from various places around the airport for return to the baggage claim area.

2.20 Develop a design concept for a system to measure the number of people passing by a storefront. Separate your data into those who enter and those who do not.

2.21 Design a system that will assist flight attendants in feeding passengers on a wide-body aircraft without blocking the aisles with food and beverage carts.

2.22 Design a system for automatically turning off a small electric baking oven when a cake is done. The system must include a means for assessing the status of the cake.

2.23 Design a system that will help a person locate misplaced eyeglasses.

2.24 Develop a concept that will assist individuals in finding keys that have been misplaced around the house.

2.25 Design an electric light switch that will turn off lights if the room is vacated, but not sooner than some user-specified time interval.

2.26 Design a device that will enable a quadriplegic to change the channels on a television set.

2.27 Devise a system for turning on security lights at dusk and turning them off at dawn. These lights are to be installed throughout a large factory. Your system should have a single master override for all lights.

2.28 Design a system for turning off a stove-top burner when a pot of water has boiled. Such a system would be valuable for cooking rice or preparing hard-boiled eggs.

2.29 Design a method or concept for dispensing transparent adhesive tape in small precut lengths.

2.30 Design a system that will automatically water houseplants when they are in need of moisture.

2.31 Design a system that will selectively water sections of a garden based on the moisture content of the soil at the location of each plant.

2.32 Design an irrigation system that will bring water from a nearby pond to your vegetable garden.

2.33 Develop a design concept for a system that will automatically pick apples from the trees of a commercial apple orchard.

2.34 Design a system that can aerate the pond in a city park so that algae growth will not overtake other forms of wildlife.

2.35 Design a device that will allow a one-armed individual to properly use dental floss.

2.36 Design a system that will prevent the user of a battery charger from inserting the batteries the wrong way. The unit charges four AAA batteries simultaneously, but each battery must be inserted with its positive (+) end in the correct direction.

2.37 Design a method for counting the number of people who attend a football game. The stadium has a maximum capacity of 40,000 fans and eight entry gates.

2.38 A big problem in nursing homes for the elderly is the misplacement of false teeth. Some dentures are inevitably discarded with dining room debris. Devise a system that will enable kitchen staff to detect dentures that appear in the waste stream.

2.39 Design a system for automatically steering a hot-air balloon along a desired compass heading.

2.40 Design a weatherproof mail slot for a house that will keep cold air out but permit the insertion of mail from outside.

2.41 Most small sailboats have a tiller (steering stick) in lieu of a steering wheel. Design a system for automatically steering a tiller-controlled sailboat on a course that lies along a user-specified compass direction. Design for a simple boat that has no onboard electricity.

2.42 Specify the components of a system that will allow a group of six to listen to music from a single MP3 player or iPod. All listeners will use headphones.

2.43 *Challenge Problem*. One of the problems with recycling post-consumer waste is the sorting of materials, for example, the various plastics and metal containers placed into curbside recycling bins. Consumers and homeowners do not always sort correctly, yet only a small amount of erroneously sorted material can ruin a large batch of recycled material when it is melted to raw material. At the present time, most municipalities resort to manual labor to sort recyclable materials. Devise a concept that will sort metal cans, plastic bottles, and plastic containers at a recycling plant. Develop a plan for modeling and testing your system.

2.44 Design a kitchen device that will crush aluminum and steel cans in preparation for recycling. Such a device would be helpful for households that practice recycling but have limited storage space.

2.45 Devise a system for painting car bodies automatically by robot. You must include a method for training the robot for each painting task.

2.46 Devise a plan for a campus-wide information system that allows any professor to access the grades of any student, while maintaining the privacy of the system to other users. Students also should be able to obtain their own grades, but not those of others.

2.47 Design an automatic pencil sharpener that will turn itself off when the pencil has been sharpened to a desired tip sharpness.

2.48 Develop a design concept for a device that will automatically close a skylight window when rain falls. The window should be closed partway when rainfall is light but should be closed completely when rainfall is moderate to heavy.

2.49 Design an apparatus that will keep a telescope pointed at a distant star despite the rotation of the earth.

2.50 Design a system for keeping solar panels pointed directly toward the sun.

2.51 Devise a system for transferring personnel in flight from one airplane to another.

2.52 Devise a system for automatically collecting tolls from cars traversing a major interstate highway. Note that many such systems exist throughout the United States. (See, for example, *www.mtafastlane.com* or *www.ezpass.com.*) This problem asks you to imagine (or find out) the details of how these systems work.

2.53 *Challenge Problem*. Laser communication, or "laser-com," is a system by which digital data is sent from one location to another via a modulated laser beam. Laser-com systems are used whenever connections via wires or fiber-optic cables are too expensive, not possible, or not desirable. One of the principal drawbacks of laser-com systems is the difficulty in maintaining beam alignment when the sender and receiver are moving. Design a system that will automatically direct the communication beam sent by one vehicle toward another receiving vehicle.

2.54 *Challenge Problem*. Design a concept for a two-way communication system that works via a modulated laser beam. In this system, only a fixed ground station will emit a beam. The other participant in the link will be a moving person who will receive the beam and reflect a modified version back to the base station.

2.55 *Challenge Problem*. Design a system consisting of several emergency buttons that will be installed at each of several workshop fabrication stations on a factory floor. Pressing any one of these buttons will activate a signal at a central control console and identify the location of the activated button. Voice communication over the system would also be a desirable feature. One matter to consider is whether a wired or a wireless system is preferable.

2.56 *Challenge Problem*. An elementary school teacher needs a calendar-teaching system to help young students learn about dates, appointments, and scheduling events. The basic system should be a large pad over which a monthly calendar can be placed. The underlying pad should have touch-sensitive sensors that can detect a finger placed on each day block in the calendar. The entire unit should interface with a computer which will run a question-and-answer game or program. Typical questions might include "You have a dentist appointment two weeks from today. Point to the day on the calendar on which you should go to the dentist," or "Sara's birthday is on February 11. Point to that day on the calendar." An appropriate acknowledgement, either visual, auditory, or both, should be issued by the computer for correct answers. A non-intimidating signal should be issued for incorrect answers. Outline the key features of your system and devise a development plan.

2.57 *Challenge Problem*. The rules of a particular design competition require an autonomous vehicle to be placed behind a starting line located 30 cm up the side of a 1.5-m inclined ramp. After the starting signal has been given, contestants may release their vehicles. Any vehicle that travels over the starting line prior to the "go" signal loses the race. Currently, the starting sequence is initiated orally by a judge and timed by stopwatch. This system leads to great variability among judges, as many use different starting signals (e.g., "on your mark, get set, go!" or "one, two, three, go!"), and any one judge may be lax in timing or checking for starting-line violations.

Design a system consisting of starting-line sensors, a start signal, and starting-line violation signals for each side of a double ramp. The judge should have a button that initiates the start sequence. A series of periodic beeps that mimic the rhythm of the words, "Ready, set, go!" should sound, with the final "go" being a loud and clearly distinguishable tone or buzzer. In addition, a green light or LED should illuminate when the "go" signal is sounded. The system should run for 15 seconds, then sound another tone or buzzer to indicate the end of the 15-second time interval signifying the end of the contest. If a vehicle crosses the starting line prior to the "go" signal, a red light should appear on the violating vehicle's side of the ramp, and a special "violation" signal should be sounded to alert the judge.

2.58 *Challenge Problem*. Teams in a model airplane design competition are called to the central runway when it is their turn to compete. After the initial call, each team has 3 minutes to arrive at its starting line. A team that does not arrive at the starting line after 3 minutes loses that run. Warnings are given 2 minutes and 1 minute before the deadline. Traditionally, the announcer has issued these warnings orally over a public address amplification system. There are several problems with this method, however. Acoustics are poor, three races run simultaneously, with different starting times, and only some teams require the full 3 minutes to arrive. Thus, the proper issuing of these cues has been lax. The judges need you to design an automated system that will inform a given team how much of its 3-minute sequence has elapsed. The system must send an appropriate signal (oral, auditory, or visual) only to the relevant team, and the timing sequence must be initiated from the judges' bench. As many as 80 teams may compete on a given day, and each is assigned one work table from a large array of 3×8-foot tables on the competition field. All too often, the team being called is delayed, because it is repairing or modifying its vehicle. One of the key design issues is whether a wireless or wired system is better, given the logistical constraints of the competition environment. Because the event operates on a strict budget, final cost also is an important factor.

2.59 The vehicles entering a student design competition must utilize batteries with a voltage no higher than a specified limit. Each vehicle is checked once with a voltmeter at the start of the day by the head judge. Having a standardized voltage-checking device would shorten the time for voltage checking. Design a unit that has a rotary (or other type of) switch that can select a predetermined battery voltage. If the measured battery falls within the acceptable range, a green light should appear. If the voltage falls below or above the range, yellow or red lights, respectively, should appear.

2.60 Outline the design of a general purpose software system for a track meet. Your system should enable judges to automatically pair up runners for matches, randomly at first, but by demonstrated ability thereafter (best runners against best runners, worst runners against worst runners). The program should display match sets before each round of the competition, and allow the recording judge to enter the result of each match after its winner has been determined. Assume a competition of up to 140 runners and six sets of matches between contenders.

2.61 Design a system for projecting matches on a display board so that audiences watching a tennis tournament can keep track of who is matched against whom, and monitor the results of each match. Assume a competition of 20 players with six sets of matches between contenders.

2.62 Design a system for detecting start-line violations for a horse race.

2.63 Design a system for determining the winner of each match in a swimming race.

2.64 Design a software system that will assist in registration for a fund-raising walk. Registration information includes the name, address, and age of the participants. Registrants must pay a small fee, sign photograph permission and liability waiver forms, and receive an event T-shirt and assigned walker number. Several volunteers will work simultaneously at the event to register participants as quickly as possible so that the event can begin on time, but a common stored database is needed.

2.65 Design a can opener that performs two tasks: a) it must not allow metal slivers to fall into the can, and b) it must catch and hold the cut lid for subsequent hands-free disposal.

2.66 Design a system for measuring and reporting accumulated snowfall at a remote monitoring station.

2.67 Design an ice tray that allows the user to easily extract a single cube at a time.

2.68 Design a system that can help a one-armed person tie a necktie.

2.69 Design a snow shovel for a one-armed individual.

2.70 Develop a design concept for trimming tall trees using a remote-controlled robot.

2.71 Design a method for automatically walking a dog in a safe and reliable manner. The system should require no human intervention other than setup.

2.72 Develop a concept for a scuba diving mask that is self-clearing. "Clearing" refers to the act of expelling water from inside the mask without surfacing.

2.73 Develop a system that can be worn by a downhill ski racer and can send the skier's traveling speed to an observing coach.

2.74 One of the problems with may small, recreational boats is that they fill up with rainwater which must be pumped out by the owner after a storm. Design a system that will automatically pump out such a watercraft. Your system may use an onboard storage battery, but it must then include a means for charging the battery during period of sunlight.

2.75 Design a set of wireless, waterproof headphones that can be used by a recreational swimmer. The source of music can be attached to the swimmer, or it can placed in a location out of the water.

2.76 If a common household toilet fails to fill its tank after flushing and is left "running," it can waste a considerable amount of water. Design an inexpensive device that can alert a homeowner to such a problem.

2.77 Design a system that will allow a blind man to properly trim sideburns with an electric shaver.

2.78 Design a method for alerting a driver of the fraying and imminent breakage of an automobile's timing belt.

2.79 Design an automated potato harvest system.

2.80 Devise a method for applying pesticides on crops that does not involve aerial spraying. Your goal should be to minimize the amount of chemicals dispersed into the environment, putting only what is needed on the plants. In the ideal case, the pesticide should be applied to the underside of the plant leaves, where most parasites reside.

2.81 Many supermarkets now offer online ordering and delivery. Often the orders are gathered by hand and put into delivery bins. Design a system, either semi- or fully automated, for filling online food shopping orders. The output should be a set of bins ready for delivery.

2.82 Devise an automatic dog walking system based on GPS navigational devices.

2.83 Devise a method for closing ornamental shade awnings when the wind becomes so high that it might damage the awnings.

2.84 Devise a method for lowing ornamental shade awnings when the sun comes out, and raising them with the sun is not present (e.g., behind clouds).

2.85 Devise an advanced, water-saving drip irrigation system that senses the moisture content of the soil near each patch of plants.

2.86 Devise a system for tracking and reporting at all times the location of spent nuclear fuel rods being transported for long-term storage.

2.87 The earliest "self-winding" watches used the motion of the wearer to wind the mechanical spring of the timepiece. Develop a similar concept to be used as a backup source of power for portable electronic devices such as cell phones and MP3 players.

2.88 Design a way to charge your iPod from the pedal power of your bicycle.

2.89 Design a system for alerting park maintenance personnel when remotely located trash cans are full and in need of emptying.

2.90 Design a system for alerting custodial workers when a given restroom needs soap and/or paper towels.

2.91 Design a system for automatically turning on an automobile's windshield washer when the windshield is dirty.

2.92 Design a system for automatically turning on an automobile's windshield washer when it begins to rain.

2.93 Design a "just in time" system for distributing home heating oil via delivery truck. Current systems used by oil delivery companies rely on statistics of "heating degree days" and histories of customer consumption. It would be preferable to have a sensor in each home's oil tank that can communicate with the central office.

2.94 Design a system to improve car mileage by measuring the vehicle's tire pressure, then automatically inflating or deflating the tires as needed. Note that recommended tire pressure depends on both tire size and the loaded weight of the vehicle.

2.95 *Challenge Problem*. A teacher wants a clock system that can help young students learn the relationship between time displayed by digital clocks and time displayed by analog clocks. The system should have a console that contains a large analog clock face, as well as a digital clock display with large digits. In operation, the teacher will set either clock, then ask the student to set the other clock to the same time. If the student sets the time correctly, the unit should signal the student appropriately. If the student fails to set the time correctly, the unit should also issue an appropriate response. Outline the salient mechanical and electrical features of such a system.

2.96 *Challenge Problem*. Develop a design concept for a computer-interfaced electronic display board that can be placed in the lobby of an office building to display messages of the day, announce upcoming seminars, or indicate the location of special events. The objective of the problem is to use a matrix of addressable light-emitting diodes (LEDs) rather than a video display. The system should accept messages by wire from a remote site. One approach might be to design your display board system so that it is capable of independently connecting to a local-area computer network. Alternatively, you could build a separate remote device that could be connected to a desktop computer and then brought down to the display board to load in the data. A wireless solution might also be possible. These examples are suggestions only. In general, any means for getting data to the board is acceptable, but a separate computer (PC) cannot become a dedicated part of the finished display.

2.97 *Challenge Problem*. Design a handheld medicine dispenser for dispensing pills at specific times of the day. The unit is to be carried by an individual and must have sufficient capacity to hold medication for at least 1 day. The unit should open a compartment and should emit an audible or visual signal when it dispenses medication. The unit must be easy to load and should be easy to program.

2.98 *Challenge Problem*. One perennial problem with radio-controlled model airplanes concerns the lack of knowledge about the flight direction and orientation of the airplane when it is far from the ground-based operator. When the airplane is too far away to be seen clearly, the operator loses the ability to correctly control its motion. Develop a design concept for a roll, pitch-, and compass-heading indicator system that can be mounted on the model airplane and used to radio the information to the operator's control console. Your system should sense the pitch and roll of the airplane over the range $+90$ degrees to -90 degrees and be able to withstand a full 360-degree roll or "loop-de-loop."

2.99 *Challenge Problem*. Design a remote readout system for a vacation home to be interrogated by a remote computer over a modem and telephone line or cellular telephone. The unit in the vacation home should answer the phone after 10 rings, provide means for an entry password, and then provide the following information: inside and outside temperatures, presence of any running water in the house, presence of any loud noises or unusual motion, and status of alarm switches installed on doors and windows. Discuss the design specifications for such a unit and develop a block diagram for its design and implementation.

2.100 *Challenge Problem*. Design a system for identifying which circuit breaker is associated with a given electrical outlet. The best system will be one that does not require the operator to move back and forth between the basement, where circuit breakers are typically found, and the locations of the outlets on the upper floors of the building.

2.101 *Challenge Problem*. Design a system for personalized airport baggage handling. Luggage is to be directed to each waiting individual, or at least to small clusters of people waiting at specified stations.

2.102 *Challenge Problem*. The future may bring a host of hydrogen-powered vehicles that run on either direct combustion or fuel cells. If such vehicles are to come into widespread use, a practical system must be put into place to distribute the fuel. Given that hydrogen, the lightest of the elements, is also extremely volatile and is the gas most prone to accidental ignition, this task is not an easy one. Design a system for nationwide distribution of hydrogen that will gradually replace the country's current network of gasoline stations. Consider cost, convenience, and safety factors in your deliberations. Design from the top down, beginning with the production of the fuel itself, and ending with proposed equipage for the refueling stations.

2.103 *Challenge Problem*. Modern technology has vastly extended the sensory capability of humans to the point where machines can talk, listen, touch, and see. Devise a system which might heretofore have been unthinkable: a means for a blind person to drive an automobile.

2.104 *Challenge Problem*. Design a system for harvesting the energy contained in ocean waves. Note that many such solutions have been proposed (see, for example, ocsenergy.anl.gov). Most of these systems, however, are oriented toward large-scale production tied to the national power grid. Your system is to be used by the owner of a small vacation home on an island near Puget sound in Washington state. The island is not connected to any external source of electric power.

2.105 *Challenge Problem*. Space debris has become a problem of note as we probe the orbital space of our planet. (See, for example, *www.orbitaldebris.jsc.nasa.gov*). Devise a system for an orbital spacecraft that can alert astronauts to an impending collision with a rogue object, and also devise a means to prevent the collision without altering the course of the spacecraft.

CHAPTER 3

Project Management and Teamwork Skills

Objectives

In this chapter, you will learn about:

- The importance of project management in ensuring design success
- Teamwork as an essential element of engineering design
- How engineers determine the tasks that will lead to a finished product
- Scheduling and managing design tasks
- The role of the project manager
- How members of a design team interact
- Documentation and its vital role in the design process
- Legal issues and their relevance to the design engineer

This chapter is devoted to the subject of project management. As a student of engineering, you may ask, "Why is this chapter necessary? Why is the topic important?" The answer lies in the nature of design problems. Design problems are inherently open ended; the more complex the task, the greater the need for a management infrastructure to ensure that elements of the project ultimately fit together. Accomplishing this goal requires that all teams and team members work together within a common strategy. Sometimes, managing a project requires only the most basic application of common sense: get things done on time, hold regular meetings to discuss progress, write things down so you don't forget them. At other times, a more formal structure is required; this formal structure often relies on time-tested methods of project management. A good engineer must know how to work within the framework of a team, keep a project on track, maintain good documentation, address legal issues, and work within a well-defined management plan. This chapter introduces several project management skills that are essential elements of engineering design.

3.1 WORKING IN TEAMS

The spirit of rugged individualism is pervasive in society, persisting as a theme in books, movies, and television. The image of a lone hero striving for truth and justice against insurmountable odds appeals to our sense of adventure and daring. Our pioneering spirit dreams of becoming the sole entrepreneur who endures economic hardship to change the face of technology, or perhaps the head of a startup company that single-handedly bests Microsoft or Intel. Yet, in real life, engineers seldom work alone. Most engineering problems are interdisciplinary, and true progress requires cooperative teamwork and the contributions of many individuals. This concept is easy to understand in the context of designing large structures, such as bridges, airports, skyscrapers, or oil refineries. It would be unimaginable to even approach such large tasks without a well-defined hierarchy of managers, job directors, engineers, and craftspeople. Similarly, the great engineering accomplishments in space exploration such as the Apollo moon landing, the International Space Station, the Hubble Space Telescope, and the Mars Exploration Rover required hundreds (in some cases thousands) of engineers working with teams of physicists, chemists, astronomers, material scientists, medical specialists, mathematicians, and project managers. Teamwork is also critical to the design of small but complicated devices such as medical prostheses, copy machines, children's mechanical toys, kitchen appliances, and cellular telephones. These devices (not an exhaustive list) cannot be designed by one person alone.

Teamwork is an important skill, and you must master it if you are to be a good engineer. Working in a team, such as the one depicted in Figure 3.1, requires that you speak clearly, write effectively, and have the ability to assimilate another person's point of view. All members of a team must understand how their tasks relate to the responsibilities of the team as a whole.

When addressing a design problem, dealing with the technical issues is only half the story. Determining how people and their time will be managed is just as important. By properly assigning tasks to the right people and ensuring that they work together cooperatively, the success of the project can be ensured. In the sections that follow, we address some of the major issues related to people management.

3.1.1 Building an Effective Team

An effective team is one that works well together. It functions at its maximum potential and thrives on a symbiosis of the special capabilities of its individual members. One key characteristic of an effective team is a good supportive attitude

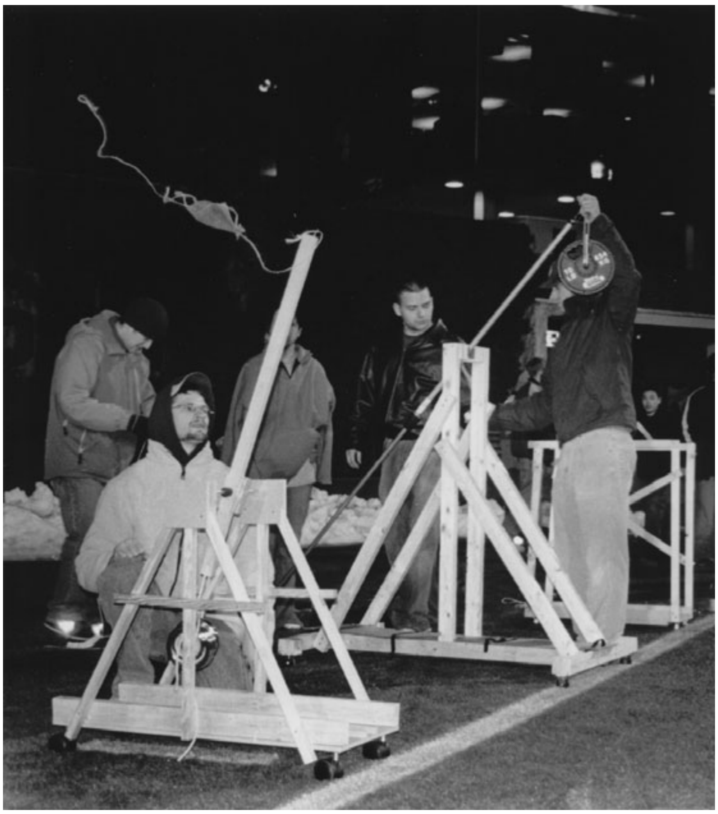


Figure 3.1
Design team works on the prototype of a Trebuchet catapult. (Photo courtesy of the Daily Free Press.)

among fellow teammates. Team morale and a sense of professionalism can be enhanced if team members agree on some basic rules of behavior. The following set of guidelines illustrates one possible approach to building an effective design team.

1. *Agree Upon Goals.* The members of your team should agree upon the goals of the project. This consensus is not as easily achieved as you might think. One teammate may want to solve the problem using a traditional, time-tested approach, while another may want to attempt a far-out, esoteric path to success. Define a realistic set of goals at the outset. If the approach you choose brings surprises, you can always redefine your goals midway through the project.
2. *Define Clear Roles*. Each team member should be assigned a specific function within the team. The responsibilities of each individual should be defined *before* project work begins. Individual roles need not be mutually exclusive, but they should be defined so that all aspects of the design problem fall within the jurisdiction of at least one person. In that way, no task will "fall between the cracks" during the design effort.
3. *Define Procedures*. You and your teammates should agree on a set of procedures for getting things done. Everything should follow a predetermined procedure, including documentation; the ordering of parts; prototype construction; and communicating with professors, clients, and customers. In that way, misunderstandings about conduct can be greatly reduced.
4. *Develop Good Interpersonal Relationships*. You must learn to work with everyone on your team, even with those individuals whom you may personally dislike. In the real world, a client will not care about any conflicts that occur behind the scenes. Engineering professionalism demands that you rise above personality clashes and concentrate on the job at hand. Be nice. Be professional. Forbid name calling, accusations, or assigning fault to team members.
5. *Define Leadership Roles*. Some teams work best when a single person emerges as the chosen leader. Others work better by consensus using distributed leadership or even no leadership at all. Regardless of your team's style, make sure that leadership hierarchy is clearly defined and agreed upon at the start of the project.

Professional Success: You're the Team Leader, One Teammate has Disappeared, and You're Doing All the Work

It's impossible to get along with all people all the time. When you work closely with other individuals, personal conflicts are inevitable. At times, these disagreements occur because one team member has failed to meet assigned responsibilities. At other times, the conflict arises from fundamental differences in personal outlook or priorities. However complicated your team relationships may become, remember that your customer does not care about them. Your customer is interested in receiving a well-designed product that reflects your best engineering abilities. It's up to you to resolve team conflicts internally. This resolution may mean that some team members will do more work than others, even if they will not be rewarded for their extra efforts. A good leader understands this trade-off and devises a plan to work around an errant teammate. Such situations may seem frustrating and unfair, but they happen in the real world all the time. Learning how to deal with them as a student is part of your engineering education.

Practice!

Define the roles, goals, and procedures that might apply to the following.

1. The design and construction of an eight-lane highway system under a major metropolitan city (*www.masspike.com/bigdig*).
2. A team of software engineers developing an auction website (*www.ebay.com*).
3. A team of electrical and mechanical engineers developing a radio-controlled robot (*www.usfirst.org*).
4. A team of biomedical engineers developing an artificial heart for mechanical implantation inside human subjects.
5. A software system for scheduling production in a "just in time" textile factory that fills customer orders as they arrive (*www.crohmiq.com*).
6. The design and construction of the Mars Exploration Rover (*origin.mars5.jpl.nasa.gov*).
7. An oil pipeline from Prudhoe Bay to Valdez, Alaska (*www.alyeska-pipe.com*).
8. A package tracking system for an air/ground shipping company (*www.fedex.com*).
9. A system for compiling, printing, and distributing a daily national newspaper (*www.usatoday.com*).
10. The design of a mineral extraction plant that produces copper, uranium, gold, and silver (*www.wmc.com*).
11. An oil refinery that must produce a variety of products, including gasoline, diesel, and home heating oil.
12. A machine to selectively apply pesticides to an agricultural area only where parasites have been detected by distributed sensors.
13. A system for monitoring the energy flow and power production in a multiplant electric power generation system.
14. A system for allowing an expert surgeon to conduct an operation via remote control from a distant location.
15. The design and construction of a portable air conditioning system for roadside tent camping.
16. The design of a command center for communicating with football players wearing individual earpieces.
17. The design of a food court in a shopping mall.
18. The design of a transportation system consisting of autonomous (driver-free) subway trains.
19. The development of an order a system for filling orders at a pizza restaurant.
20. The design of an agricultural management system for a large farm collective.

3.1.2 Organizational Chart

When engineers work on a team-oriented project, they often establish some hierarchy among individuals. It would be nice if an engineering team could always function as a simple group of colleagues, but inevitably some team members will be

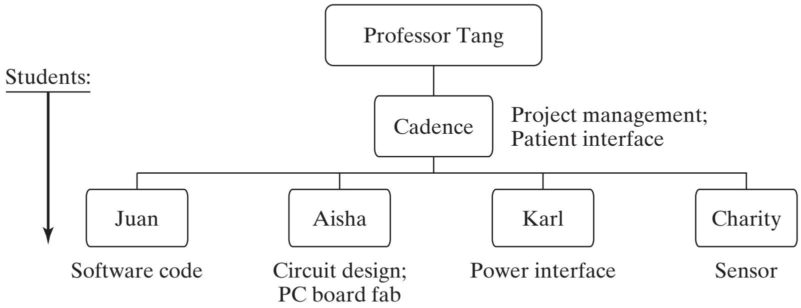


Figure 3.2
Team organizational chart for heart defibrillator project.

burdened more than others even if everyone's responsibilities are clearly spelled out. Likewise, it will be easy for some tasks to fall between the cracks if roles and responsibilities are not understood by all. One vehicle for specifying the management structure of a team is called the *organizational chart.* An organizational chart indicates who is responsible for each aspect of an engineering project. It also describes the hierarchy and reporting structure of the team. Figure 3.2 illustrates a simple organizational chart that might be used by students working on a design project for an engineering class. The objective of this particular project is to design a heart rate monitor for a professor doing research in cardiac defibrillation. Cadence acts as the team leader, and she, in turn, reports to the professor in charge for leadership and guidance. In the corporate world, where the structuring of workers and bosses can become complex, organizational charts are essential because each employee must understand the entire responsibility chain beginning with upper management.

3.1.3 The Job Description

When you work for an engineering company (or any company, for that matter), your responsibilities are spelled out in a document called your *job description*. A job description can be as informal as a simple letter of employment, or it can be a detailed, multipage document. In general, the larger the company and the more complex the organizational chart, the more detailed the job description for each person. Smaller companies may have more loosely defined job descriptions because fewer people are available to handle all the tasks required to keep the company running. A job description is tied to the work to be performed and not to any specific individual who may hold the job at any particular time. Job descriptions become most prominent when a job is vacant and is subsequently advertised.

A typical formal job description might contain the following information:

- Job title
- Grade level (defines the salary range of the job)
- Immediate supervisor (specified as another job position, not a named individual)
- List of responsibilities

Note that job descriptions often form the basis of employment postings as well. One example of a specific engineering job description might read as follows:

Structural Engineer, Zilmore Civil Engineering, SG 74
Tracking Code 1743/G274

Job Description Develop and manage construction of various large scale project such as the food court renovation in the Peach Tree Mall. Coordinate new equipment purchases, installation, and commissioning for food service equipment. Collaborate with Zilmore staff and partner companies to create processes and manage workflow at construction site. Train interns, hourly staff, and personnel from partner companies to use equipment and supervise its use. Responsible for the maintenance of the job site: order supplies, establish and enforce policies and procedures, and maintain and calibrate equipment.

Required Skills Master of science or equivalent in civil or architectural engineering and four to six years of experience with onsite construction project management. Excellent interpersonal skills with the ability to work with a variety of individuals. Professional registration required.

3.1.4 Team Contact List

As obvious as it may seem, it's important to maintain a contact list for all personnel working on a particular project. One team member (or a staff person if one exists) should have the responsibility of maintaining the list. It should contain e-mail addresses and telephone numbers for everyone on the team, as well as home or cell phone numbers and instructions for when it's permissible to call outside of working hours. If resources permit, it's a good idea to maintain the list as a web page so that it is easily updated and constrained to a *single* accurate list. Password protection may be needed in some situations.

3.1.5 Team Meetings

It's important for an engineering design team to meet regularly to review project status, design issues, and problem resolution. Frequency is entirely up to the team, but it is usually decided by the team leader. Meeting once per week seems to be the norm in many engineering organizations, including college design courses. Others may choose to meet only when deemed necessary (called meeting "on demand"), while other projects may require daily meetings. However often your team meets, it will be important to impose some type of structure so that meetings do not degrade into free-for-all chaos. Although a preset agenda is always helpful, setting the tone for the meeting is the responsibility of the team leader. This task can be particularly difficult in a course situation where the team is composed of otherwise equal peers. Even in company settings, personality differences between employees can get in the way of team cooperation and progress. Learning to deal with these situations in college will help you prepare for the job market. It is an important component of your engineering education.

3.1.6 Working with Other Teams in the Organization

More often than not, a complex design effort will involve more than one team. Assigning multiple teams to a project is common practice in companies that manufacture products for sale. The classic division of labor, still used in many companies, divides responsibilities into the broad areas of research, development, manufacturing, and marketing. The *research team* conducts fundamental studies that seek to probe new forefronts of knowledge relating to the company's core expertise. The *development team*, often composed of different individuals, is assigned the task of transforming fundamental discoveries into product concepts that culminate in working prototypes. The *manufacturing team* must take the prototype and develop a method for mass producing the product in a cost-effective and profitable way. The *marketing team*, which often contains engineers who understand how the product works, has the job of seeking and securing customers.

Traditional thinking in project management asks these four teams to interact serially, with each one passing its work "over the wall" to the next group down the chain of command. In such a scenario, Research thinks up the ideas, Development reduces them to practice, Manufacturing determines how to make the product in quantity, and Marketing seeks out new customers. Traditionally, the only feedback in the loop might be from Marketing back to Research, wherein the former communicates customers' needs to the latter. For long-term reference, teams typically operate as separate entities, with each holding on to its own set of priorities and rivalries. Often these rivalries bog down the design process and greatly increase the time span from concept to finished product.

More modern project management philosophies recognize the importance of continuous interaction between the various components of a company's organizational chart. The most successful companies are those in which the needs and priorities of each team are considered from the start and given appropriate weight when decisions are made. In such an interactive team environment, for example, Development might not be given sole authority to specify materials and dimensions of a product. Rather, manufacturing will ask that options be limited to pre-existing processes that can be enacted without requiring expensive new tooling. Marketing may insist that the design incorporate ergonomic features that will allow the product to fare well against a competitor's product. Research may seek the assistance of Development and Manufacturing to decide which projects to address, and Development may seek the help of Marketing to assess customer needs. Manufacturing may collaborate with Development to adopt rapid-prototyping methods.

In some companies, the classic team divisions described above may not have distinct boundaries at all. Research, Development, and Manufacturing may be the responsibilities of one blended group of individuals. This approach has found success, for example, in the Saturn Corporation, a subsidiary of General Motors. Their team philosophy and work unit structure are summarized in the abridged diagram of Figure 3.3. The structure of Saturn is based on "work units" and "modules." Work units are responsible for the primary tasks related to automobile production. Modules are groups of work units that perform similar types of labor. Both work units

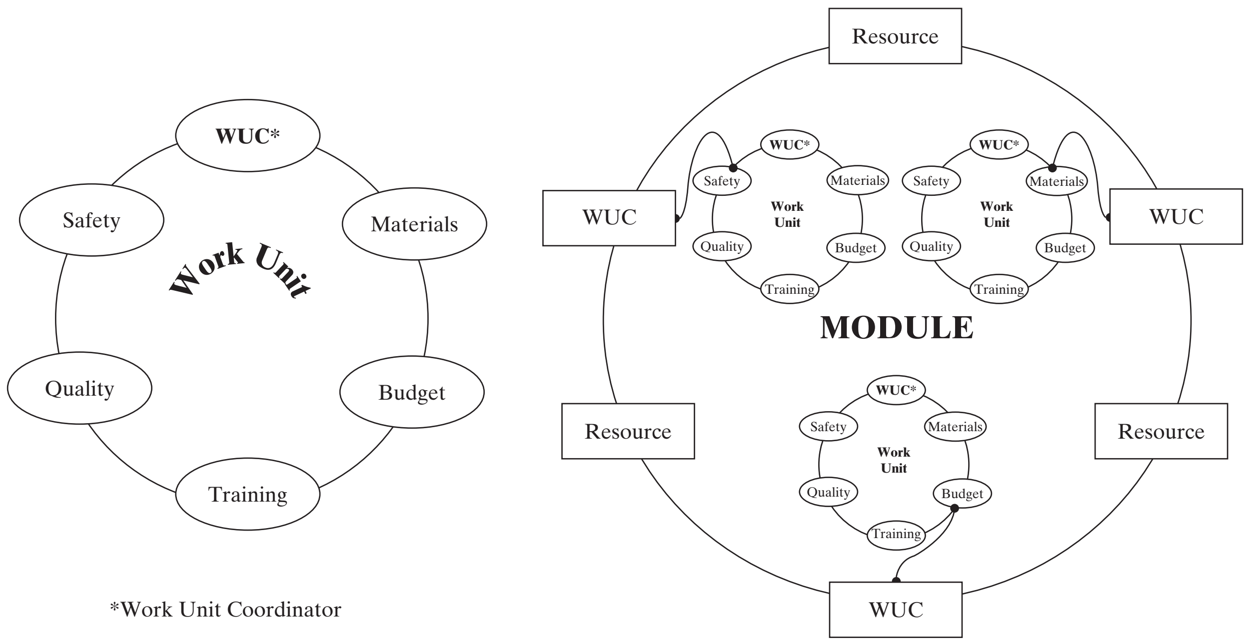


Figure 3.3
Work unit and module organizational structure for the Saturn automobile manufacturing company.

and modules are responsible for all decisions made within the circle; each circle has an elected representative on the next highest order circle. When first introduced, this self-directed, team-integrated approach to project management was unique to the U.S. auto industry and still stands out today as a refreshing way to approach large-scale endeavors.

When confronted with the classic compartmentalized approach to product design, it's important for engineers to avoid rivalries and "turf wars." Remember that ultimate success requires the symbiotic cooperation of all teams involved in the design process. While the various team structures may occupy distinct branches of the company's organizational chart, as in Figure 3.4, it's the unseen bridges between them that will keep the company strong and lead to rapid and successful product development.

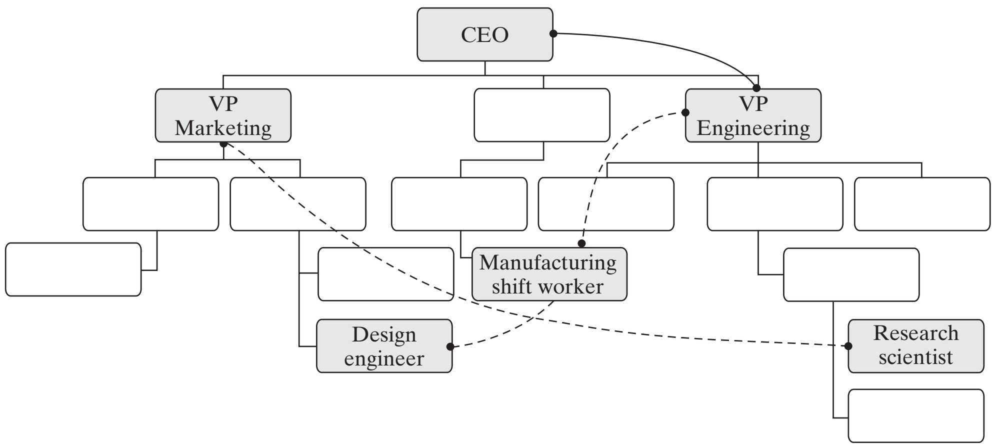


Figure 3.4
The unseen bridges between branches of an organizational chart keep the company strong and lead to rapid and successful product development.

Practice!

1. Devise an organizational chart and time line for building stage scenery for a drama production at your college or university.
2. A large, nonprofit organization is planning a walk-a-thon in which 3,000 people will walk 60 miles in 3 days and will sleep in tent camps each night. Develop an organizational chart for all persons involved in planning and implementing this event.
3. A student organization is planning to enter the Mini Baja vehicle competition for students sponsored by the Society of Automotive Engineers (*students.sae.org*). Develop an organizational chart that will guide the team through the design and construction of a competition vehicle.
4. Imagine that you work for a company that makes wind turbines for electric power generation. Define an organizational chart for such a company from design and fabrication through installation and contracted maintenance.

5. Even sports teams have organizational charts. Choose your favorite sports team and draw its organizational chart.
6. Your college or university has an administrative organizational structure. Learn about this structure and draw an organizational chart, from the president down to the level of department heads.
7. Draw the organizational chart for a major petroleum company. Include all aspects of exploration, recovery, refinery, and distribution.
8. Write the job description for an engineer assigned to a team designing a plastics processing plant.
9. Write the job description for someone who works for on online hardware store.
10. Write the job description for an engineer who has just joined a company that makes underwater hydrophones. The company has a total of ten employees.
11. Write the job description for an engineer who works for a large defense contractor that makes military aircraft.
12. Write the job description for an engineer who works for a company that makes pipeline valves.
13. Write the job description for an engineer who works for a company and helps them optimize factory floor operations for a cosmetics manufacturer.
14. Suppose you want to hire an industrial engineer for a company that makes large kitchen appliances. Write an advertisement that you might put on a nationally circulated job site (e.g., *www.monster.com*).
15. Suppose that you want to hire a nuclear engineer to oversee the operations of an electric power plant construction project. Write the advertisement that you might submit to a national trade magazine.

3.2 MANAGING TASKS: KEEPING THE PROJECT ON TRACK

Time management is critical to the success of any engineering project. In a perfect world, engineers would have as much time as needed to work on all aspects of a project; in the real world, however, deadlines have a nasty habit of creating pressure to get the product out the door. Demands for demonstrations of progress, prototype tests, something for "sales and marketing to show," and the pressures of corporate life require that an engineer develop a sense of how much time will be needed for each aspect of product development.

Even the simplest design project requires time management. A systematic approach to design tasks is always preferable to a random, hit-or-miss approach. While the subject of time management can (and does) occupy the contents of entire books, several time management tools form a basic set that should be understood by all engineers.

3.2.1 Checklist

A simple checklist enables the monitoring of engineering tasks related to a specific design project. It differs very little from the "to-do" list that you might compile for a set of weekend chores. The tasks enumerated on an engineering checklist need not be completed in any particular order. An example of a simple checklist that might apply to the design of a wheelchair ramp is shown in Figure 3.5.

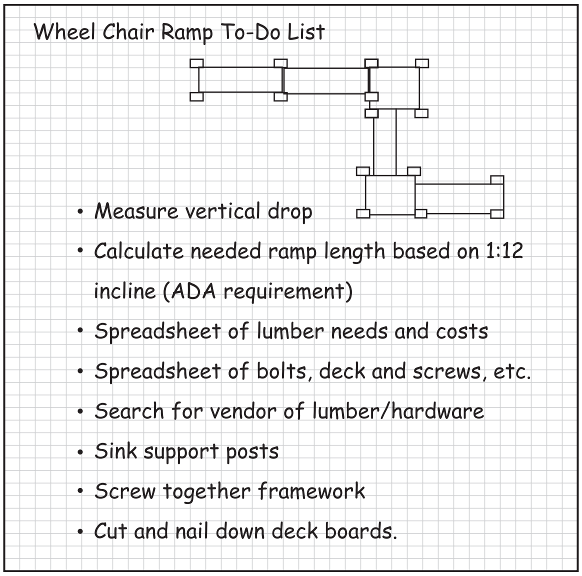


Figure 3.5
Checklist for the design of a wheelchair ramp.

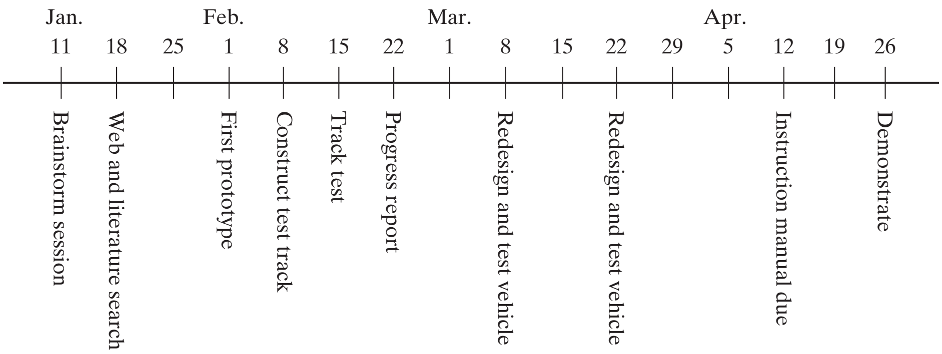
3.2.2 Timeline

A *timeline* is a valuable tool for keeping a project on schedule. A timeline is similar to a checklist, but its various tasks are expected to be completed sequentially by specified milestone dates. The timeline is very appropriate when the entire team works in unison, with the differentiation of tasks occurring serially in time. If a given task is in danger of not being completed before its designated milestone date, it's the job of the project manager to allocate more time, and overtime if necessary, so that the task can be completed on schedule. A typical timeline (in this case, one prepared by students designing a vehicle for a class design project) is shown in Figure 3.6.

3.2.3 Gantt Chart

When a project is complex and involves many people, a simple timeline may be inadequate for managing all aspects of the project. Similarly, if the project's various tasks are interdependent, so that the completion of one phase depends on the success of several others, the *Gantt Chart* of Figure 3.7 may be a more appropriate time-management tool. The Gantt chart is simply a two-dimensional plot in which the

Figure 3.6
Timeline for tasks pertaining to a vehicle design competition.



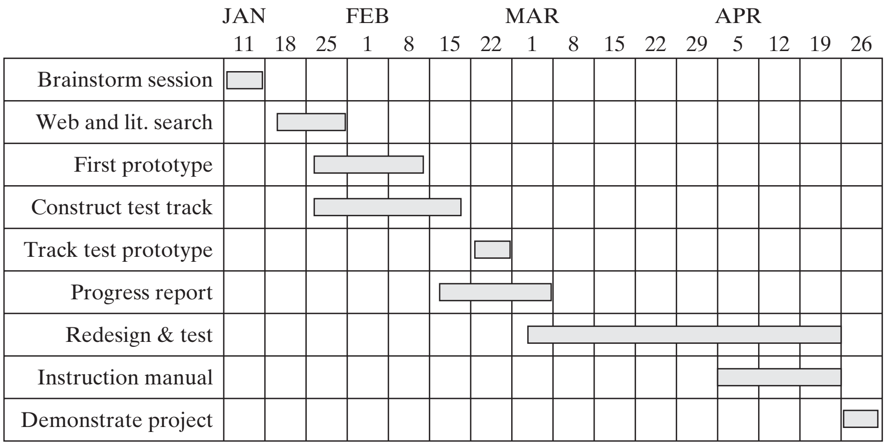


Figure 3.7
A Gantt chart provides a more comprehensive, two-dimensional method of scheduling the tasks shown in Figure 3.6.

horizontal axis reflects time measured in days, weeks, or months, and the vertical axis represents either the tasks to be completed or the individuals responsible for those tasks. Unlike the checklist, which simply enumerates the tasks to be completed, and the one-dimensional timeline, which merely displays sequential time allocations for each phase of the project, the Gantt chart shows how much time is allotted to multiple tasks performed in parallel. It also provides for overlapping time periods that help indicate the interdependency between the various aspects of the project. When a particular task has been completed, it can be shaded on the Gantt chart, so that the status of the project can be determined at a glance.

3.2.4 PERT Chart

The Project Evaluation and Review Technique (PERT) was first proposed by the United States Navy and developed by the consulting firm of Booz, Allen, and Hamilton in 1958. Its purpose at the time was to coordinate the activities of over 10,000 separate subcontractors involved in the Polaris missile development program. The PERT method is very similar to the *critical path method* (CPM), and these terms are essentially interchangeable. The PERT technique is fundamentally a method for prioritizing and scheduling complex interrelated activities. The PERT chart helps to identify the most time-critical events in the design process.

The essence of the technique is embodied in a graphical network called the *PERT chart*, depicted in generic form in Figure 3.8. The PERT chart consists of

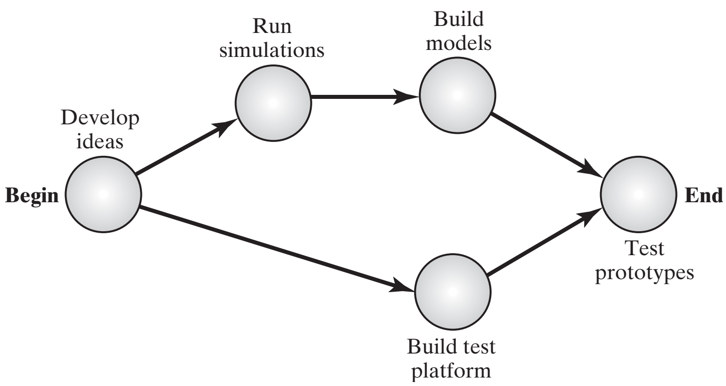


Figure 3.8
The generic form of a PERT chart. The circles represent milestone points, and each arrow represents a task leading up to a node. Each task is allocated a completion time.

numbered milestone circles and pathway branches. Each branch is labeled by a time interval allocated to the completion of the task to which the branch leads. Branches are labeled in appropriate time units (e.g., days, weeks, or months). Like the Gantt chart, the PERT chart summarizes the time allocated for each task and notes task completion milestones. Unlike the Gantt chart, however, the PERT chart also shows the way in which the tasks depend on one another. This interdependency is indicated by the branch lines that connect the task-completion circles of the chart.

A PERT chart must have a starting point, or *node*, and a single ending milestone (the last node to which all pathways must lead). As in the Gantt chart, time progresses from left to right. The time allocated for the pathway between any two milestone nodes will be equal to the sum of the times allocated for each task in the pathway. In Figure 3.9, for example, the sequence of tasks leading from milestone A to milestone C is allocated a total of $3 + 5 = 8$ days.

As each task depicted on a PERT chart is completed, the project manager checks it off on the chart. The manager can thus monitor the progress of the entire project and be alerted to any possible path delays. Some project managers prefer the PERT chart over the Gantt chart because it clearly illustrates task dependencies. A PERT chart, however, can be much more difficult to interpret, especially on complex projects. Alternatively, some project managers may choose to use both techniques.

When compiling a PERT chart for project management, it's possible (and often preferable) for the sum of branch times over one pathway to be less than the sum of times over a parallel pathway. The excess, called *slack time,* can be used to compensate for the inevitable delays that will accompany the design process. If the delay experienced along the way does not exceed the slack time of the pathway, the entire project will still be on track. Of most interest, therefore, are so-called *critical pathways*. The latter are those branches containing zero slack time. Any delays in a

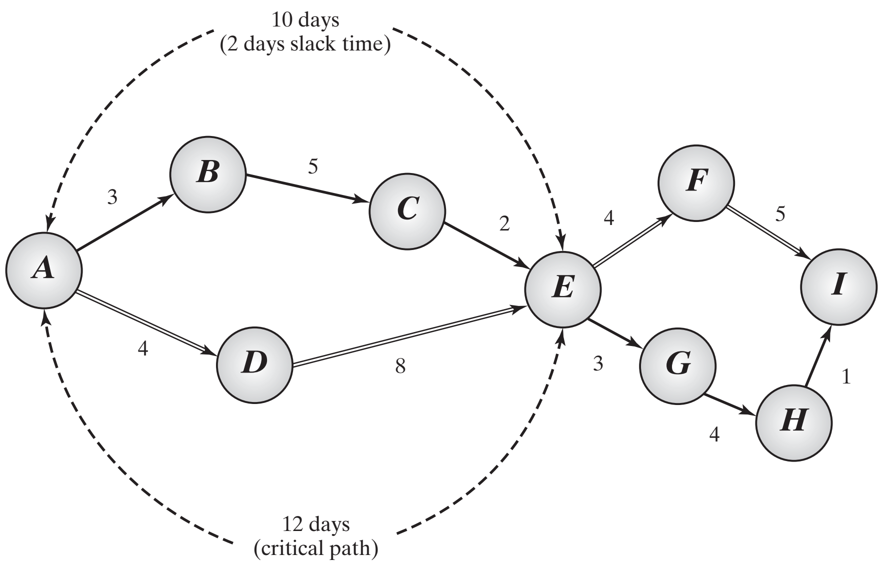


Figure 3.9
A PERT chart showing milestone nodes and task time allocations in days. On this chart, critical pathways are shown as double lines.

critical pathway can jeopardize the time flow of the entire project and should be monitored carefully. The pathway from node A to node E (via node D) in Figure 3.9, for example, is a critical pathway.

EXAMPLE 3.1

Managing a Building Construction Project

The major steps required to erect a framed house (somewhat simplified in this case) are summarized by the PERT chart of Figure 3.10. Such a chart might typically be used by a general contractor who must hire many different subcontractors to complete various aspects of the project. Node 0 denotes the starting point of construction. Before anything else can transpire, the building site must be excavated so that the foundation can be framed, as well as molded and poured. In Figure 3.10, the former is allocated 4 days, and the latter 2 days. After the foundation has been poured and cured, the external skeleton or frame of the building can be erected. This frame will form the support structure for all the exterior walls of the building, as well as any interior walls specified by the architect. This task has been allocated a total of 5 days.

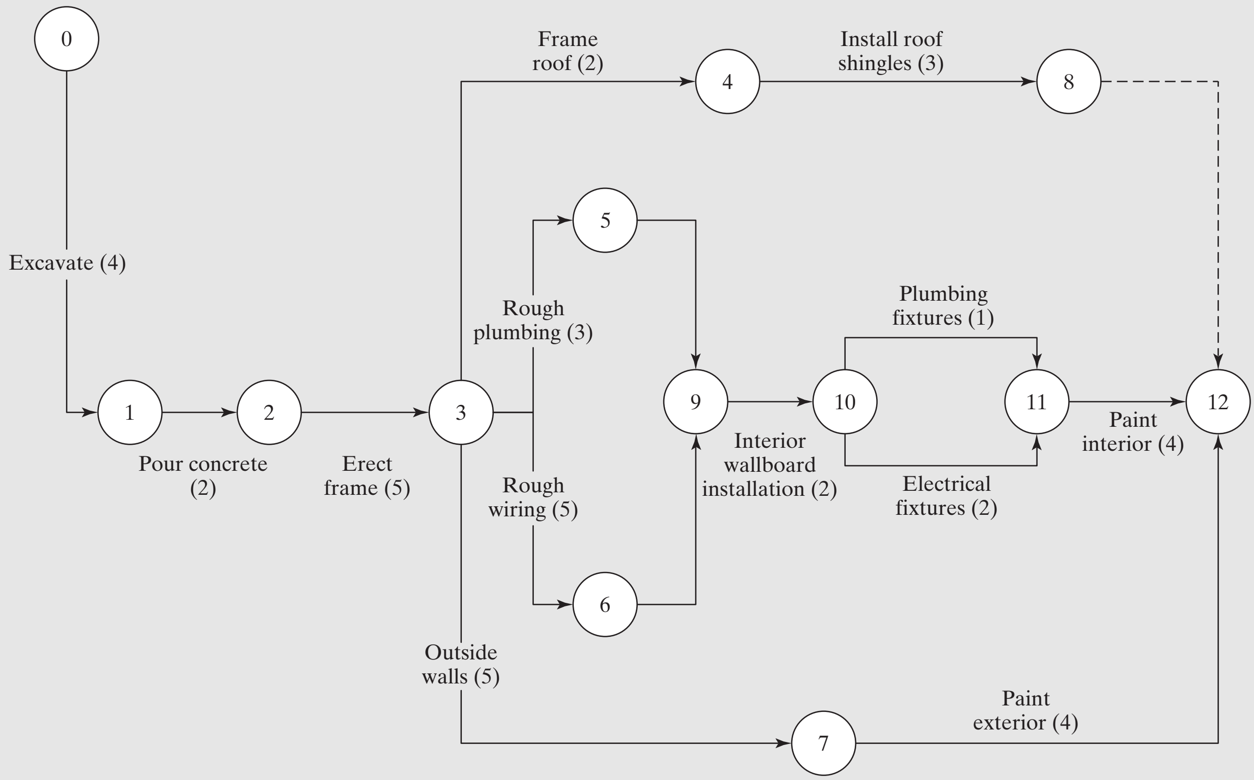


Figure 3.10
PERT chart that describes the principal steps involved in building a house. Numbered circles (nodes) designate task completion points. Each pathway is labeled with a time allocated to that task. The numbering of the nodes is arbitrary.

After the building frame has been completed, the major tasks continue over parallel pathways. The framing for the roof must be completed, followed by the weather protection (in this case, standard roofing shingles). These tasks have been allocated 2 and 3 days, respectively, leaving considerable slack time compared to the other paths. Similarly, following arrival at node 3, work begins in parallel on the installation of the building's exterior walls. The rough plumbing and electrical tasks, to be described in the next paragraph, require that the interior walls remain open, but not the exterior walls.

In parallel with the finishing of the roof and outside walls, the installation of the rough plumbing is now initiated. Rough plumbing refers to the piping—both supply and waste—that must lie within the walls of the structure. Obviously, this task must be completed before the interior walls themselves can be installed. Yet another parallel pathway begins after node 3, consisting of the rough electrical wiring. The latter must also be completed before the interior walls can go up. The rough plumbing and wiring tasks are allocated 3 and 5 days, respectively.

Following the completion of the rough work, the interior walls (e.g., standard gypsum wallboard; see *www.nationalgypsum.com*) can now be installed (2 days). Once the interior walls have been completed, the plumbing and electrical crews can return to install fixtures; afterwards, the interior walls may be painted. Usually, this task is performed after the electrical and plumbing work are finished, because the latter tasks might cause workers to mar the finished paintwork. Some contractors, however, prefer to paint before fixture installation, because the resulting paint job is much cleaner around the edges of the plumbing and electrical fixtures.

The completion of the roof, interior paint, and exterior paint on the PERT chart all arrive at the last node on the diagram (node 12), signifying the completion of the job. The house may now be occupied. The critical pathway in this PERT chart consists of the following tasks, beginning at node 3: rough electrical wiring (5 days), wallboard installation (2 days), wiring completion (2 days), and interior painting (4 days). These tasks require a total of $5 + 2 + 2 + 4 = 13$ days. Any delays over this critical pathway will lead to a delay in occupancy of the house.

EXAMPLE 3.2

Managing a Software Project

Figure 3.11 shows a PERT chart used by a development team tasked with the design of a cell phone running on firmware (machine-level binary software). The unit, once manufactured and ready for sale, is to be shipped with a user manual and online help files. Once the specifications have been set, the PERT chart divides into three distinct pathways—one related to hardware, one to the firmware, and one to user documentation. The critical pathway in this project runs from node 1 to node 2, and then via nodes 3, 5, 6, 8, and 7 to the final node 13, for a total time allocation of $2 + 4 + 2 + 3 + 4 + 1 + 4 = 20$ weeks.

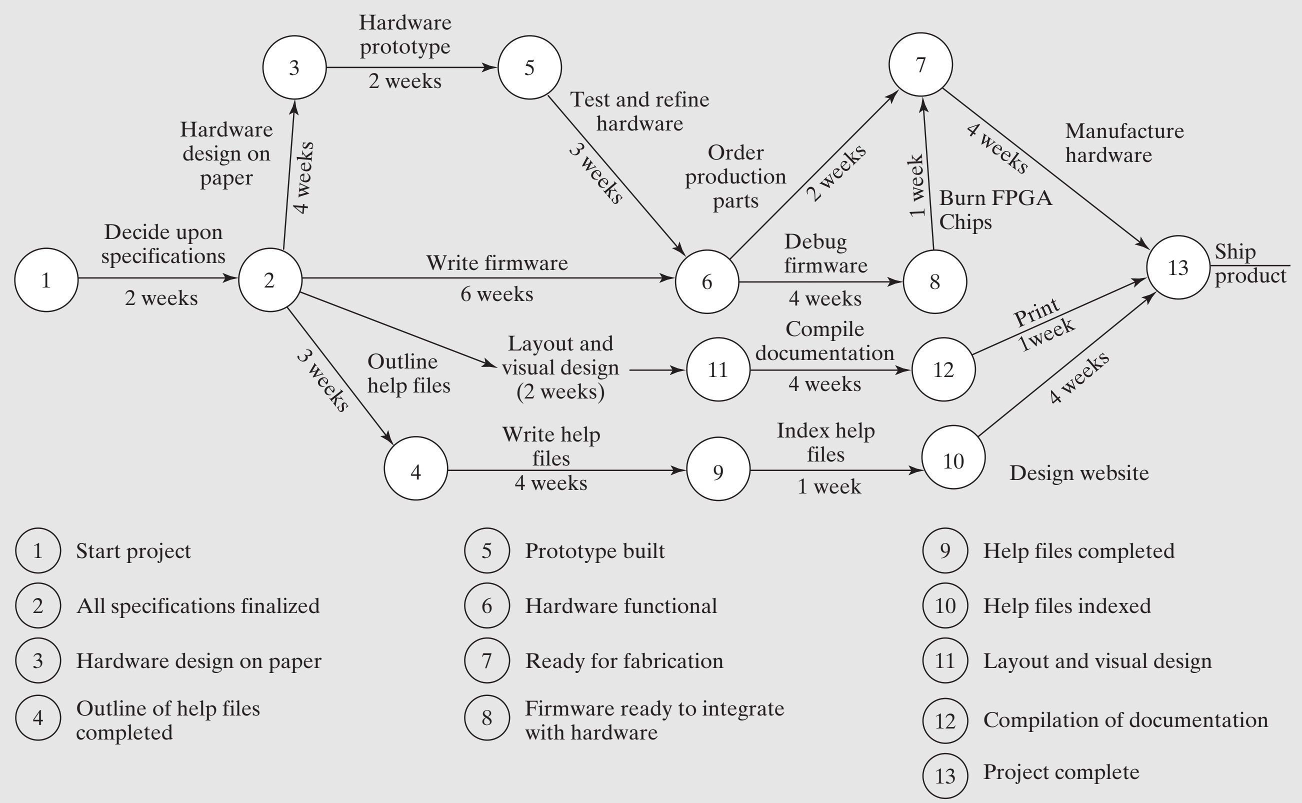


Figure 3.11
PERT chart that describes the development of a cell phone running on firmware.

Professional Success: The Laws of Time Estimation

How long will it take to perform a particular design task? How much time should you allocate to each segment of a PERT chart or Gantt chart? The following Laws of Time Estimation will help you to determine the time required for a given design task:

1. Everything takes longer than expected.
2. If you've done the same task before on a different project, estimate the amount of time required to finish the task. The actual amount of time required will be about twice as long. Something will always be different in the current project.
3. If you've worked on something *similar* before, but not exactly the same task, estimate the amount of time required to finish the task. The actual amount of time required will be about four times as long.

4. If you've *never* worked on something similar before, estimate the amount of time required to finish the task. The actual amount of time required will be the next highest time unit. For example, something estimated to take an hour will really take a day; something estimated to take a day will take a week, etc.

3.3 DOCUMENTATION: THE KEY TO PROJECT SUCCESS

Engineering design is never performed in isolation. Even the simplest of projects involves a designer and an end user. More often, a design effort involves considerably more individuals concerned with various aspects of the product. Additionally, the uses of the product may involve an entire segment of the population. The design of an automobile, for example, encompasses the work of mechanical, electrical, industrial, materials, and safety engineers, and the entire driving public constitutes the group of end users. A consumer products company involved in the production of cellular telephones will bring together computer, systems, electrical, mechanical, and manufacturing engineers in a multidisciplinary team that may include people from sales and marketing. A public works management corporation, tasked with designing a waste water treatment facility, might solicit the help of civil, chemical, mechanical, and environmental engineers, along with the city planners and systems engineers. Complex engineering projects are successful only if everyone on the design team communicates with everyone else at all phases of the design effort.

One way in which engineers communicate with each other is through careful recordkeeping. Good documentation is essential when you work as a member of a design team. As a practicing engineer, it will be your responsibility to maintain a comprehensive collection of design concepts, sketches, detailed drawings, test results, redesigns, reports, and schematics—whatever records are pertinent to the project. This *documentation trail* will serve as a tool for passing information on to team members who may need to repeat or verify your work. The documentation trail is critical to those who will manufacture your product from a prototype, apply for patents based on your inventions, or even take over your job if you are promoted or move to another company. Written records are also a good way to communicate with yourself. Many an engineer has been unable to reproduce design accomplishments due to sloppy recordkeeping. Indeed, one of the marks of a professional engineer is the discipline needed to keep organized, neat, up-to-date records. Documentation should never be performed as an afterthought. If a project is dropped by one team member, the state of documentation should always be such that another team member can resume the project without delay. As a student of engineering, you should learn the art of recordkeeping and develop good documentation habits early in your career. Most companies, laboratories, and other technical firms require their employees to keep records that document the results of engineering efforts.

3.3.1 Paper versus Electronic Documentation

Today, just about every piece of engineering documentation, with the exception of the engineer's logbook (described in the next section), is produced electronically. This situation was not true only a decade ago. Examples of documents destined for preservation include text documents, spreadsheets, computer codes, schematics, drawings, design layouts, and simulated test results. Most engineers prefer to store information electronically so that it can be viewed onscreen and printed only as needed. Some still prefer to preserve documentation by printing everything on paper and storing the documents in a physical file cabinet. Whichever method you choose, take heed of the following important guidelines:

- *Organize your information.* It's important to store documentation in an organized and logical manner. If the project is small, its documentation should be stored in a single folder (paper or electronic). Larger projects may require a group of folders, each relating to different aspects of the project. The folders should be labeled and dated with informative titles (such as "Propulsion System for XYZ Project") and kept in a place that will be easy to find in the future.
- *Back up your information.* It's equally important to store a duplicate copy of all documentation. This guideline applies to written as well as electronic information. Fire, flood, theft, misplacement, the all-too-common disk crash, and the unfortunate havoc wreaked by so-called "malware" can lead to the loss of a project's entire documentation trail. Archival storage of records in a different physical location will help to keep a project on track should one of these catastrophes occur. Companies exist that will provide secure offsite storage of critical data.

3.3.2 The Engineer's Logbook (Notebook)

One important vehicle for recordkeeping is the *engineer's logbook,* sometimes called the *engineer's notebook.* A well-maintained logbook serves as a permanent record that includes all ideas, calculations, innovations, and test results that emerge from the design effort. When engineers work in a team, each member keeps a separate logbook reflecting that individual's assigned tasks. When the project is brought to completion, the logbooks of all team members are placed in an archive and remain the property of the company. An engineering notebook thus serves as an archival record of new ideas and engineering research achievements *whether or not they lead to commercial use.*

A complete logbook also serves as evidence of inventorship and establishes the date of conception and "reduction to practice" of a new idea. It shows that the inventor (e.g., you) has used diligence in advancing the invention to completion. In this respect, the engineer's logbook is more than just a simple lab notebook. It serves as a valuable document that has legal implications. When you work as an engineer, you have a professional responsibility to your employer, your colleagues, and to the integrity of your job to keep a good logbook.

The notebook shown in Figure 3.12 is typical of many used in industry, government labs, and research institutions. The company, laboratory, or project name is printed at the top, and the notebook is assigned a unique number by the user. In some large institutions, a central office may assign notebook numbers to its employees when the notebook is issued.

The techniques for logbook use differ from those used in most science and (unfortunately) some introductory engineering classes where instructors encourage students to write things down first on loose scratch paper and then recopy relevant items into a neat notebook. This procedure is bad practice for the design engineer. Although notebooks prepared in this way are easier for instructors to grade, the finished notebook seldom resembles a running record of what *actually* occurred in the laboratory; it is not especially useful for engineering design projects. Design is as much a *process* as it is a final product, and the act of recording ideas as they emerge

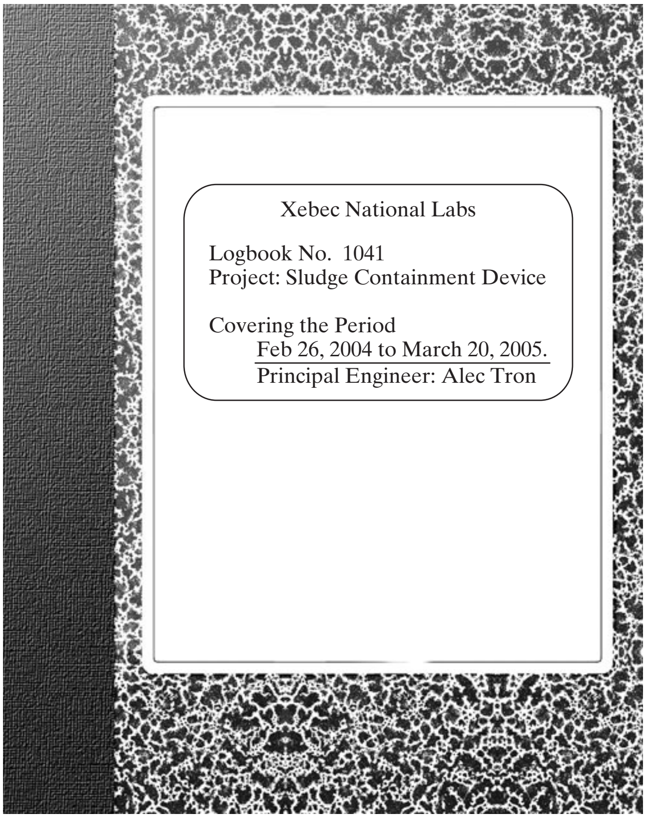


Figure 3.12
Cover and label of a typical engineer's logbook.

and events as they happen helps engineers to think and be creative. Also, keeping a record of what did *not* work is just as important as recording what did work; this practice ensures that mistakes will not be repeated in the future.

3.3.3 Logbook Format

An engineering logbook should be used as a design tool. Enter everything into your logbook, no matter how seemingly irrelevant. Write down ideas as you think of them, even if you have no immediate plans to pursue them. Keep an ongoing record of successes and failures. Record the results of every test—mechanical, structural, electrical, system, flight, flow, pressure, performance—even if the results may not be used in the final design. Stop to write things down! This habit – sometimes hard, but important to learn – will require discipline but will always be worth the effort. Important information, including some you might otherwise have forgotten, will be in your logbook and will be preserved for a time when you may need it.

Any logbook format that meets your needs and those of your team is suitable, as long as it forms a permanent record of your contributions to the design project. Ban loose paper from the laboratory. It is easily lost, misfiled, or damaged. Resist the temptation to reach for loose paper when you need to do a calculation. Instead of grabbing that pad to draw a sketch or discuss an idea, take the time to open your logbook. You'll be glad you did when those numbers and sketches you need are readily available. Unbound paper used for anything other than doodling has no place in an engineering laboratory.

3.3.4 Using Your Engineer's Logbook

As chief author of your logbook, you have the freedom to set your own objectives for its use. The following guidelines, however, are typical of those used by many engineers and design teams:

1. Each person working on a project should keep a separate logbook specifically for that project. When the logbook is full, it should be stored in a safe place specifically designated for logbook storage. In that way, everyone will know where to find the logbook when it's needed.
2. All ideas, calculations, experiments, tests, mechanical sketches, flowcharts, circuit diagrams, etc., related to the project should be entered into the logbook. Entries should be dated and written in ink (pencil has a nasty habit of smudging). It's no crime to cross out errors made in pen. Any computer-generated plots, graphics, schematics, or photos printed on loose paper should be affixed to bound logbook pages. This procedure will help prevent loss of important data.
3. Logbook entries should outline the problem addressed, tests performed, and so forth, but subjective conclusions about the success of the tests (e.g., "I believe") should be avoided. The facts should speak for themselves.
4. The voice of the logbook may be written in the first person (*I tested the widget . . .*) , but it should speak to another reader. Assume that your logbook will be read by teammates, your boss, or perhaps someone from marketing.
5. In settings where intellectual property is at stake, the concluding page of each session should be dated and, where appropriate, signed. This practice eliminates all ambiguity with regard to dates of invention and disclosure.
6. Logbook pages should not be left blank. If a portion of a page would otherwise be left blank, a vertical or slanted line should be drawn through it. Pages should be numbered consecutively and not be torn out. Do not make changes using correction fluid. Cross out instead. These procedures will prevent you from creating obscure or questionable entries should your logbook be entered as legal evidence in patent or liability actions. Although this precaution probably won't be relevant to logbooks you keep for college design courses, it's a good idea to begin following it now so that the procedure becomes a career habit.

EXAMPLE 3.3

An Engineer's Logbook

The following example illustrates proper use of an engineering logbook. Imagine that the logbook pages shown describe your team's design for a telescoping flag for a motorized wheelchair. The intent is to increase visibility when the user operates the wheelchair in city streets. The first page, Figure 3.13, shows your preliminary sketch of a basic concept based on the use of a commercially available telescoping car radio antenna. The second page, Figure 3.14, contains some calculations that estimate the battery drain as the flag is raised and lowered. The entries on the third page, Figure 3.15, show a list of parts and materials that your team has decided to purchase. These parts will enable you to build a prototype and test your system's ability to raise and lower the flag on demand.

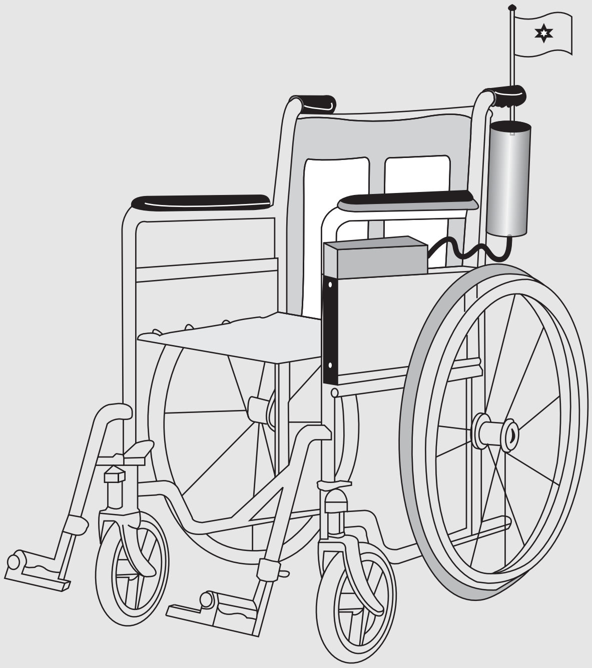


Figure 3.13
Preliminary logbook sketch for a telescoping wheelchair flag.

Figure 3.14
Calculations to show estimates of battery drain.

Battery Energy Requirements 10/1/09

Measured motor current: 0.45 A $\approx \frac{1}{2}$ A

Rod Speed: (estimated) abt. 10 cm/sec

→ Motor ON time = Dist/Rate = $\frac{121\text{cm}}{10\text{ cm/sec}}$ = 12.1 sec

Here 12 seconds = $\frac{1}{5}$ minute = $\frac{1}{300}$ hour

...so each extension requires about...

$0.45\text{ A} \times \frac{1}{300}\text{ hour} \approx 1.5 \times 10^{-3}\text{ A-h}$

A 0.3 amp-hour battery can provide about

0.3 A-h 1.5×10^{-3} A-h ≈ 200 extensions of flag.

Note to Mike: Good for a start

3.3.5 Technical Reports and Memoranda

A logbook represents only one component of a good documentation trail. Engineers also communicate by writing technical reports at significant project milestones. A technical report describes a particular accomplishment and perhaps provides some background material as well. The report may contain theory, data, test results, calculations, design parameters, or fabrication dimensions. Technical reports form the backbone of a company's technical database. Reports are typically stored in archival format, each with its own title and catalog number. Information for technical reports is easily gathered from logbooks that are accurate and up to date. When the time comes to write a patent disclosure, journal paper, or product application note, the technical report becomes an indispensable reference tool. Taking the time to write a technical report about a negative result or design failure can save considerable time should a design concept be revisited by engineers who were not present when the original project was undertaken.

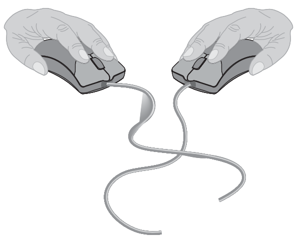
> Yet another way in which engineers communicate their ideas to other engineers is through the writing of formal journal articles. A journal article is appropriate when the work represents new knowledge unknown to those working in the field. While often used to report experimental and theoretical findings, journal articles are also frequently used to report design innovations. The structure of a typical journal paper is discussed in more detail in other areas of this book.
>
> *Peer review* is the process by which a paper is evaluated and critiqued, then either accepted or rejected for publication. The editor of the journal will typically send a submitted paper to one or more knowledgeable reviewers who will return a list of comments and questions for the author. It is common for a submitted paper to be returned at least one time to the author for revision. It's most unusual for a paper to be accepted unchanged upon its first submission. Conversely, some papers may be rejected as unsuitable for publication. This peer-review method ensures that papers appearing in the best journals are accurate, relevant, and up to date.

3.3.6 Software Documentation and the Role of the Engineering Notebook

Of all design endeavors, software writing is the one most prone to poor documentation. The revision loop of a software design cycle can be extremely rapid, because the typical software development tool enables a programmer to make small changes and test their effects immediately. This rapid-fire method of development is good for prototyping but invites poor documentation habits. Seldom does the software engineer find a good time to stop and document the flow of a program, because most pauses are short and change is frequent. As a result, the documentation for many software programs is added after the fact, if at all.

If you find yourself writing software, get into the habit of including documentation in your program as you go along. All software development tools provide a means for embedding comments in the program code. Add them frequently to explain why you've taken a certain approach or written a particular section of the code. Explain the meaning of object names and program variables. Your program documentation should enable other engineers on your team to completely understand and take over your sections of the code simply by reading the comment lines. Good documentation will also be invaluable should you need to modify your code at a later time. It's amazing how quickly a programmer can forget the internal logic of a program after setting it aside for only a short time.

If your program is destined for commercial sale, then good internal documentation and truly helpful "help" files are essential. Documentation included inside the program on a regular basis will easily translate into help files when the need arises. One trick used by top-notch software developers is to write the help and instruction files as the program code is developed, rather than as an afterthought. Changes to the help files can be made at the same time that changes are made in the program code. The abundance of commercial software packages with pathetic or poorly written help files is testimony to generations of software engineers who have perpetuated a tendency toward poor documentation habits. If you master the skill of documenting software, your software products will be better utilized and more successful than those having poor documentation.



Although keeping engineering logbooks is less relevant to software development than to other types of engineering, logbooks still play a role. On the pages of your notebook, you can outline the overall structure of the program (e.g., using flowcharts) and the interconnections between its various modules. You can enter sketches of graphical user interfaces without writing actual computer code. You can similarly draw block diagrams of relational databases and make lists of the variables to be used in the software.

Professional Success: How to Keep Good Records All the Time

If you want to keep a good documentation trail, carry some sort of logbook with you at all times. It will then be available whenever you have an idea that needs recording. Buy a medium-size notebook that can fit easily into your backpack. Clip a pen right inside the front cover. Be sure to write your name and contact information on the cover in case you lose it! A tiny 3" $\times$ 5" bound notebook will do nicely. Although writing space will be limited because of the smaller size, you'll be more likely to carry it if it's not overly large. You can then tape its smaller pages into those of your central, full-sized logbook.

Practice!

1. Refer to the logbook calculations in Figure 3.14. Revise the estimate of the number of extensions if the motor requires 2.1 A. Rewrite the logbook page.
2. Refer to the logbook calculations in Figure 3.14. Revise the estimate of the number of extensions if the motor requires 300 mA, and a 200 A-h battery (similar to a lead-acid car battery) is used. Rewrite the logbook page.
3. Do some Internet research and identify sources and vendors for the telescoping antenna shown in Figure 3.13. Prepare the resulting logbook page.
4. For the flag system outlined in Figure 3.13, what are the advantages and disadvantages of using a separate battery for the flagpole (as

opposed to tapping the primary storage battery that powers the wheelchair.) Write a logbook page that records your ideas.

5. On a simulated logbook page, outline some ideas for marketing your telescoping flag invention. Include cost estimates for its manufacture.
6. Imagine that you are one of the Wright brothers developing the first airplane. Sketch what you imagine to have been a typical logbook page from the project.
7. Look up the history of the famous 20th-century American inventor Lee DeForest. Sketch one page of a logbook that he might have kept during the time of his invention.
8. Sketch a logbook page that might have been recorded by Josephine Cochran, the inventor of the modern dishwasher.
9. Imagine what it was like to be Philo T. Farnsworth, the original inventor of the television. Sketch several logbook pages that summarize how the system works.
10. Develop some logbook pages related to the development of a personalized air transportation device.

3.3.7 The Importance of Logbooks: a Case Study

This case involves a small biomedical engineering company called Heartthrob[1] that was a leading contender for the development of a self-contained artificial human heart designed to be a permanent replacement for individuals who could otherwise stay alive only with a human heart transplant.

The major components of the heart system, depicted in Figure 3.16, include the central implanted pump and a system for transferring electrical power to run the pump through the skin from a battery pack worn outside the body. One key feature of the power transfer process, the lack of wires piercing the skin, is essential for the heart's long-term efficacy, because skin perforations are prime entry points for infection and require constant medical supervision in a skilled-care facility. Rather than requiring the patients to be tethered to a console, the fully self-contained device is designed to provide the patient some semblance of a normal, mobile, home life. The system for transferring electrical power, called the transcutaneous energy transfer device, or "TET," consists of two concentric AC magnetic coils. One is implanted under the skin, and the other is worn outside the skin. (Transcutaneous means "through the skin.") Heartthrob wished its engineers to fully focus on the daunting task of developing the heart pump itself, so it hired another biomedical engineering company, Tech-Heart, to design the energy transfer module.

After about four years of effort, Tech-Heart was still unable to produce a TET that met Hearthrob's stringent technical specifications. Although Tech-Heart claimed to be converging on a solution, Heartthrob was not convinced that a satisfactory TET device was imminent. Faced with an impending critical animal test that would determine future funding of its entire heart project from the National

[1]Names have been changed to protect privacy, but the story is entirely true.

Figure 3.16
Heartthrob's total artificial heart system.

Institutes of Health, Heartthrob decided to sever its reliance on the Tech-Heart TET. The Heartthrob CEO instructed one of his engineers, Dr. Maven, to develop a home-grown TET device as quickly as possible. Dr. Maven was a very capable fellow, and after only four months of effort, he succeeded in designing and testing a fully working version of a TET device that met all the requirements of Heartthrob's impending heart-pump test.

This development led to a lawsuit by Tech-Heart who claimed that Heartthrob could not have developed its own TET device in the mere time span of four months without having stolen secrets and technology from Tech-Heart. After all, Tech-Heart claimed, its engineers had worked on the project for four years and were only just beginning to converge on a possible solution. How could the Heartthrob engineer have designed a superior TET in only four months? Heartthrob countered with a claim that its short path to success was due solely to the high competency of its engineer, and that, in fact, it had taken special precautions to ensure that nothing would be stolen from the previous unsuccessful Tech-Heart design effort. The suit went to court and, in the end, Heartthrob prevailed. The jury recognized that Heartthrob's TET design, while performing the same basic transcutaneous energy-transfer function as the Tech-Heart device, was completely different with regard to all details of implementation. The Heartthrob device, the jury concluded, used different circuits, materials, magnetic construction, and semiconductor components.

During the trial, a key component of Heartthrob's defense was the logbook kept by the engineer who designed the TET. His logbook was used to prove that Heartthrob had designed its own independent version of the TET. Following the company's customary logbook policy, as well as sound engineering practice, Dr. Maven had kept careful records of his TET design, having entered every design concept, schematic, circuit layout, and test result that emerged during the design process. He had even noted the various circuit configurations that had gone up in smoke on the test bench before his first working model emerged. Each page of his logbook had been dated, and each lab session involving successful tests had been signed and countersigned by another Heartthrob engineer. During trial, entire pages of Dr. Maven's logbook were reproduced and projected on a large screen for the jury to see. Dr. Maven's logbook played a crucial role in the success of Heartthrob's legal defense.

The presentation of Dr. Maven's logbook in court, while critical to the outcome of the trial, did not proceed flawlessly, however. Several pages of the logbook involving work done in January 1996 had been incorrectly dated with the year 1995. Following a common mistake that many individuals make when the year changes, Dr. Maven had, without thinking, hastily written the year from the previous month of December. The lawyers for Tech-Heart were quick to seize upon this error as prima facie evidence that something was "fishy." They claimed Dr. Maven had forged portions of his logbook in an attempt to present a false picture of his accomplishments. In the end, the jury was not convinced and realized that Dr. Maven's error was nothing more than a common calendar mistake. Nevertheless, this seemingly small lack of attention to detail in logbook procedure put the case against Heartthrob in jeopardy for a time.

Professional Success: Developing Good Logbook Habits

Most of us follow routines without thinking. When we wake up in the morning, we brush our teeth. When we eat, we instinctively reach for a clean plate. When we get into a car, we (hopefully) buckle our seatbelts automatically. An as engineer, the urge to write things down in a logbook should become as instinctive as these other common tasks. In contrast to these personal procedures that enhance our own well being, we engineers are not trained from childhood to record our experiences in a notebook. Developing this instinct requires practice, but it can become part of your routine over time. When personal computers and the Internet first came into being, most people did not think very much about the novelty of e-mail. The same was true for cell-phone text messaging. Now these activities have become daily routines for most. You developed these unnatural skills by practicing them over time. It should be the same with your engineer's logbook. Force yourself to get into the habit of using your logbook whenever you practice design. Over time, it will become as natural as brushing your teeth.

3.4 LEGAL ISSUES: INTELLECTUAL PROPERTY, PATENTS, AND TRADE SECRETS

It would be nice if engineers could focus solely on technical issues. After all, engineering students spend enormous amounts of time learning about fundamentals and applications, plus many technical skills. Of all the non-technical topics addressed in engineering curricula, arguably the most important of these is the role that legal issues play in the design process.

The juxtaposition between legal issues and design practice falls squarely within the domain of project management. Central to this juxtaposition is the issue of patent protection. The worldwide system of patents and licensing, part of the broader world known as *intellectual property,* has as its noble goal the protection of new ideas and inventions. The patent system originated as a means of encouraging innovation by preventing large companies with lots of money from gobbling up the ideas of smaller inventors and dominating the market. While well intentioned in concept, the patent system has evolved into a maze of regulations and practices that can be most perplexing to engineers uninitiated in the world of legal procedures. For this reason, most large companies employ attorneys whose job it is to navigate the company through the often bewildering world of intellectual property. If you come up with an idea in the course of your company work, a resident attorney will likely guide you through the patent process. The patent will be assigned to your company with you listed as the inventor.

Another important arena in which legal issues intersect engineering is in the area of product liability. The western world, particularly the United States, has become a litigious society in which companies can be sued for all sorts of real or perceived product defects leading to injury, loss of property, or loss of life. The more dramatic stories, particularly those related to automobile accidents, are revealed to the general public via the media. But countless other cases that have filled civil courtrooms everywhere are not as widely disseminated. Understanding how the management of a design project impacts the issue of product liability is a critical engineering skill.

This section introduces some of the basic legal concepts that underscore the relationship between engineering and the law. While the material presented here merely skims the surface of intellectual property law, it will introduce you to the language of the legal profession and build your awareness of legal issues as they relate to engineering design.

3.4.1 Patents

A patent can be issued for any invention provided that certain criteria are met. The invention must introduce a new concept or way of doing something. The product must be something that can actually be produced, and it must have been *reduced to practice* (i.e., produced in at least prototype form) prior to the initial patent application. Also, the subject of the patent must not simply be an obvious synthesis of preexisting ideas.

A patent is valid for twenty years (in the United States) during which time the inventor has sole rights to produce or license the invention. A patent *license* is a legal contract binding the inventor, who may not have the resources to actually produce the invention, with a company that has the resources and desires to manufacture and market the invention. In the United States, patents are awarded, or *issued* by the United States Patent and Trademark Office (USPTO, or simply "Patent Office"). This organization maintains a comprehensive public website (*www.uspto.gov*) from which anyone may download patents dating back as far as 1976. Earlier patents may also be ordered in hardcopy from the patent archive.

3.4.2 Patent Jargon

Lawyers have their own vocabulary for describing the patent process. The concept of *prior art* refers to the body of knowledge that existed at the time of the patented invention. A device cannot be patented if it is described anywhere in the prior art. The invention must be reproducible, and the language of the patent must be sufficiently clear that it can be understood by an individual *skilled in the art*. The latter phrase is used to describe someone who, at the time of the invention, would have been familiar with the field of endeavor to which the invention applies and would have had the requisite education typical of those working in the general area of technology. To be patentable, a new invention must pass the tests of *obviousness* and *anticipation.* In legal terms, an idea is "obvious" if elements of prior art can be combined to produce the invention, *and* if, at the time of the patent application, the general literature provided suggestions for doing so. An invention is "anticipated" if a single piece of prior art describes the invention in its entirety. These tests are applied as part of the application process, known simply as the patent's *prosecution history*. If an invention is deemed obvious or anticipated in the prior art by the USPTO, then it is not patentable.

KEY TERMS

Documentation	Patent	Teamwork
Gantt chart	PERT chart	Time line
Organizational chart	Project management	

PROBLEMS

3.1 Develop a simple checklist for building a fence.

3.2 Prepare a checklist of tasks required to tune a bicycle for optimum performance.

3.3 Prepare a checklist that will help guide you in the design of a child's safety seat.

3.4 Imagine that you work for a company that is designing a hybrid gas-electric car. Create an organizational chart for the company and a Gantt chart for designing the vehicle's drive train.

3.5 Choose an engineering company with which you are familiar. Develop an organizational chart for the company. Information about a company's personnel can often be found on the company's website.

3.6 Imagine that you wish to start your own company to write software tools for others developing online businesses. Create an organizational chart that outlines the positions you'll need to fill in order to get the company started.

3.7 Develop a timeline for the completion of the prototype of an automobile powered from fuel cells rather than an internal combustion engine.

3.8 Develop a timeline for completing your course requirements over the time span of 4 academic years.

3.9 Suppose that you've been given the assignment to develop a human-powered airplane. Develop a timeline for completing this ambitious assignment.

3.10 Create a Gantt chart for an entry into the national solar-powered vehicle design competition, First Solar (*www.firstsolar.com*).

3.11 Prepare a Gantt chart for the design of a retrofit fire escape for a 10-storey city building.

3.12 Prepare your own version of a Gantt chart that might have been used for the construction of the Golden Gate Bridge in San Francisco, California.

3.13 Develop a Gantt chart for housing an educational conference on engineering design. Consider all needed arrangements, including food, transportation, lodging, and meeting facilities.

3.14 Develop a Gantt chart for the design of a cell phone tower.

3.15 Consider the case of four engineers who are designing an entry into a material handling competition (see *www.mhiq.org*). Develop a Gantt chart for the design of a system based on a complete list of ideas that you develop. The vertical axis of your Gantt chart should reflect members of the design team, not specific project tasks.

3.16 Construct a "fuzzy" Gantt chart depicting the tasks required to design a software system for tracking inventory at a hardware store. Each time allocation should include an error estimate—an increment of fuzzy time—that allows for possible early or late completion of every task on the chart. Based on your fuzzy estimates, what are the longest and shortest possible time durations of the design effort? The vertical axis of your chart should indicate software developers, not individual design tasks.

3.17 Consider the fuzzy Gantt chart scenario of the previous problem. Develop one that might apply to the design of a pilotless model surveillance airplane.

3.18 Can you create a Gantt chart for the creation of the Earth? Your chart can be based on either a religious, evolutionary, or cosmological perspective, as you prefer.

3.19 Do some research into the steps required to build a two-storey commercial-grade building. Then construct a PERT chart applicable to the design and construction of a public library.

3.20 Construct a PERT chart that you imagine to be applicable to the design of the International Space Station.

3.21 Imagine that you lead a team of engineers designing a breakwater for a coastal sea port. Develop a PERT chart for the completion of this project. Consider all elements, from basic research and data analysis to final construction. Identify any critical pathways in your chart.

3.22 Consider the case of a car design competition in which the object is to be the first to drop a small beanbag (a "Hacky Sack®") into a 10-cm square hole cut into a 3-m square tabletop. Develop a PERT chart for the competition of a successful design effort. Identify any critical pathways in your chart and then adjust time allocations in the branches so that the project minimizes the former but results in a project that can be completed within one academic semester.

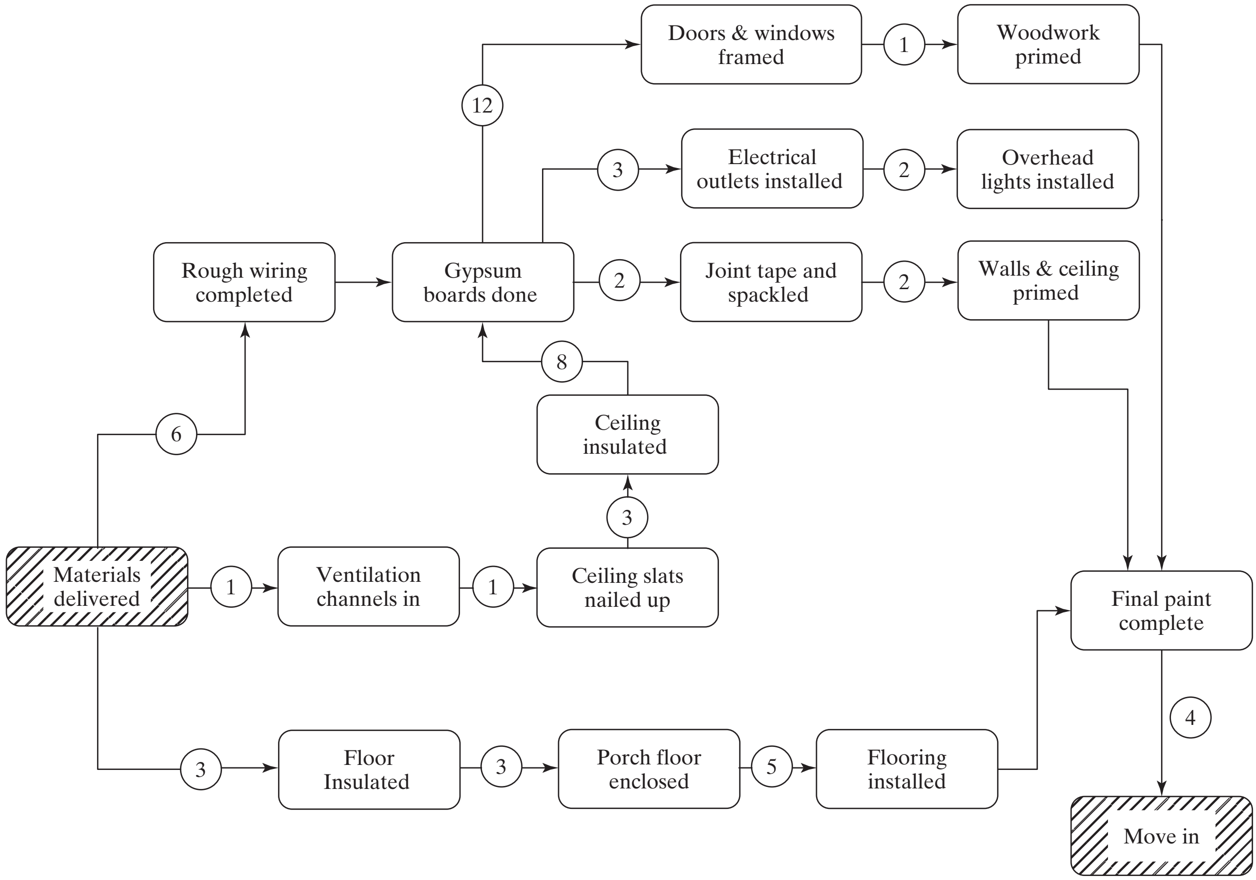


Figure 3.17
PERT chart for Problems 24–26.

3.23 Make a list of conditions under which you might choose a Gantt chart over a PERT chart for time management. Then make a similar list for the opposite case.

3.24 Examine the PERT chart of Figure 3.17. Make a list of all critical pathways as well as the location and duration of all slack time intervals.

3.25 For the PERT chart of Figure 3.17, what is the total time allocated to the completion of the entire design task?

3.26 For the PERT chart of Figure 3.17, identify all the different pathways and their total allocated path intervals.

3.27 Develop a PERT chart for the design of a tunnel linking Beijing to New York City.

3.28 Outline a PERT chart for the completion of the first self-sustaining lunar exploration base.

3.29 Develop a PERT chart for university commencement exercises.

3.30 Begin to keep a logbook of your class activities. Enter sketches and records of design assignments, inventions, and ideas.

3.31 Sketch a logbook page that describes a design concept for a recumbent bicycle.

3.32 Prepare a logbook page that describes the inner workings of a common DVD player.

3.33 Develop a logbook entry describing a machine that shells and stores peanuts.

3.34 Develop a logbook page for the design of the cooling system for an indoor ice-hockey rink.

3.35 Pretend that you are Alexander Graham Bell, the inventor of the telephone. Prepare several logbook pages that describe your invention.

3.36 Pretend that you are Marie Curie, the person who discovered the radioactive element radium. Prepare several logbook pages that describe the activities leading to your discovery.

3.37 Pretend that you are Dr. Zephram Cockrane, the inventor of plasma warp drive on the television and movie series *Star Trek*. Prepare several logbook pages that describe your invention.

3.38 Imagine that you are Elias Howe, the first inventor to perfect the sewing machine by putting the eye of the needle in its tip. This innovation made possible the bobbin system still in use in sewing machines today. Prepare several logbook pages that describe your invention and its initial tests.

3.39 Reconstruct logbook pages as they might have been written by Johan Vaaler, the Norwegian inventor of the common paperclip. (Write your entries in English).

3.40 Imagine that you are Dr. Maven, the engineer involved in the Heartthrob case of Section 3.3.8. Sketch the logbook pages that outline the basic operating concept of your transcutaneous energy transfer device.

3.41 The invention of the incandescent light bulb is largely attributed to the famous American inventor, Thomas Edison. Reconstruct the logbook pages that Edison may have kept describing his classic design efforts.

3.42 The first computerized telephone system was invented by Erna Hoover in the 1950s Her switching system used a computer to monitor incoming calls and adjust their acceptance rate by the central switching station. This process helped eliminate system overloads problems. Her U.S. Patent No. 3,623,007, entitled "Feedback Control Monitor for Stored Program Data Processing System," was one of the first software patents awarded in the United States. Look up this patent by its number at *www.uspto.gov*, then develop a logbook page that describes the kernel of Hoover's invention.

3.43 Patricia Bath, an ophthalmologist from New York, invented a method for removing cataracts. This invention transformed the art of eye surgery by using a laser to improve accuracy. Look up U.S. Patent No. 4,744,360 and reconstruct what you imagine to have been logbook pages pertinent to Bath's invention.

3.44 The cotton gin was developed by an American inventor, Eli Whitney, around 1800. This invention had a profound effect on the economic history of the early United States. Reconstruct logbook pages in which Whitney outlines the basic features and development of his invention. Note that patent law in America was in its infancy around the time that Whitney did his work on the cotton gin.

3.45 Famed actress Hedy Lamarr was also a pioneer in wireless communications. She helped develop a secret communication system to help the allies in World War II. Her system was based on manipulating radio frequencies at irregular intervals between transmission and reception. This method of transmitting formed an unbreakable code that prevented classified messages from being intercepted and decoded by hostile listeners. Develop a logbook page that describes the kernel of Lamarr's invention.

3.46 Samuel F.B. Morse, inventor of the telegraph in the 1830s and the pioneer who launched the world's first "information age," was actually an artist by profession when he developed his classic invention. During a long voyage home from study in France, he passed his time thinking about conversations he had heard concerning ongoing experiments in Europe on electricity and magnetism. He developed his ideas for the telegraph while returning to the United States. Sketch the logbook pages that Morse may have kept during his long sea voyage.

3.47 The first pocket calculator was designed by Jack Kilby, an engineer for Texas Instruments. Look up the history of this inventor, and see if you can reconstruct the probable appearance of one or more pages from his logbook.

3.48 Imagine that you are Bessie Blount, a physical therapist who worked with soldiers injured during the Second World War. In 1951, she patented a device that allowed amputees to feed themselves. The device allowed an individual sitting in a wheelchair to bite down on a tube to control the delivery of mouthfuls of food. She later invented a portable device of the same type worn around the patient's neck. Look up U.S. Patent No. 2,550,554 and develop several logbook pages pertinent to Blount's invention.

3.49 Sarah Boone patented an improved ironing board in 1892. The new board was designed to permit better ironing of sleeves and ladies' garments. Her narrow board was reversible, making it easy to iron both sides of a sleeve. Look up U.S. Patent No. 473,653 and reconstruct what may have been one of Boone's logbook pages.

3.50 Augustus Jackson was a candy confectioner from Philadelphia who created several ice cream recipes and invented an improved method of manufacturing ice cream around 1832. Look up the details of Jackson's invention and reconstruct what might have been one of his logbook pages.

3.51 Kevin Woolfolk is the listed inventor on U.S. Patent 5,649,503, entitled "Squirrel Cage Having a Cyclometer and Method for Monitoring the Activity of an Animal." In essence, this patent title describes an improved "hamster workout wheel" that records a pet's mileage or wheel revolutions. Look up U.S. Patent No. 5,649,503 and reconstruct what may have been one of Woolfolk's logbook pages.

3.52 Rachel Zimmerman is the inventor of a software program that has helped people who have difficulty communicating. While only twelve years old she created her software program using Blissymbols. The latter are symbols that enable non-speaking people, such as those having severe physical disabilities like cerebral palsy, to communicate with others. Develop a logbook page as Rachel may have kept it (even at age twelve) in which you outline the flowchart of the program.

3.53 The common automobile windshield wiper was invented by Mary Anderson around 1905. She received a patent for her window cleaning device in 1903.

Anderson conceived of her invention when she noticed that streetcar drivers had to open their car windows in order to see in the rain. To help solve this problem, she conceived of a swinging arm holding a rubber blade that could be operated by the driver from inside the streetcar via a lever. At first, the public was wary of her invention, thinking it would distract drivers, but by about fifteen years later, windshield wipers had become standard equipment on most vehicles. Imagine that you are Ms. Anderson, and sketch out logbook pages that describe your new invention.

CHAPTER 4

Engineering Tools

Objectives

In this chapter, you will:

- Learn the importance of estimation in engineering design.
- Examine the important role of the engineering prototype.
- Read about the role of reverse engineering in the design process.
- Examine the role of the computer in engineering design.
- Learn about the Internet and several software programs that are central to the engineering profession.
- Learn when and when not to use the computer.
- Discuss several examples of computer use for analysis, data collection, simulation, and computer-aided design.

You would not expect to visit a doctor's office without confronting an array of medical diagnostics, including a stethoscope, tongue depressors, blood pressure cuff, reflex hammer, and an examining table. Likewise, if you were to take a car to an auto mechanic, you would not expect that person to have an empty shop. As a professional, the mechanic would have an array of hand and power tools, wrenches, air hammers, drills, and screwdrivers. A good mechanic probably would also have on hand some common parts or even raw materials as needed to finish any repair job. Like these professionals, engineers also rely on numerous tools to aid in all facets of the design process. While some of an engineer's tools can literally be carried around in a toolkit, many fall into the category of knowledge tools. A knowledge tool is defined as a practice or methodology that the engineer has learned on the job or in school. Other tools exist in the form of software programs developed to help engineers address specific classes of problems. The purpose of this chapter is to highlight some of the more important knowledge and software tools that are found in an engineer's toolkit.

4.1 ESTIMATION

Engineering and estimation go hand in hand. When considering a new design strategy, it's a good idea to test it for feasibility by doing some rough calculations of important quantities and parameters. Simple hand calculations of a proposed strategy may eliminate gross inconsistencies before the detailed design process even begins. These calculations need not be elaborate or precise. Given today's very sophisticated calculators, students sometimes feel that answers with lots of digits imply better or more accurate answers. In many cases, however, "back of the envelope" calculations done by hand (and recorded in your engineer's logbook) are all that are required to determine the soundness of a design strategy.

EXAMPLE 4.1

Estimating Power Flow From a Battery

The following example illustrates the usefulness of estimation as a design tool. Suppose that you have been assigned the task of designing the power delivery system for a mobile (i.e., battery-powered) robot involved in automated chemical processing. One customer specification requires that the robot hook onto a bucket, then lift it and dump its contents into a receptacle located 0.5 meter above the floor. The empty bucket weight is negligible, but its contents may weigh as much as one pound (2.2 kg). Your team has decided to use separate batteries to power the drive train (the motor and gear system that moves the robot) and the lifting mechanism. In this way, neither system will be affected if the other runs low on battery power.

In an effort to conserve weight, your team would like to use the smallest battery possible. For a given battery technology—for example, alkaline, nickel-metal-hydride (NiMH), lithium, and so forth—the total energy stored in the battery is proportional to its physical volume. Hence, one important task requires that you estimate the total energy requirements associated with lifting the 2.2-kg weight to a height of 0.5 meter. The energy required for each lift, multiplied by the number of times the lifting operation must be performed, will help define the size of the battery.

Calculate the Energy Per Lift Required from the Battery

For this calculation, you must consider the maximum possible mass of the bucket. In the worst case, the bucket to be lifted will have a mass of 2.2 kg. Assuming a gravitational constant of about 10 N/kg (newtons per kilogram), the force of gravity to be overcome is easily calculated:

$$F = mg = (2.2\text{ kg})(10\text{ N/kg}) = 22\text{ N} \tag{4.1}$$

Another simple calculation will reveal the mechanical energy W, or "work" (measured in joules), required to lift the weight to a height of 0.5 meters:

$$W = Fy = (22\text{ N})(0.5\text{ m}) = 11\text{ J} \tag{4.2}$$

As this latter calculation shows, a total of 11 joules of potential energy must be imparted to the weight in order to lift it from the ground into the receptacle. Ultimately, this mechanical energy must come from the battery in electrical form. The motor's job is to convert electrical energy into mechanical energy. Thus, the total electrical energy entering the motor will have to equal the total mechanical energy transmitted to the weight plus any electrical and mechanical losses in the system. This energy-flow relationship is summarized in Figure 4.1,

$$\text{power} = \text{energy flow per unit time.}$$

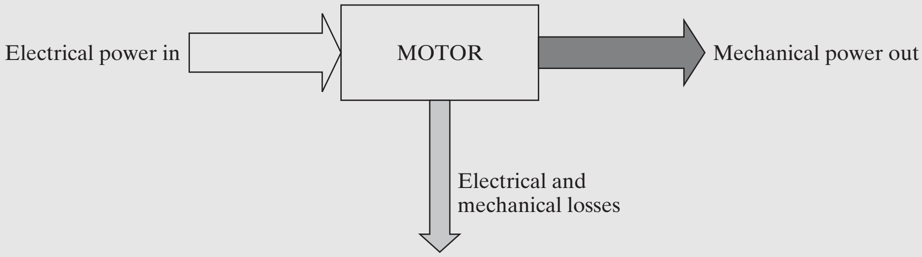


Figure 4.1
Power-flow diagram.

Estimate the Required Electrical Power

Power flow is equal to the energy flowing per unit time (measured in joules per second). For estimation purposes, let's assume that lifting the weight requires about 10 seconds. The needed power flow can then be estimated by dividing the total energy added to the weight by the appropriate time interval:

$$P = W \div \Delta T = 11\text{ J} \div 10\text{ s} = 1.1\text{ watts}. \tag{4.3}$$

This type of calculation should always be examined to make sure that the answer is reasonable. As a basis for comparison, consider a small bathroom night-light that draws about 4 watts. Your experience shows that such a lamp does not get very hot, even when it is left on all the time. Expecting the motor to draw about one quarter that amount for 10 seconds without getting excessively hot indeed seems reasonable. The answer is believable.

Estimate the Battery Current

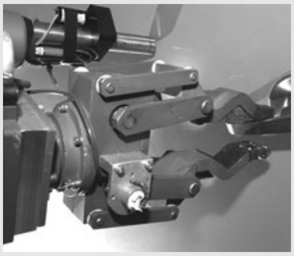
Another important parameter of the system will be the current drawn from the battery as the robot lifts the weight. By estimating the current, you can appropriately size the electrical components, such as switches and transistors, needed to control the lifting mechanism. The electrical power supplied by the battery to the motor must at *least* be equal to the mechanical power required to lift the weight, plus any losses that may occur in the motor and drive train (e.g., the gears, belts, pulleys, bearings). Neglecting these losses, you can arrive at the simple conclusion that $P_{\text{mech}} = P_{\text{elec}}$. The electrical power supplied by the battery will be equal to the battery voltage multiplied by the current drawn out of the battery:

$$P_{\text{elec}} = VI \tag{4.4}$$

Suppose that you try to operate your lifting mechanism from a standard 9-volt battery (the type used, for example, in smoke detectors.) At a power drain of 1.1 watts, the 9-volt battery will need to supply a current of

$$I = \frac{P}{V} = \frac{1.1\text{ W}}{9\text{ V}} = 0.12\text{ A} = 120\text{ mA} \tag{4.5}$$

At this point, you look up the properties of standard 9-V batteries on the Internet to determine whether 120 mA exceeds the recommended current drain for this type of battery. You find that the typical 9-V battery can supply about 100 mA of current for short periods of time (about 1 hour or less). This level of battery performance places your design specification just below the border of feasibility.



On Second Thought

After reviewing your calculations and assumptions, you realize that you've neglected all losses in the system. In reality, the conversion efficiency from electrical to mechanical power will be far from perfect. According to handbook rules of thumb, you might expect a power conversion efficiency of up to 90% from a well-designed electromechanical system, but you've decided to use inexpensive motors and parts that you can buy cheaply over the Internet. Similarly, no more than about 60% of the converted mechanical power supplied by the motor shaft will be usable because of frictional losses in the gears and drive belts, leaving only about 50% of the power taken from the battery to actually lift the 2.2-kg weight. Your robot will thus require about 240 mA, rather than 120 mA, to lift the bucket.

A single battery will simply be incapable of sustaining its 9-volt output while supplying 240 mA of current. As an alternative, suppose that you were to use two 9-volt batteries in series, for a total of 18 V. This change would reduce the current estimate computed in Equation (4.5) to 60 mA, so the actual current required, taking losses into account, will now indeed be about 120 mA. This value is again within the range of capability of each battery.

This sort of re-evaluation is common in engineering. Using two batteries doubles the net battery volume, and thus the net energy stored in the batteries. Another alternative would be to use two 1.5-V type-D batteries (the kind used in flashlights) connected in series. In this latter case, your current estimate would change to the value

$$I = P/V = 1.1\text{ W}/3\text{ V} \approx 370\text{ mA} \tag{4.6}$$

While this current is almost three times the value calculated for a single 9-volt battery (the voltage is only one-third as large, and the *V-I* product must remain the same), it is well within the capabilities of type-D batteries. A standard alkaline version of the latter can sustain currents up to about 500 mA (0.5 A) with little degradation in voltage. That's because its volume, which, for a given battery type, determines the amount of energy it contains, is far greater that that of a 9-volt battery.

Professional Success: Be Willing to Modify Your Conclusions When Necessary

Despite the time and effort that go into making design choices, a good engineer knows when it's time to admit an oversight and change a basic design decision. Engineering history is replete with in cases where a design had to be abandoned because it did not work. One example of this principle can be found in a light rail vehicle (streetcar) developed for a major city. The engineers thought they could design a door that maximized room inside the streetcar by having all its parts located outside the car. Their door design consisted of a single, large (and heavy) piece that slid along the side of the car on tracks (much like the side door of a minivan). The doors jammed frequently, often requiring the operator to get out of the car to push them closed by hand. After some effort, the engineers abandoned the design entirely, going instead with the standard dual-bifurcated doors that had been on the predecessor cars.

EXAMPLE 4.2

Estimating the Volume of Paint Needed to Coat a Large Object

This example from the world of automobile manufacturing illustrates the usefulness of estimation as an engineering design tool. Imagine that you work for a company that makes automobiles. The head of manufacturing thinks that the company could save a lot of money by changing from liquid paint to an electrostatically applied dry powder coating. To produce the finished coat, the latter is baked after it's been applied. So that the materials cost savings can be weighed against the capital equipment cost of new coating equipment, as well as the added energy cost of the baking process, the head of manufacturing has asked you to estimate the total amount of paint required. The steps involved in such an estimate are outlined in the following discussion.

Draw a Rough Sketch of the Surfaces to Be Painted

As a first step, draw a rough hand sketch of the car body. One such sketch that depicts the various car surfaces is shown in Figure 4.2. The largest areas to be painted include the hood, trunk, roof, and two side fenders. The quantity of paint required to cover the window frames is negligible.

Estimate the Area of Each Section

Next, estimate the area of each section of the car. For this purpose, the actual sections of the vehicle are represented by very basic shapes such as those in Figure 4.3. The hood, for example, is essentially a $1.2\ \mathrm{m} \times 1.2\ \mathrm{m}$ rectangle, for an area of about $1.4\ \mathrm{m}^2$. Note that the result of the multiplication is specifically *not* written as $1.44\ \mathrm{m}^2$, which would be the exact product of the two dimensions. Because our

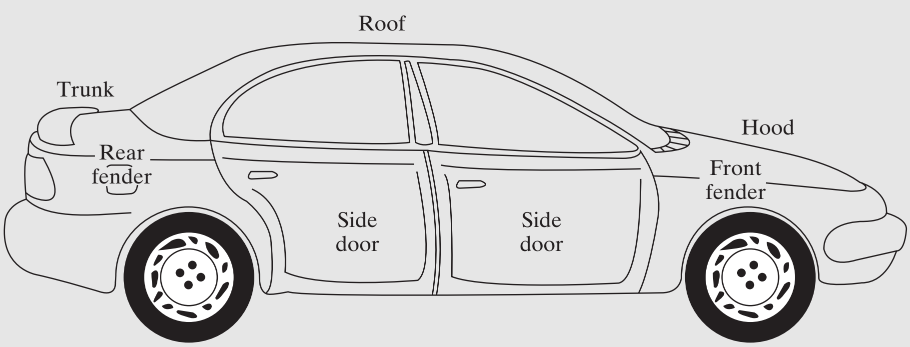


Figure 4.2
Rough sketch of car body.

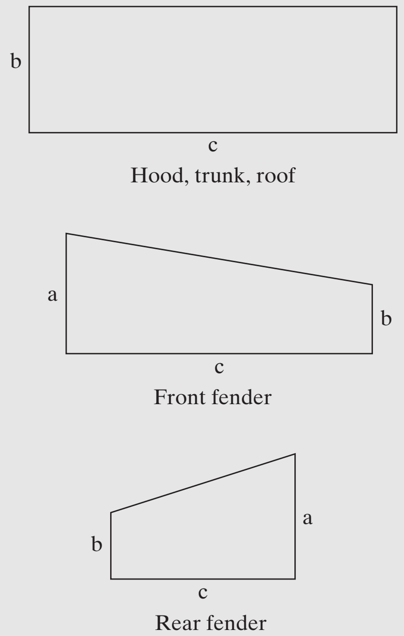


Figure 4.3 Estimated shape of side fenders.

estimate is only *approximate*, there is no point in writing down extra digits after the decimal point, because they would imply a precision that is not justified.

The trunk is also nearly rectangular, measuring about 1.2×1.5 m, for an additional 1.8 m^2. The doors measure about 1 m long by 0.8 m tall, or 0.8 m^2 each. The dimensions of the roof are about 1.4 m long by 1.2 m wide, for a total of 1.7 m^2.

For estimation purposes, each of the fenders can be modeled as trapezoids. The window areas not be counted, because they are not painted. The area of each fender can thus be calculated from the area formula for a trapezoid:

$$A = \frac{a + b}{2} c \tag{4.7}$$

where a and b are the parallel sides and c is the height.

Reasonable numbers for each front fender might be $a \approx 0.8$ m, $b \approx 0.4$ m, and $c \approx 1.5$ m for an area of 0.9 m^2. Similarly, rear fender estimates of $a \approx 0.8$ m, $b \approx 0.4$ m, and $c \approx 1$ m yield 0.6 m^2. The following table provides a summary of the estimated values:

Hood	1.4 m^2
Trunk	1.8 m^2
Doors (four)	3.2 m^2
Roof	1.7 m^2
Front fenders (two)	1.8 m^2
Rear fenders (two)	1.2 m^2
Total	11 m^2

The result is equal to about 11 square meters. Note again that each value is computed to a few digits only, because it's only an estimate.

Multiply by the Thickness of the Paint

Next, we can estimate the needed volume of by multiplying the surface area by the paint thickness.[1] A average paint coat is typically about 4 mils. For this thickness, the volume of paint required to coat the car can easily be calculated:

$$\begin{aligned} \text{volume} &= \text{area} \times \text{thickness} = 11\ \text{m}^2 \times 4\ \text{mils} \times 25 \times 10^{-6}\ \text{m/mil} \\ &= 0.001\ \text{m}^3 \end{aligned} \tag{4.9}$$

or about 1 liter.

[1] The latter usually is measured in mils (1 mil ≡ 0.001 inch ≈ 0.025 mm = 25×10^{-6} m)

Practice!

1. Determine the power required of the battery in Example 4.1 if the bucket must be lifted in 25 seconds instead of 10. Will the total energy requirement change?
2. Determine the power required of the battery in the first estimate of Example 4.1 if a set of four 1.5-V AAA cells is used instead of a single 9-V battery.
3. How much mechanical power can be derived from a 6-V electric motor that is 85% efficient if its maximum allowed current is 1 A?
4. How much internal heat in watts will be generated by an electric motor that is 60% efficient if it provides 20 W of mechanical power to an external load?
5. Estimate the amount of paint required to cover a single wooden pencil.
6. Estimate the physical length of a 90-minute audio cassette tape.
7. Estimate the number of platforms needed to build a scaffolding shell that encircles the Statue of Liberty.
8. Estimate the volume of water contained within the supply pipes of a one-storey single family house. How much energy is required to heat this water from 20°C (room temperature) to 80°C (shower temperature)? What is the significance of this energy quantity?
9. Estimate the number of staples in the loading clip of a standard office stapler.
10. How many gallons of paint should you buy to paint the exterior of a garage that measures 20 ft × 30 ft × 10 ft tall?
11. Estimate the volume of paint required to cover a Boeing 747.
12. Estimate the volume of ink required to print an 8.5 × 11 inch paper document in Arial 10-point font, single-spaced type, with 1-inch margins. How many such pages do you think you could print from a typical inkjet cartridge?

13. Estimate the cost of the energy consumed by a porch light left on for 24 hours.
14. Look up the daily per capita consumption of take-out coffee by the national population, then estimate the total weight of paper needed to make the required coffee cups. For this exercise, assume all cups to be paper; ignore plastic.
15. Estimate the track thickness of a 2-hour long DVD.
16. Estimate the number of fiber tufts in a square yard of carpeting.
17. Estimate the number of hand contacts endured by a basketball during a single NBA game.
18. Estimate the time required for a bowling ball to fall to the bottom of an ocean that is 2 km deep.
19. Estimate the total writing distance capability of a common ball-point pen.
20. Estimate the total writing distance capability of a typical felt-tip marker.
21. Estimate the number of plastic bags used per year in the nation's supermarkets.
22. Estimate the gas volume lost to evaporation during car refueling. Make this calculation for stations that do not have a nozzle vapor recovery system.
23. Estimate the number of alkaline batteries discarded each year.
24. Estimate the number of apples eaten each year by the national population
25. Estimate the number of times that a one-dollar bill changes hands each month.
26. Estimate the total number of traffic lights in all the intersections in the country.
27. Estimate the number of keystrokes that your fingers make during a typical day in your life. Divide this calculation into those made on a computer keyboard versus those made on a cell phone or PDA.
28. Estimate the number of plastic bags used each day in produce sections of the nation's supermarkets.
29. Estimate the volume of oil contained in all the oil tankers that are at sea at any given moment.
30. Estimate the volume of asphalt needed to pave a mile of four-lane highway.

4.2 WORKING WITH NUMBERS

4.2.1 International System of Units (SI)

While much of the corporate manufacturing base in the United States still uses the English system of units (feet, pounds, etc.) the predominant unit system throughout the world (including England!) is the metric International System of units. Originally used only in the sciences, the set of "SI" units (from the French *Le Système*

International d'Unités) has become the predominant measurement language in worldwide commerce and trade. The SI units and their associated usage rules were established in 1960 by the European 11th General Conference on Weights and Measures.

Under the SI system, length is measured in *meters*, mass in *kilograms*, and time in *seconds*. Other fundamental SI units include the *ampere* (electric current), *Kelvin* (temperature), *mole* (quantity of atoms or molecules), and *candela* (intensity of light). Other quantities, such as area, volume, velocity, pressure, and density, are described in terms of these seven fundamental SI units. A complete description of the SI system and its rules can be found on the website of the U.S. National Institute of Standards and Technology at *physics.nist.gov/cuu*.

The SI system embodies a convention with regard to symbols, punctuation, and capitalization. Every SI unit has a standard abbreviation; some of the more commonly used abbreviations appear in Table 4.1. Unit abbreviations are always printed in lower case *unless* the unit is derived from the name of a person (e.g., Pascal, Watt, Hertz, Becquerel). In this latter case, the first letter of the unit's abbreviation is capitalized (e.g. Pa, W, Hz, Bq). However, when the unit is spelled out as a complete word, it appears entirely in lower case, even if it's derived from the name of a person (e.g., pascal, watt, hertz). An SI unit abbreviation is never followed by a period except when it appears at the end of a sentence.

Table 4.1 Abbreviations for Some Common SI Units[1]

Unit	Abbreviation	Quantity	Person honored by the unit
meter	m	length	
kilogram	kg	mass	
second	s	time	
activity (of a radionuclide)	Bq	becquerel	Henri Becquerel (1852 –1908)
ampere	A	current	Andre-Marie Ampere (1775–1836)
curie	C	radioactivity	Marie Curie (1867–1934)
degrees celsius	°C	temperature	Anders Celsius (1701–1744)
Farad	F	Capacitance	Michael Faraday (1791–1867)
hertz	Hz	frequency	Heinrich Hertz (1857–1894)
joule	J	energy	James Joule (1818–1889)
kelvin	K	absolute temperature	William Thomson, 1st Baron Kelvin (1824–1907)
lumen	lm	light intensity	
neper[2]	Np	natural log ratio	John Napier (1550 – 1617)
newton	N	force	Sir Isaac Newton (1642–1727)
ohm	Ω	resistance	Georg Ohm (1789–1854)
pascal	Pa	pressure	Blaise Pascal (1623–1662)
volt	V	voltage	Alessandro Volta (1745–1827)
watt	W	power	James Watt (1736–1819)

[1]The abbreviation of a unit named after a person begins with a capital letter. The word for such a unit always appears in lower case.
[2]Not a genuine SI unit, but often included in the list

Table 4.2 Power-of-Ten Prefixes for the International System of Units

Factor	10^{12}	10^{9}	10^{6}	10^{3}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}
Name	tera	giga	mega	kilo	centi	milli	micro	nano	pico
Prefix	T	G	M	k	c	m	μ	n	p

When a quantity is much smaller or larger than its corresponding SI unit, it can be expressed using one of the power-of-ten prefixes shown in Table 4.2. The prefixes above 10^3 are capitalized. (This table lists the prefixes most often used by engineers; prefixes spanning the entire range from 10^{24} to 10^{-24} exist within the SI system.) Note that the kilogram is the only fundamental SI unit that contains its own prefix. When describing very large or small masses, a power-of-ten prefix is not used with kg. Rather, the mass is converted to grams and then preceded by a prefix. For example, 10^{-6} kg is expressed as 1 mg (one milligram), not 1 μkg (one microkilogram).

4.2.2 Reconciling Units

When working with equations, one good way to check the results of a calculation is to make sure that the result has the proper units. If it does not, then an error in calculation has probably been made. This test is sometimes called *unit reconciliation*. The check is easily performed, provided that numbers which have been written are accompanied by their individual SI units. For example, suppose that we wish to compute the volume of a cylindrical tank given by the formula $V = \pi r^2 h$. If, for example, $r = 20$ cm and $h = 40$ cm, then the calculation would result in the following:

$$\text{volume} = \pi(0.2\text{ m})^2(0.4\text{ m}) = 0.05\text{ m}^3 \tag{4.10}$$

The right-hand side of Equation (4.10) yields m $\times$ m $\times$ m, or cubic meters, which we know to be the SI unit for volume. The units properly match on both sides of the equation.

Similarly, suppose that we wish to compute the distance that an object has fallen within a fixed amount of time. The vertical distance traveled by an object under the force of gravity is given by the formula $y = -\frac{1}{2}gt^2 + v_o t$, where $g = 9.8\text{ m/s}^2$ is the gravitational constant, v_{oy} is the initial vertical velocity in meters per second, and t is the time in seconds. Applying this formula to a projectile shot from a cannon for the case $v_o = 20$ m/s and $t = 4$ s yields a total distance of

$$\begin{aligned} y &= -\frac{1}{2}(9.8\text{ m/s}^2)(4\text{ s})^2 + (20\text{ m/s})(4\text{ s}) \\ &= -78.4\text{ m} + 80\text{ m} = 1.6\text{ m} \end{aligned} \tag{4.11}$$

Each of the computations on the left-hand side of the equation yields a net unit of length. The first term m/s^2 $\times$ s^2 equals meters, while the second term m/s $\times$ s also equals meters. Hence the units in Equation (4.11) match over both sides of the formula. The units are properly reconciled.

4.2.3 Significant Figures

When a number is used in any engineering context, you should be concerned with the number of significant figures that it contains. A significant figure is any nonzero digit, or any zero other than a leading zero. A number cannot be interpreted as being any more precise than its least significant digit, nor should a quantity be specified with any more digits than are justifiable by its measured precision.

The numbers 128.1, 0.50, and 5.4, for example, imply quantities that have known precisions of ± 0.1, ± 0.01, and ± 0.1, respectively. The first is specified to four significant figures, while the second and third are specified to only two. Note that if *trailing* zeros are placed on the right side of the decimal point, they carry the weight of significant figures. Thus, the number 0.50 means 0.5 ± 0.01.

1st significant figure

3rd significant figure

0.0254

2nd significant figure

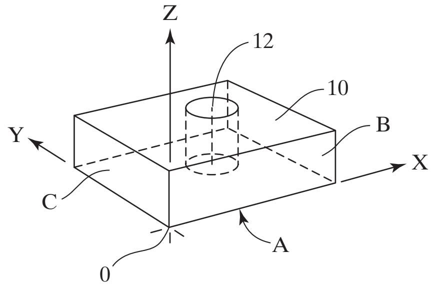
The precision of any calculation will be determined by the least precise number entering into the computation. For example, the product and quotient $127 \times 0.50 \div 5.3$ entered into a calculator produces the digits 11.98113. But because 0.50 and 5.3 are specified to only two significant figures, the rounded-off result of the multiplication should be recorded as 12, also with only two significant figures. Note that a digit is rounded up if the digit to its right is 5 or more. If the digit to its right is less than 5, the digit is rounded down.

Professional Success: The Right Way to Use Your Calculator

The typical calculator allows for 8 or more significant figures in its calculations. The appearance of digits on a calculator display does *not* mean that those digits are significant. As an engineer, you must be mindful of the number of significant figures to which you are entitled in any given calculation, and summarily discard the extra digits produced by your calculator. Remember that the extra digits *have no meaning* if they do not represent significant figures. Develop the habit of trimming extraneous, trailing digits. Providing answers with the proper number of digits will demonstrate that you are a professional who understands the importance of significant figures.

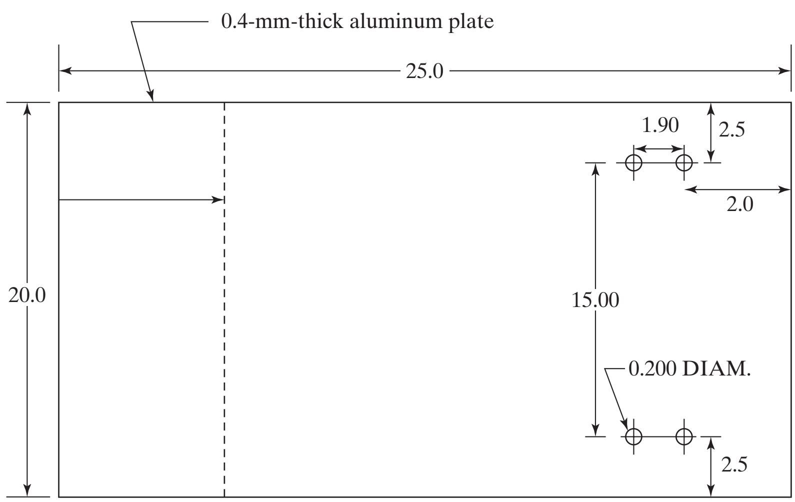
4.2.4 Dimensioning and Tolerance

When numbers find their way into technical drawings, the number of significant figures takes on a special meaning. No physical part can ever be fabricated to exact dimensions, because machine tools do not cut perfectly. A cutting tool, for example, wanders about its intended position during the machining process. Changes in temperature, humidity, or vibration during the cutting process can also cause the tool to follow a less-than-perfect path. Other fabrication methods, such as casting and injection molding, introduce similar uncertainties in a part's dimensions. The tolerance of each dimension shown in a drawing specifies the degree of error that will be acceptable for the finished part. As a rule, creating parts with tight tolerances involves the use of more expensive machining equipment and more time, because material cuts or fabrication steps must proceed more slowly. These features add considerable expense to the finished part. As the designer, you must decide which dimensions are truly critical and worthy of the extra cost.



Suppose that you wish to make the support plate shown in Figure 4.4. The plate, to be made from 0.4-mm–thick aluminum, contains several holes to which brackets are to be secured. This fabrication job is a bit complicated for simple hand tools, so you've decided to have a professional machinist make it. The job requires specialized machining tools, including a milling machine, drill press, and a reamer to make holes of an accurate diameter. One issue that you might think about concerns the precision with which the part would need to be built. For a rough prototype, you might be content with an approximate version of the plate that can be produced quickly. For the finished product, however, you might want the machinist to take the extra time to adhere more closely to the specified dimensions. One way that

Figure 4.4
Support plate with dimensions and tolerance table.



Main chassis plate

Tolerance table	
All dimensions in cm	
X	±0.5
X.X	±0.1
X.XX	±0.05
X.XXX	±0.001

engineers and machinists communicate on issues of this nature is through the numerical notations on parts drawings.

Carefully note the labeled dimensions shown in Figure 4.4. These numbers communicate to the machinist the acceptable deviation, or *tolerance*, for each of the plate's various dimensions. The numbers on the drawing have meaning for any machinist who reads the tolerance table. For this particular machining job, the numbers reveal that only the hole diameters, which are specified with the most significant figures, are especially critical dimensions. The length of the support plate, for example, is 25 cm. The numbers 25.0, 25.00, and 25.000, though all mathematically equivalent, would mean different things to the machinist. According to the tolerance table, the number 25.0, with one digit after the decimal point, should be interpreted by the machinist to mean 25 $\pm$ 0.1 cm. A support plate with a finished width diameter anywhere between 24.9 and 25.1 cm would be deemed acceptable. Similarly, the holes are specified as lying 15.00 cm apart, implying a machined tolerance of 15 $\pm$ 0.05 cm. The minimum and maximum tolerance limits for the hole centers as machined would be between 14.95 cm and 15.05 cm.

The tolerance table in Figure 4.4 indicates the most stringent dimensions to be those of the hole diameters. The holes in this particular part are intended to hold pins inserted by friction fit, hence their diameters are specified to three decimal points, implying a strict machining tolerance of 0.200 $\pm$ 0.001 cm.

Practice!

1. Refer to the tolerance table shown in Figure 4.4. Compute the difference between the maximum and minimum permissible physical values for dimensions specified by the following numbers: 21.0 cm, 8.75 cm, 10 cm, 2.375 cm, and 0.003 cm.
2. Write down the result of the following computation, using only the number of significant figures to which you are entitled: $(45 + 8.2) \times 91.0 \div 12.1$.
3. What is the value of the sum $3.00 + 54.0 + 174 + 250$?
4. What is the sum of the integers $3 + 54 + 174 + 250$? How does the issue of significant figures manifest itself in this case?
5. Using the tolerance table in Figure 4.4, write down the following dimensions specified to $\pm$1 mm: 5.1 cm, 954 cm, 573 cm, and 15 mm.
6. If all dimensions on a part are specified to be within $\pm$1 mil ($\pm$0.001 inch), what is the minimum possible angle between the sides of a 1-inch square?
7. The 5-cm sides of a nominally equilateral triangle are specified to have a tolerance of $\pm$0.2 cm. What are the tolerance limits in degrees for any given angle?
8. The sides of a 3 cm $\times$ 4 cm $\times$ 5 cm triangle are specified to have tolerances of $\pm$1 mm.
   a. If the sides are perfect, what are the values of the triangle's three angles?
   b. What are the $\pm$ tolerance limits in degrees of each of these angles?
9. To what tolerance can you measure objects using a common tape measure of the type found in most hardware stores?

10. Suppose that you are building a 10 ft $\times$ 10 ft wooden frame in which you will pour a 3-in thick concrete foundation for an outdoor patio. You wish to locate a hole in the geometrical center for the placement of a birdfeeder pole. You plan to locate the exact center by stretching strings across the corners of the box, so as to make an X. By how much will the hole be off center if the cross strings differ in length by 0.5 inch?
11. The typical four-function calculator allows for 8 significant figures in its calculations. Think of at least three applications in which such precision is either required or is justified. (One might be computing your income taxes if you are very wealthy.)
12. Compute the percent error if $\sin\theta$ is approximated by θ over the range $-4° < \theta < +4°$.

4.3 TYPES OF GRAPHS

Most engineering students are familiar with the x–y graphs used in algebra and calculus. Graphs depicted in x–y format can convey all sorts of information in compact form. The plot of Figure 4.5(a), for example, shows the stretching, or *strain*, of a sample of structural steel as a function of the loading force, or *stress*, applied to it. Similarly, Figure 4.5(b) depicts the percentage of central processor usage of a computation facility as a function of the time of day. These figures are both examples of simple x–y plots having linear scales. By definition, a linear scale has equidistant "tick" marks.

There are times when simple x–y graphs cannot do an adequate job of depicting numerical information. For these situations, engineers resort to other types of graphs, including *semilog* plots, *log-log* plots, *polar* plots, *three-dimensional* plots, and *histograms*. We provide brief descriptions of each of these types of graphs in the following sections.

4.3.1 Semilog Plots

A semilog plot (short for semi-logarithmic) is used if one range of numbers extends over several orders of magnitude. An example can be found in biotechnology. Specifically, the growth of cells in a nutrient medium obeys an equation of the approximate form

$$n = n_o e^{at/T} \tag{4.12}$$

Figure 4.5
Examples of x-y plots having simple linear scales.

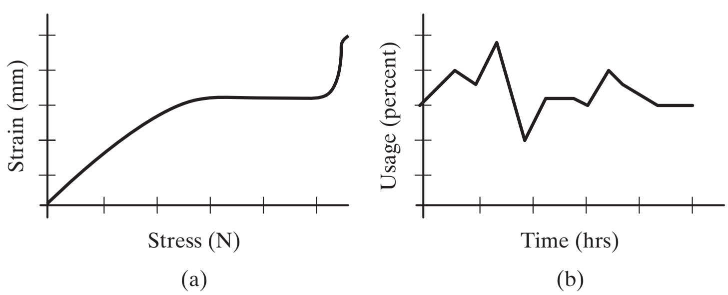


Table 4.3 Cell Density versus Time

Time (hours)	Cell Density (per cm^3)	Log of Cell Density
0	1.00 E+00	0.00
1	3.32 E+00	0.52
2	1.10 E+01	1.04
3	3.66 E+01	1.56
4	1.22 E+02	2.08
5	4.03 E+02	2.61
6	1.34 E+03	3.13
7	4.45 E+03	3.65
8	1.48 E+04	4.17
9	4.90 E+04	4.69
10	1.63 E+05	5.21
11	5.40 E+05	5.73
12	1.79 E+06	6.25
13	5.96 E+06	6.77
14	1.98 E+07	7.30
15	6.57 E+07	7.82
16	2.18 E+08	8.34
17	7.24 E+08	8.86
18	2.40 E+09	9.38
19	7.98 E+09	9.90
20	2.65 E+10	10.42
21	8.79 E+10	10.94
22	2.92 E+11	11.47
23	9.69 E+11	11.99
24	3.22 E+12	12.51

Here, t is time in hours, n is the population density of the cells in units of cm^{-3}, n_o is the density at $t = 0$, a is a growth constant, and T is a characteristic time constant measured in hours. Suppose that you wish to plot the growth in cell density, starting with a single cell, over a time period of 24 hours for the case $a = 1.2$, $n_o = 1/cm^3$, and $T = 1$ hour. Table 4.3 provides the values of t and n obtained from Equation (4.12).

A simple x-y plot of the first two columns from the table is shown in Figure 4.6. As you can see, the exponential dependency of the equation causes the cell density to rise steeply with time. Only for times greater than about 20 hours can one read any meaningful data from the graph. From the table, we see that the data range over twelve orders of magnitude. Thus, although the x–y plot depicts the exponential nature of the cell growth, it is difficult for the user to obtain useful quantitative information over the full range of data represented.

For comparison, the same equation is plotted in Figure 4.7, but the vertical axis represent the base-10 logarithm of the cell density. In other words, the cell density is represented on a logarithmic scale. Each interval on the vertical axis (e.g., each "tick" mark) represents a factor of 10 increase in cell density. The complete range of

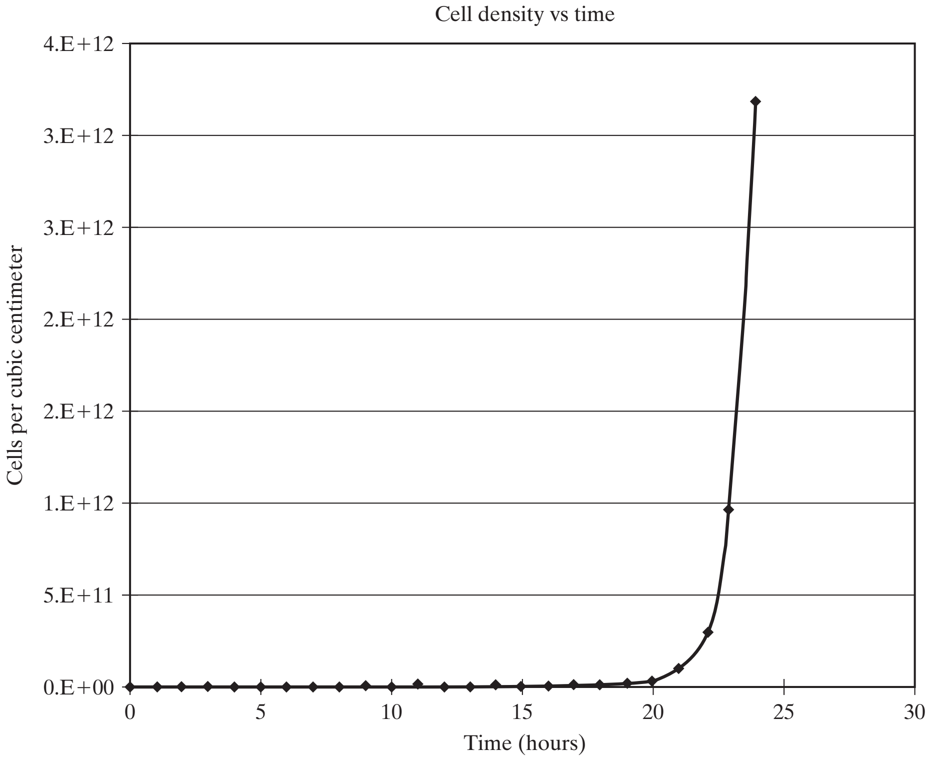


Figure 4.6
Plot of cell density versus time. Both axes of the graph are linear.

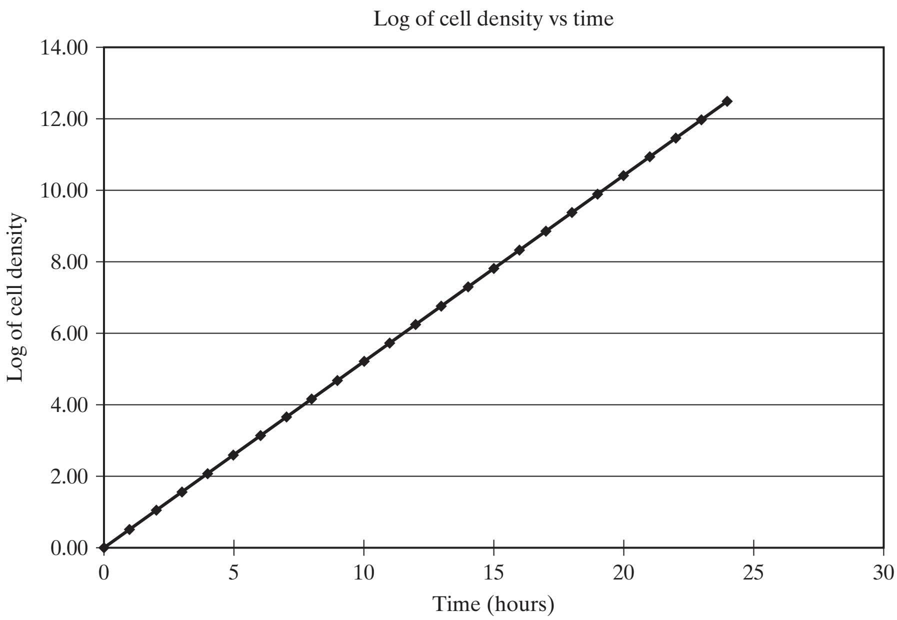
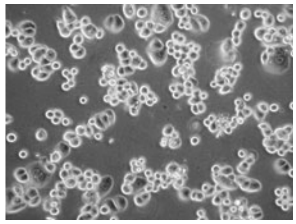


Figure 4.7
Data points of Table 4.3 plotted on a semilog graph. Because the cell density increases exponentially with time, using a logarithmic vertical axis allows more points to be included in the range of the graph.

density values from Table 4.3 can now be plotted, and the graph allows the user to determine the cell density for any value of time over the 24-hour period.

The vertical scale is called "logarithmic" because the measured span of the axis in physical units (centimeters, for example) will be equal to the logarithm of the number being represented. The plot is called "semilogarithmic" because only one of the axes is represented on a log scale, and the other is represented by a simple linear scale. Note that a logarithmic scale is a relative scale in which the current value must be normalized to a reference value. In the case of Figure 4.7, the reference value is $1/\text{cm}^3$, and the scale is represented as a base-10 logarithm. Hence, when the actual cell density is $1/\text{cm}^3$, its logarithmic value becomes zero. Similarly, when $n = 10/\text{cm}^3$, its log value is 1.0; when $n = 100/\text{cm}^3$, its log value is 10.

A semilog plot can also be used when the data to be represented on the horizontal axis extends over many orders of magnitude. One example might be the need to depict the velocity of a high-speed aircraft as a function of engine thrust. Because aerodynamic drag increases as the cube of the velocity, more and more engine power is required to achieve higher speeds, so a plot of the velocity versus the log of the thrust might be appropriate.



4.3.2 Log–Log Plots

Sometimes engineers wish to convey data in which both variables extend over many orders of magnitude. In such a case, the *log-log* plot becomes a useful tool. In a log-log plot, both horizontal and vertical axes are represented using logarithmic scales. Log-log plots are often used to represent the physical response of something versus the frequency of the stimulating variable. (The term "frequency" in this case refers to the number of times a periodic stimulus acts per second.) The graph of Figure 4.8, for example, shows the vibration magnitude of a car's suspension system, measured in centimeters, as a function of the frequency of a sinusoidal force applied to the undercarriage. For this plot, it is understood that the peak magnitude of the applied sinusoidal force is always equal to the same number of newtons regardless of its excitation frequency. The designer might use such a log-log plot to graph a wide range of vibration magnitudes versus a similarly large range of applied frequencies.

4.3.3 Polar Plots

Sometimes an engineer needs to represent the measured value of a quantity as a function of angle. Examples might include the sensitivity of a directional antenna, the hearing capability of the human ear, or the intensity of a light source. In such cases, the *polar* plot becomes a valuable engineering tool. The coordinate variables

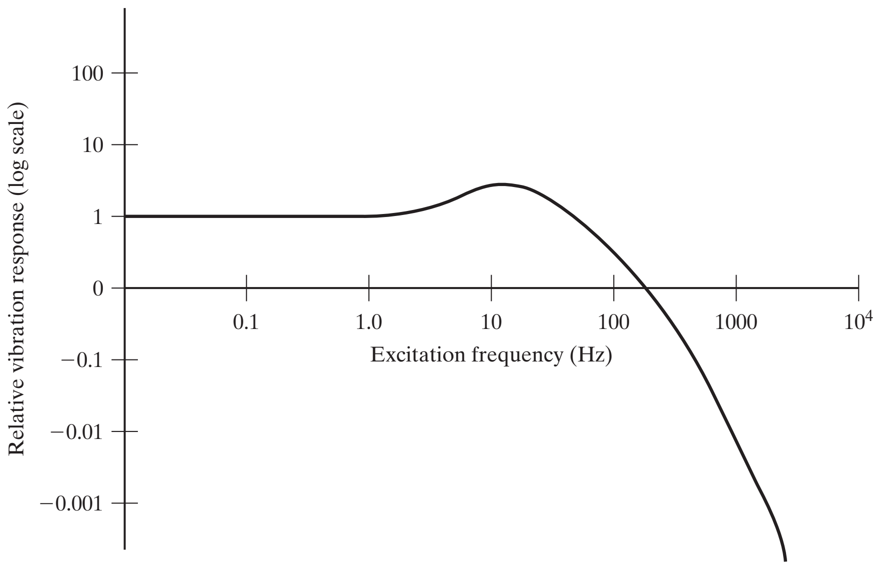


Figure 4.8
Response of a car suspension system to a constant magnitude stimulus of varying frequency. In this case, both scales are best represented logarithmically.

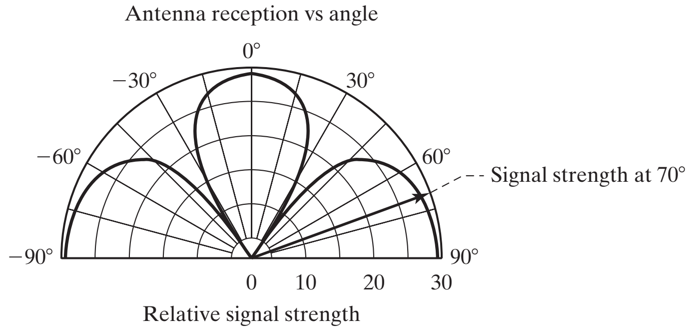


Figure 4.9
Polar plot of antenna pattern. The length of the vector from the origin represents the strength of the reception at a given angle θ.

of a polar plot are the radial value r and the angle θ, rather than the usual variables x and y. In a polar plot, the radial distance from the center represents the plotted value for a given angle.

One example of a polar plot is shown in Figure 4.9. This graph shows the sensitivity of a receiving antenna to radio waves arriving from different angles. The incoming radio waves are assumed have constant magnitude regardless of angle. The signal from the antenna will be fed to a receiving circuit that will convert the coded radio waves into sound or digital data. The maximum sensitivity angles for this antenna (longest values of radial distance r) occur at 0°, −90°, and +90°. Conversely, two *nulls*, or angles of zero reception, occur at about −37° and +37°. At these latter angles, the radial distance from the origin to the plot wither to zero.

Sometimes the range of data to be represented on the r-axis extends over several orders of magnitude. In such cases, a log-radial plot may be used to adequately depict the data. In a log-radial plot, the linear distance from the center to a point on the graph represents the logarithm of the data value. An example of a log-radial plot is shown in Figure 4.10. This graph represents the response of a "popcorn"

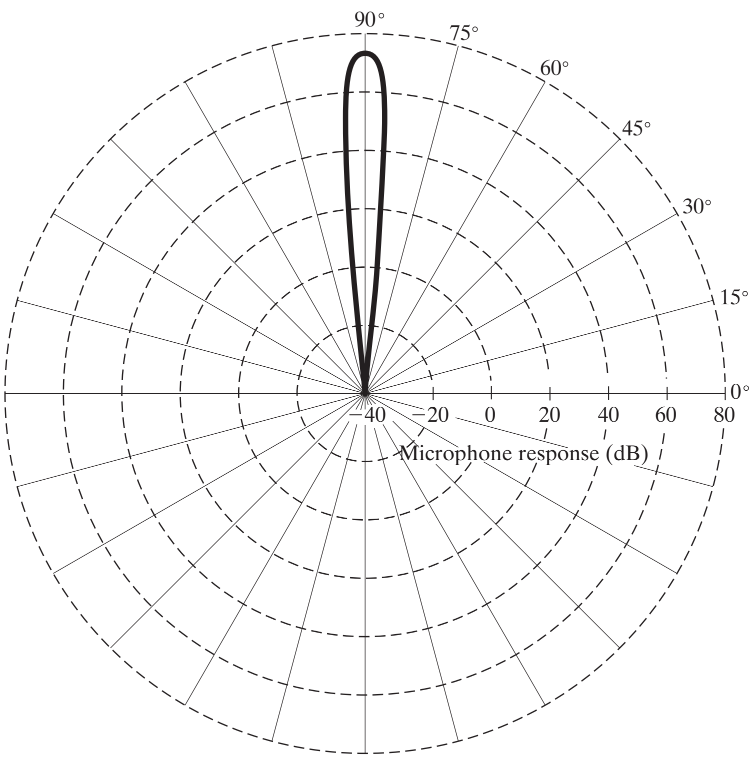


Figure 4.10
Response of a highly directional "popcorn" microphone is best plotted on a polar plot in which the radial scale is logarithmic. In this case, the decibel (dB) scale has been chosen. An increase in 20 dB is equivalent to multiplication by 10.

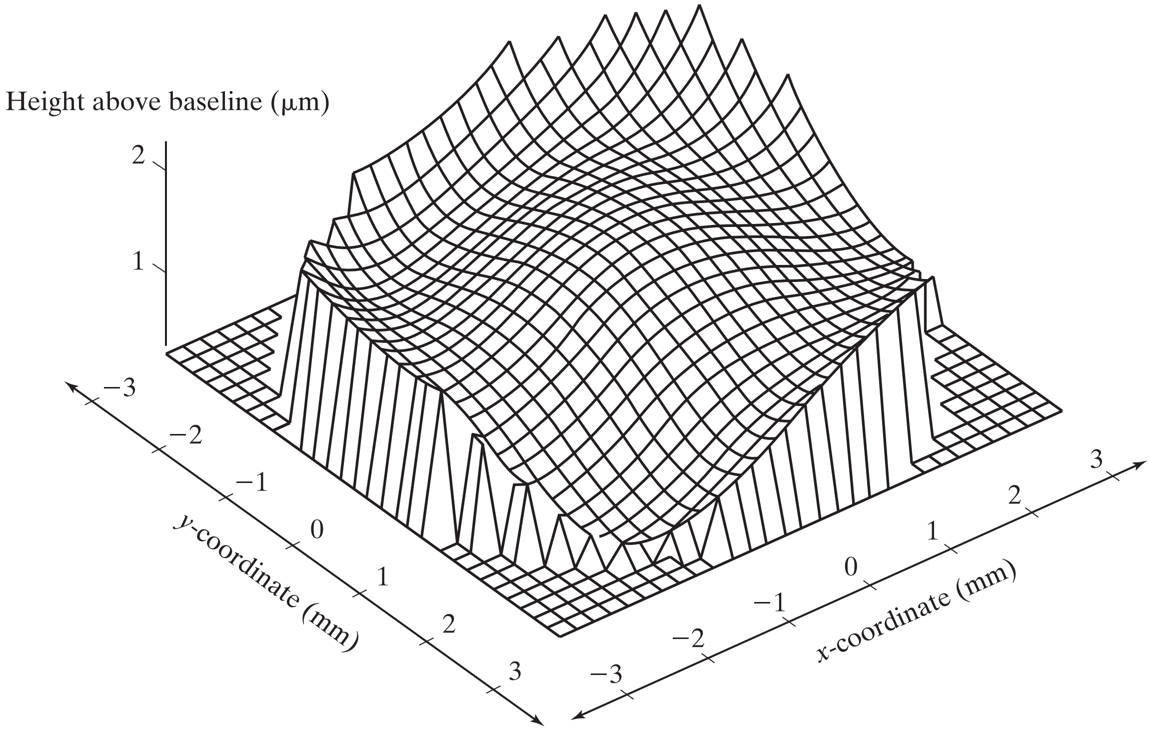


Figure 4.11
Isometric plot of the height of a semiconductor surface as a function of position *x*-*y* over the plane.

(highly directional) type of microphone as a function of angle. The radial coordinate in this case is the *decibel* (dB), defined by the formula

$$\mathrm{dB} = 20 \log_{10} M \tag{4.13}$$

where M is the microphone output normalized to the output level that would be produced by a fixed reference sound pressure.

4.3.4 Three-Dimensional Graphs

Sometimes a two-dimensional graph cannot adequately represent engineering data. When a given output variable is a function of *two* input variables, a three-dimensional (x-y-z) plot may be used. Unfortunately, paper and computer screens are two-dimensional, hence special techniques are required to plot functions of two variables. In many cases, an *isometric* plot of the type shown in Figure 4.11 can be a good choice. This graph represents the surface depth of a semiconductor sample as a function of x and y coordinates. The thickness of the sample, measured relative to a defined zero, or "flat" level, is represented by the height of the mountain-like contour above the x-y ground plane. The plot of Figure 4.11 was obtained using an interferometric optical scanner; the vertical units are in micrometers, or "microns."

If the z variable varies significantly as a function of the x and y coordinates, sometimes a flat *contour* plot is a better choice. In a contour plot, loci of constant z value are represented by lines (sometimes called *isobars*), and the steepness of the plot is inversely proportional to the distance between adjacent isobars. The closer

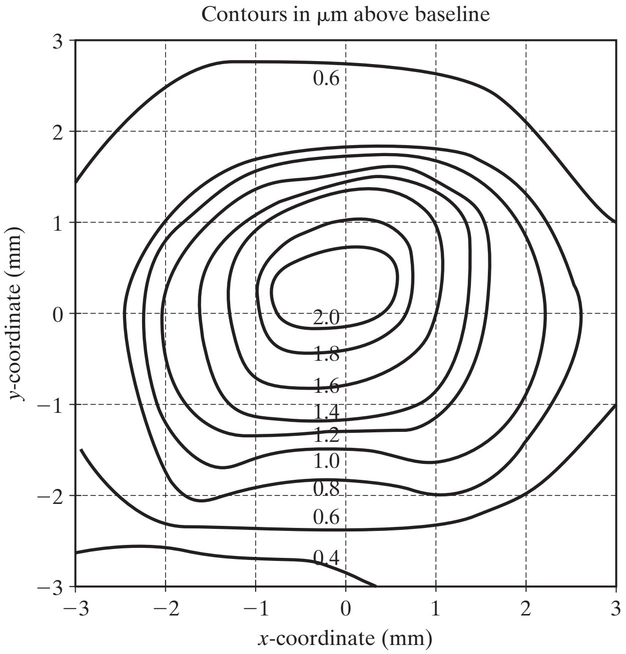


Figure 4.12
Example of a contour plot. The isobans indicate the surface profile of a silicon chip.

together the isobars, the steeper the slope. Figure 4.12 shows an example of a contour plot. One common use of contour plots may be found in cartography, where the height of land over the area of a map is represented by lines of constant altitude.

Practice!

1. Plot the area of a circle as a function of radius over the range $0 < r < 1$ m. Which is more appropriate, a linear *x-y* plot or a semilog plot?
2. Plot the function $y = \sqrt[3]{x + 12}$ on both linear and semilog axes. For the latter case, should the logarithmic axis be horizontal or vertical?
3. Plot the function $y = 4x^3 + 6.2x + 12$ on both linear and semilog axes. For the latter case, should the logarithmic axis be horizontal or vertical?
4. Suppose that you wish to plot the population of the fifty U.S. states as a function of alphabetical order. What type of graph might you use?
5. The current through an electronic component known as a "diode" depends on the applied voltage according to the equation

$$i = I_o e^{v/V_T} \tag{4.14}$$

Plot this equation for the values $I_o = 10^{-12}$ amperes and $V_T = 25$ millivolt.

6. Under certain conditions, the frequency response of the human ear can be represented by the equation

$$H = \frac{f/f_0}{1 + (f/f_0)^2} \tag{4.15}$$

where f is the frequency in hertz, or "cycles per second,"and f_0 is a reference frequency. Plot this equation over the range 1 Hz $< f <$ 100 kHz for the case $f_0 = 15$ kHz. Which type of graph should you choose?

7. The Fibonacci sequence of integers is defined by the following rules: The first number of the sequence is 0, the second number is 1, and each subsequent number is equal to the sum of the previous two numbers of the sequence itself, yielding the sequence 0, 1, 1, 2, 3, 5, 8 . . . . Plot the first 50 values of the series as a function of their ordinal numbers. Which type of graph is most appropriate?

8. Imagine that you are centered in Omaha, Nebraska. Plot the populations of the following cities as a function of compass angle:

Brownsville	Des Moines	Olympia
Butte	Detroit	Orlando
Chicago	Mesa	Providence
Cleveland	Minneapolis	San Diego
Dayton	Mobile	San Francisco

9. Many physical phenomena are covered by the equation $x = N_o(1 - e^{-t/T})$ This equation is sometimes called a "rising exponential," even though the exponent has a negative argument. Plot this equation for the case $N_o = 100$ and $T = 5$. What type of graph is most appropriate?

10. Look up wind data from Buoy No. 44011 at the National Buoy Data Center (*www.nbdc.noaa.gov*). What type of plot would be appropriate to plot the time history of wind over a one-week period?

11. The power output of a cell phone antenna can be expressed as

$$P = 2P_o \sin^2(2\pi \cos \theta)$$

where P_o is the power output that would exist if the antenna output were not a function of angle. Make a polar plot of P as a function of θ.

12. Make a plot of the diameter of each of the planets in the solar system as a function of their respective radii from the sun.

13. Use the appropriate semilog plot to graph the equation $y = K(1 - e^{-x/x_o})$ where $K = 12.2$ and $x_o = 0.01$.

14. Plot the per capita consumption of oil as a function of national population. You can find these data by doing an appropriate Web search.

15. Plot the per capita consumption of salt as a function of country. You can find these data by doing an appropriate Web search.
16. Plot the number of people of a particular height versus height values for the national population. You can find these data by doing an appropriate Web search.

4.4 PROTOTYPING

Designing anything for the first time requires careful planning. From the brainstorming phase through the subsequent iterations around the design cycle, foresight is always more valuable than hindsight. In the earlier phases of a project, an engineer often relies on estimation, sketching, approximation, and other preliminary tools to test ideas for feasibility. Later phases may involve computer simulations, if appropriate. At some point in the design cycle, however, it will be time to construct a first working prototype. A prototype is a mock-up of the finished product that embodies all its salient features but omits nonessential elements, such as a refined appearance or features not critical to fundamental operation. Prototypes are used in nearly every engineering industry. Figure 4.13, for example, shows the prototype mock-up of one of two Mars Rover vehicles that landed successfully on January 4, 2004 (Spirit) and January 25, 2004 (Opportunity). The Rover prototype is on permanent display in the Smithsonian National Air and Space Museum in Washington, DC.

The prototype of a product can take many forms. If the product is electronic, its prototype is often built on a temporary breadboard. A breadboard allows an engineer to wire together the various electrical devices, such as resistors, capacitors, transistors, and integrated circuits, to make working circuits. A breadboard readily permits changes and alterations to a circuit—a feature essential to the testing and retesting inherent to the design cycle. An example of a well laid-out electronic breadboard is shown in Figure 4.14.

Producing a mechanical product likewise requires the use of easy-to-modify prototypes. The latter may be fabricated from easily machined materials to produce a version that will enable testing and evaluation but may not be as durable or

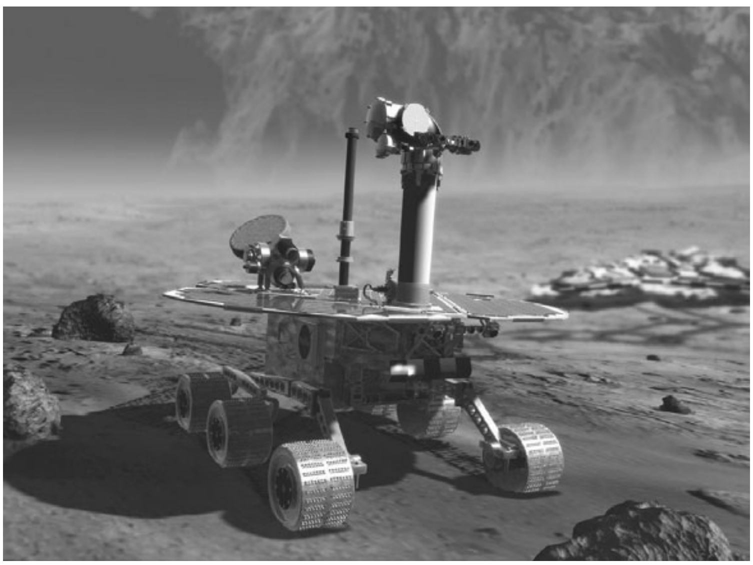


Figure 4.13 Prototype of the Mars Pathfinder Rover developed by NASA. (*Image Courtesy of NASA.*)

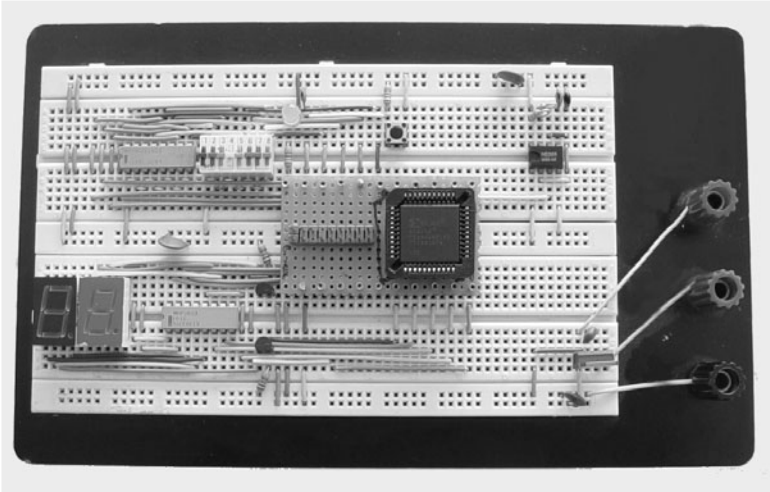


Figure 4.14
A well laid-out circuit on an electronic breadboard.

Figure 4.15
Temporary structure made from bars with holes, plywood, and metal screening.

visually attractive as the finished product. A robotic arm, while ultimately destined for fabrication from stainless steel, might be made in prototype form from wood and aluminum for initial tests of part compatibility and overall performance. Wood and aluminum are easily drilled and formed, and they are readily available, but they are much less durable than stainless steel or titanium for demanding applications. Mechanical prototypes also can be fabricated from various forms of bars, straps, angle iron, and similar construction materials. An example of mechanical prototyping is shown in Figure 4.15. The bars used for this prototype have holes in numerous places to allow for rapid construction and adaptation in revision stages of the design cycle. This feature allows a nearly unlimited combination of locations for the placement of the mechanical components of the apparatus.

Another example of physical prototyping can be found in the ball-and-socket human hip replacement joint shown in Figure 4.16. During development, this device might be fabricated from aluminum and polyethylene—again both easily machined materials—for testing its range of motion or for developing the tooling needed to mass produce the device. The finished product ready for implantation would be made from surgical-grade titanium and high-strength polymers at ten times the cost.

Engineers and architects who design large structures, such as buildings, bridges, and dams, face a handicap not encountered by other engineers. It's simply not practical

Figure 4.16
Ball-and-socket human hip joint replacement. The finished product is made from expensive titanium. During development, initial prototypes might be made from aluminum or stainless steel.

to build a full-size prototype of these structures for testing purposes. It would be cost prohibitive, for example, to test the frame of a tall building, perhaps in some remote desert location, to determine its maximum sustainable wind speed before collapse. Engineers who build large structures rely on scale modeling to guide them through the prototyping phase. Scale modeling uses dimensional similarity to extrapolate to full scale the observations made on a model of reduced size. Effects such as structural stability, wind loading, and large-scale motion are readily scaled, tested, then extrapolated to the full-sized structure. Wind tunnels are widely used to test scale models for aerodynamic effects. Vibration, combustion, and wave phenomena do not scale well because these effects are governed by physical parameters that are fixed regardless of size scale. (That's one reason why movie scenes filmed using scale models of ships at sea or burning buildings often look unrealistic.)

Software modules also undergo a prototype phase. The typical software kernel (the part of a software program that does the actual thinking) is surrounded by a graphical user interface (GUI) that provides access to the user. A software designer will sometimes write and test the kernel portions of a program long before writing the graphical user interface.

EXAMPLE 4.3

Electrical Prototyping

As discussed in the previous section, the prototype phase helps engineers reveal design flaws and problems that may have escaped the initial planning and estimation phases. The following scenario illustrates the importance of careful prototyping

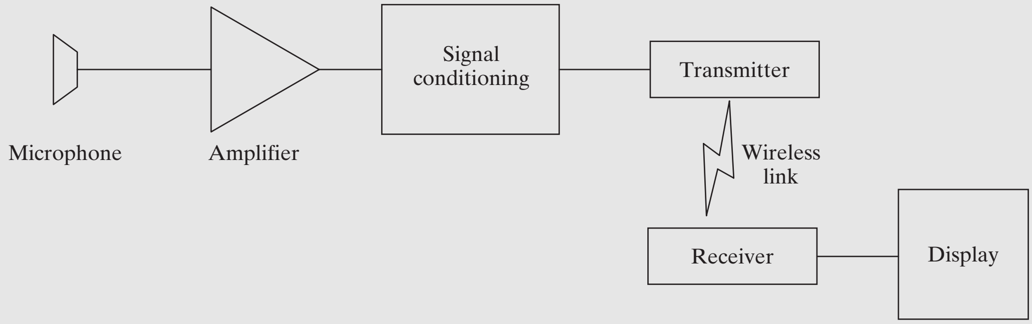


Figure 4.17
Block diagram of a heart monitor that transmits data about a runner to a trackside base station.

in engineering design. In this scenario, three students, Tina, Tim, and Tally, test the prototype of a heart rate monitor that they have been designing for a multidisciplinary project course. The goal is to design a device that can measure a runner's heart rate and then transfer the data over a wireless interface to the track coach. The device will also be useful as a medical diagnostic tool for monitoring ambulatory heart patients. Tina, an electrical engineering major, has been primarily responsible for the heart-monitoring sensor. Tim, a mechanical engineer, has designed the case and the harness that will hold the sensor over the runner's heart. Tally, a computer engineer, must design the microprocessor system to measure the heart rate and design the wireless link that will transmit the data to a trackside base station. A sketch of their overall system is shown in Figure 4.17.

The students are currently testing the microphone sensor that will be worn by the jogger. They plan to perfect this particular section, including Tina's circuitry and Tim's harness, before adding Tally's timing circuit, wireless link, and base station. Tina's portion of the system consists of a microphone, amplifier, and signal conditioning circuit. The microphone and amplifier re-create the human heartbeat as an analog signal, while the conditioning circuit transforms each heartbeat signature into a single digital pulse that can be fed to Tally's measuring system. Tina has built her monitoring circuit on a temporary breadboard that sits on a nearby table. In the prototype's final version, the circuit will be hardwired on a compact printed board and placed in Tim's soft plastic case to be worn by the jogger.

Using Tim's harness, the students have mounted a microphone onto Tally, who has volunteered to be the jogger. Tally stands in place while Tina looks at the output of her amplifier on an oscilloscope. The signal looks like the trace shown in Figure 4.18. The students recognize the waveform as the standard signature of a human heartbeat. Tina connects the oscilloscope to the output of the signal conditioning circuit. The pulses produced by the latter have the form shown in Figure 4.19. By measuring the number of horizontal graticule divisions between these pulses and noting the time-per-division setting of the "scope," the students estimate Tally's heart rate to be about 60 beats per minute.

Next, Tina asks Tally to jog in place. The pulses appearing on the oscilloscope now appear as in Figure 4.20. The pulses are no longer evenly spaced, suggesting that Tally's heart rate has become dangerously erratic. Tally feels fine, of course, and when asked to stop jogging, the pulses return to their evenly spaced, regular timing pattern. The students wisely rule out any health problems that might cause an

Figure 4.18
Output of the amplifier section in Figure 4.17. The waveform resembles the sound signature of the human heartbeat.

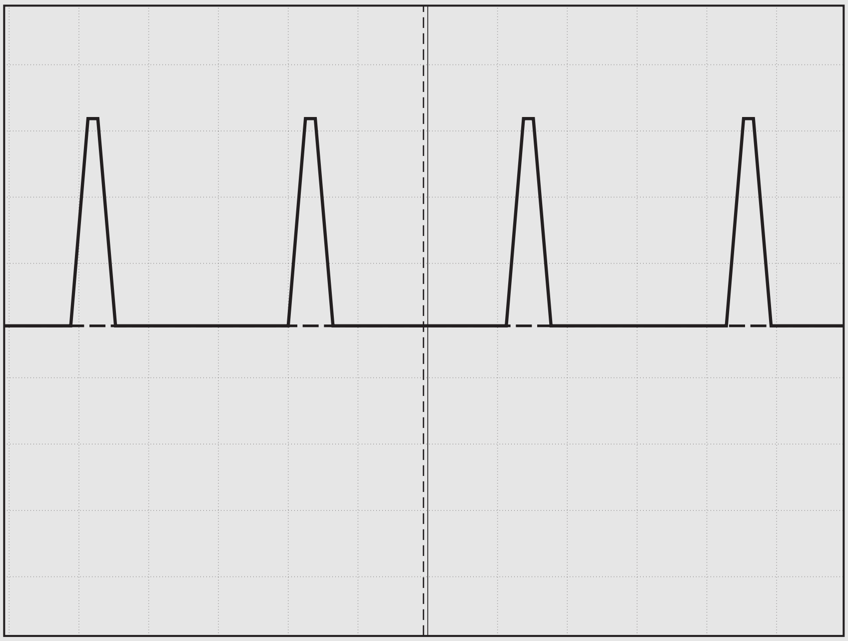


Figure 4.19
Output of the signal conditioning circuit of Figure 4.17 in response to the signal shown in Figure 4.18. The number of pulses per minute is determined by the heart rate.

erratic heartbeat. *What could possibly be wrong*? Tina asks herself. She asks Tally to resume jogging in place, and the same thing happens: the pulse train becomes erratic and unevenly spaced.

After some brief thought, the students suspect a bad microphone connection that manifests itself when Tally begins to jog. They manipulate the microphone wire by jiggling it back and forth but observe no change in the pulse pattern. Tally begins to jog in place again, and the pulses again become erratic.

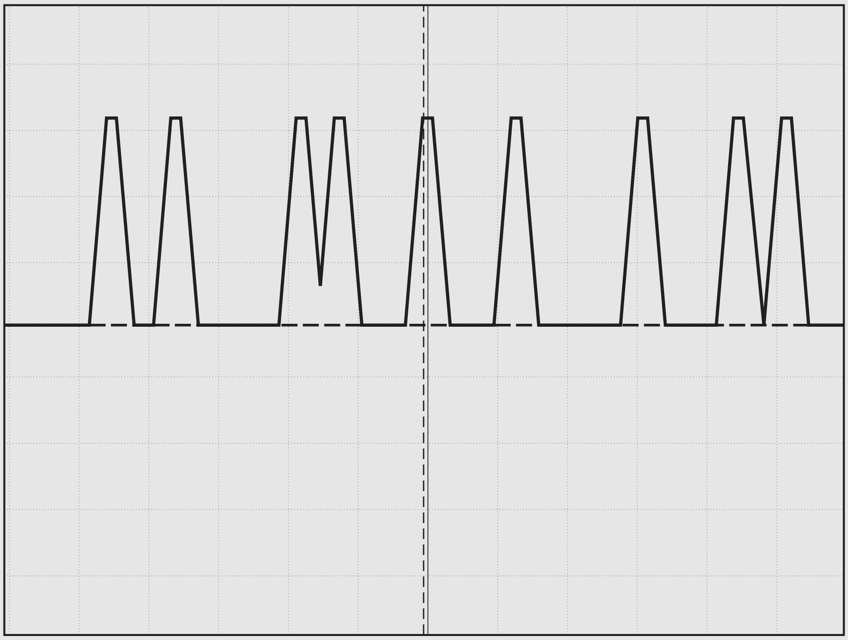


Figure 4.20
Output of the signal conditioning circuit with runner jogging in place. The signal appears erratic, a sign that something is wrong with the system.

Figure 4.21
Amplified microphone signal with runner jogging in place. The students discover that the additional portions of the trace correspond to the sound of the runner's feet hitting the floor.

Tim examines the output of the prototype amplifier at the point where it feeds into Tina's signal conditioning circuit. With Tally at rest, the microphone signal appears normal, as in Figure 4.18, and the conditioned signal takes the form shown in Figure 4.19.

"Jog with an irregular step," suggests Tom. "I want to check something." Tally begins a "hip-hop" jog, and the trace takes the form of Figure 4.21.

"I see what you're after," says Tina. "It looks like our microphone is also picking up the sound of Tally's feet hitting the floor." Mystery solved.

"Can you alter your amplifier circuit somehow?" asks Tally.

Tina replies, "The problem, I think, can be solved by redesigning Tim's microphone harness. Adding some soft padding where it contacts Tally's chest and encasing it in sound-deadening foam might help." The students agree to try this inexpensive solution before embarking on a circuit redesign.

They find some packing foam in the lab and cut it up to test their idea. Adding the foam greatly reduces the unwanted signals on the oscilloscope. They will have to work on perfecting this solution via some design iterations, but they seem to have solved this particular problem.

Professional Success: Where to Find Prototyping Materials

The materials needed to create prototypes can be found in many places. For building mechanical structures, your local hardware store is a great start. A well-stocked hardware store sells all sorts of nuts, bolts, rods, dowels, fasteners, springs, hinges, and brackets. Many common electrical parts, such as wires, terminal connectors, tape, sockets, and switches, can also be found at the local hardware store. A home center—a large hardware store, lumber yard, plumbing supply, electrical supply, and garden shop all rolled into one—is an excellent source of structural prototyping materials such as plywood, strapping, angle iron, pipe, and brackets. (See, for example, *www.homedepot.com*.) A selection of very basic electronic parts and breadboards can be found at local consumer stores such as Radio Shack™. More complete selections with lower prices can be found on the Internet. Examples include *www.digikey.com*, *www.jameco.com*, *www.mpja.com*, and *www.newark.com*.

4.5 REVERSE ENGINEERING

Reverse engineering refers to the process by which an engineer dissects someone else's product to learn how it works. This design tool is particularly useful if the goal is to create your own version of a competitor's product using your own technology. Reverse engineering is practiced on a regular basis by companies worldwide. Although it may appear to be an unfair practice, it can be a good way to avoid patent infringement and other legal problems by specifically avoiding an approach taken by a competitor. Reverse engineering one of your own company's products can be a good way to understand its operation if its documentation trail has been lost or is inadequate.

One obvious way to reverse engineer a product is to take it apart. Completely disassembling a device will reveal the details of its components and how they interact to allow the device to function properly. Figure 4.22, for example, shows the disassembled parts of a satellite-based infrared detector module. The dotted lines indicate how the various pieces of the module are to be assembled.

Reverse engineering in the software realm is encouraged when writing web pages on the Internet. All of the major Web browsers provide a means to view and

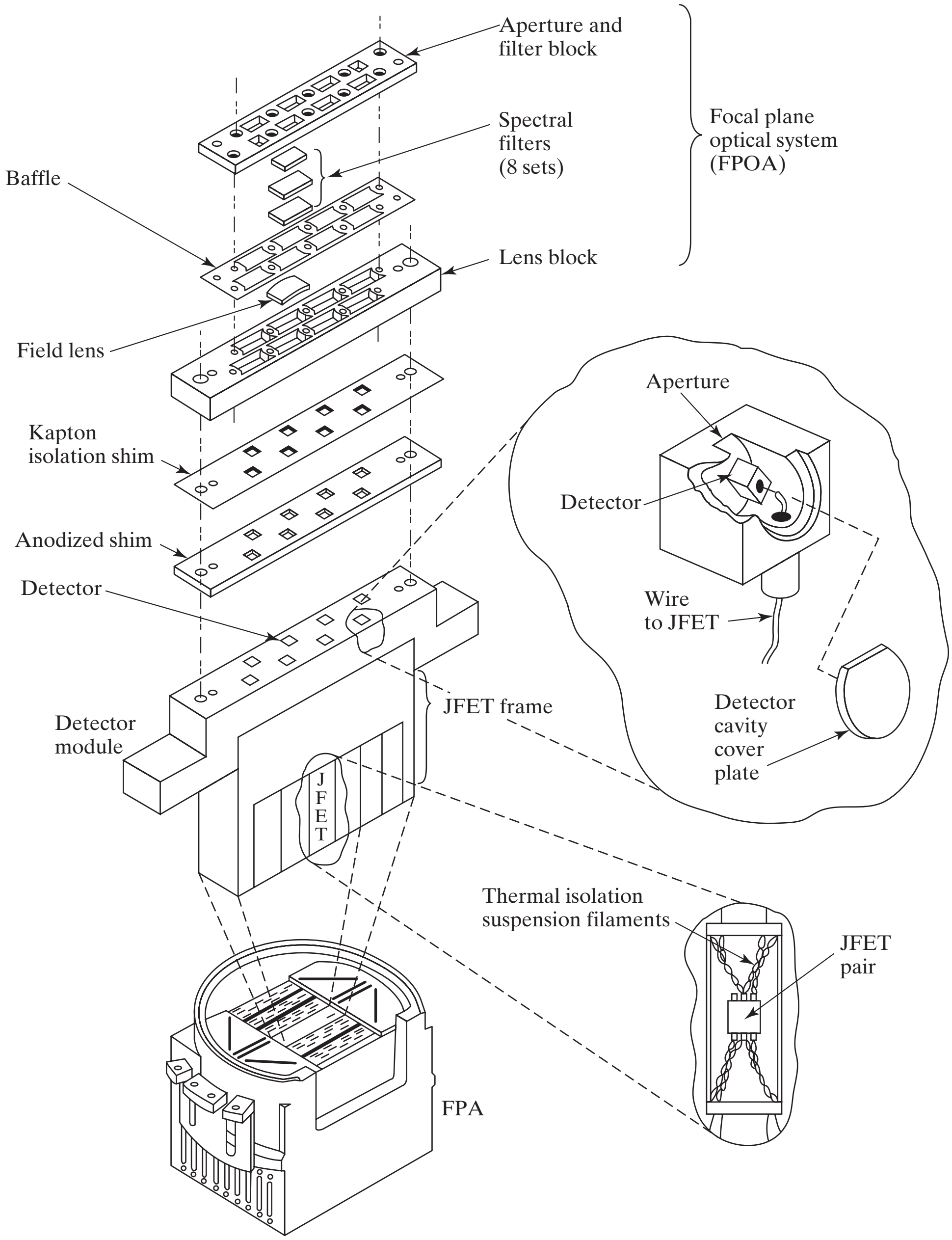


Figure 4.22
Exploded assembly view of a satellite-based infrared detector module. (*Image courtesy of NASA.*)

decipher the hypertext mark-up language (HTML) code, the instructions used to encode the web page that has been downloaded into the computer. This practice fosters an environment of open information exchange that has been the hallmark of the Internet since its inception. In contrast, software that has been written in a high-level programming language such as C, C++, Java, MATLAB, Mathematica, MathCAD, or Fortran, can be especially difficult to reverse engineer, particularly if the software has been poorly documented. A multitude of flow paths and logical junctions in software programs can lead to confusion on the part of the reader and make it hard to understand how a program operates.

4.6 COMPUTER ANALYSIS

When engineers design something for the first time, they often build simplified prototypes to test the basic operating principles of the device. In many cases, simple hand calculations are all that are needed as a prelude to building a working prototype. At other times, however, more complex calculations are required to verify the feasibility of a design concept. Computers can be an important part of this verification process. Simulation is one major task that computers perform extremely well, and numerous software programs exist that help engineers simulate everything from bridges to electronic circuits. Examples of popular simulation programs include PSpice (electrical and electronic circuits), Pro-Engineer™ and Solidworks™ (solid modeling), Simulink™ (engineering system analysis), and FEMLAB™ (structural and field analysis). General mathematical programs, such as MATLAB™, Mathcad™, and Mathematica™ are also extremely useful in the analysis of engineering problems. In the following example, a simulation is used to aid the design of a kinetic sculpture. The analysis steps are illustrated using the MATLAB programming language. Although this specific software environment has been chosen for the example, the methodology illustrated is universal and could be used with any computer language or software program capable of performing numerical calculations.

EXAMPLE 4.4

Calculating the Trajectory of a Moving Object

This example describes the calculations used to design a kinetic sculpture of the type found in science museums and airports. An example of such a machine is shown in Figure 4.23. A feeder loads balls into a ball elevator which sets them loose down one of several pathways determined by the travel history of previous balls. Along their way to the bottom of the machine, individual balls ring bells, flip levers, clip-clop down staircases, and perform numerous sorts of acrobatics. One common component of a kinetic sculpture is a downward sloping track that has an upward lip at the bottom. A ball released from the top will accelerate down the track, enter an adjustable launch tube, then be launched upward toward some distant target point. As suggested by the drawing of Figure 4.24, designing a track and launching tube so that the ball precisely hits its target requires some analysis based on Newtonian physics.

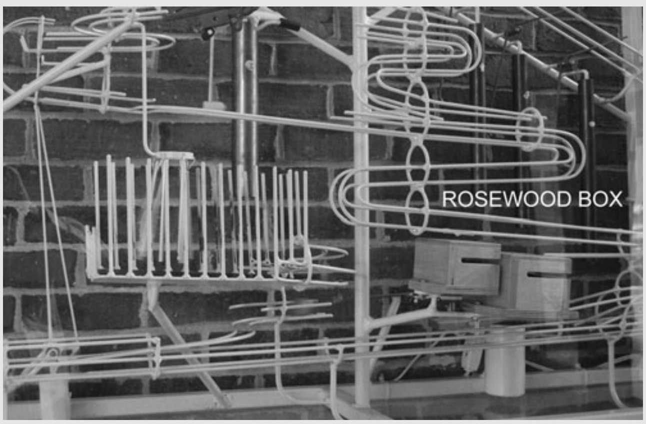


Figure 4.23
A kinetic sculpture. The ball falls on the rosewood box, making a percussive noise.

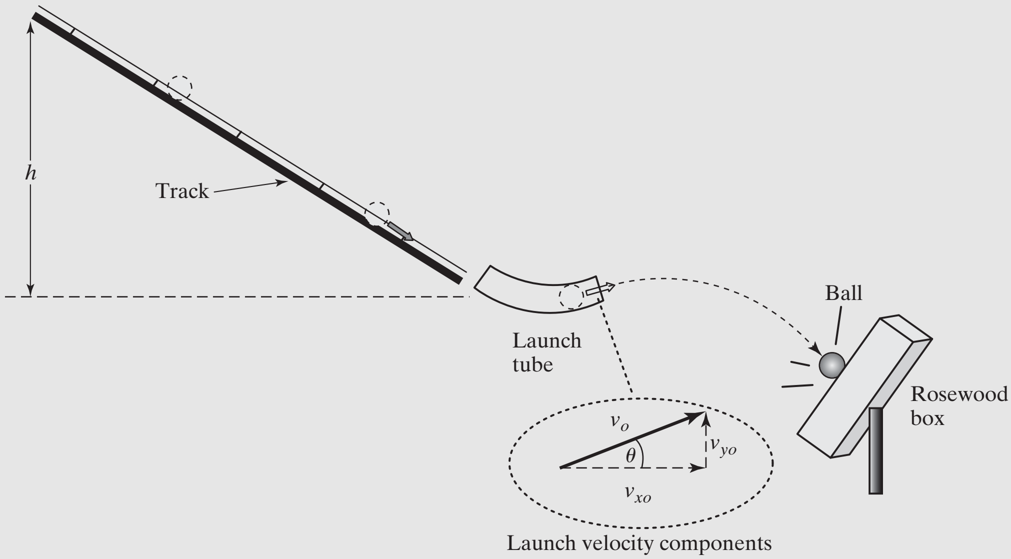


Figure 4.24
Designing a track and launching tube so that a ball precisely hits its target requires some analysis.

The typical kinetic sculpture may have several such ball launching tracks. The following example explores the calculations needed to ensure that every ball launched from one particular track will hit a wooden "rosewood box" (a type of wooden musical instrument that makes a hollow sound when struck). The distance between the end of the launch track and its target is one of the parameters set by the designer of the sculpture. After choosing a position for the rosewood box, the designer must then determine the correct track angle, track length, and launch angle so that the ball hits its target. The chosen track parameters must then be tested on a track prototype before the finished sculpture is built.

The test system, shown in Figure 4.25, consists of a launching track of fixed length, a flexible launch tube section at the end, and a holding bracket that allows

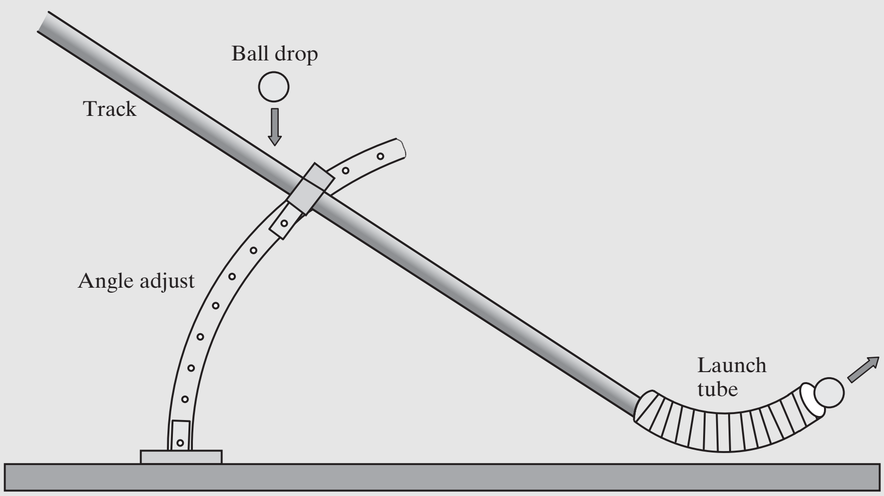


Figure 4.25
Launch track of fixed length and a flexible tube section at the end. A holding bracket allows the incline of the track to be set to various angles.

the incline of the track to be set to various angles. Various track lengths are simulated by simply changing the release point of the ball.

For one particular section of the sculpture, the rosewood box is to be positioned 40 cm beyond, and 20 cm above, the end of a launch tube. The ball has a diameter of 5 cm and weight of 135 gm. If aerodynamic forces are negligible, the ball, once released, will be acted upon only by gravity and will follow a parabolic trajectory. The choices of track length, angle of inclination, and launch tube angle thus become part of the overall design.

A computer can easily solve for the ball's trajectory. Assuming that the track will impart an initial velocity v_o to the ball, the ball's equation of motion after release will be determined by Newton's law of motion:

$$\mathbf{F} = m\mathbf{a} \tag{4.16}$$

Here, **F** is the total force acting on the ball, and **a** is the ball's acceleration. To the extent that aerodynamic forces can be ignored, **F** is due solely to gravity and acts in the y-direction only.

The x- and y-components of Newton's law can be integrated using calculus, yielding

$$x = x_o + v_{xo}t \tag{4.17}$$

and

$$y = y_o + v_{yo}t - \frac{gt^2}{2} \tag{4.18}$$

Here, x_o and y_o define the position of the ball at $t = 0$, and v_{xo} and v_{yo} describe the initial x- and y-components, respectively, of the ball's initial velocity. The quantity $g = 9.8\ \text{m/s}^2$ is the gravitational constant, and the quantity $gt^2/2$ describes the fall of the ball due to gravity—a result of integrating the y-component of Equation (4.16). Note that gravity does not affect the value of x; once free of the launch tube, the ball's horizontal velocity will be constant in time. Only the height of the ball will be affected by gravity.

The ball's exit velocity at $t = 0$ will be determined by the potential energy W stored in the ball at its starting point at the top of the track:

$$W = mgh \tag{4.19}$$

Here, m is the mass of the ball in kilograms, mg is the gravitational force on the ball, and h is its vertical height in meters relative to the launch point. Equation (4.19), of course, can be derived using calculus by integrating the vertical force equation $F_y = -mg$ as a function of the vertical direction y to yield the total potential energy, or work, required to lift the ball to a height h:

$$W = -\int F_y\,dy = mgh \tag{4.20}$$

As the ball rolls down, this potential energy is converted to kinetic energy in the form of forward motion and rotation. Only the former is of interest in determining the ball's trajectory. The rotational energy represents the portion of potential energy that is not converted into the kinetic energy of forward motion.

Although the most accurate analysis would account for the rotational energy stored in the ball, we assume for the sake of this discussion that both frictional losses and the rotational energy of the ball are negligible.

The kinetic energy K of the ball at the moment of launch can be expressed in terms of the energy of forward motion:

$$K = \frac{mv_o^2}{2} \tag{4.21}$$

where v_o is the ball's initial velocity. Equating K to W (i.e., by assuming that all of the potential energy is converted to kinetic) results in an expression for v_o as a function of initial height h:

$$v_o = \sqrt{2gh} \tag{4.22}$$

Note that v_o is independent of the ball's mass m. We expect this result from our knowledge that all objects fall at the same velocity regardless of mass.

Using simple trigonometry, the horizontal and vertical components of the launch velocity can be expressed in terms of the launch angle as

$$v_{xo} = \sqrt{2gh}\cos\theta \tag{4.23}$$

and

$$v_{yo} = \sqrt{2gh}\sin\theta \tag{4.24}$$

where θ is the launch angle imparted by the launch tube. Using Equations (4.17), (4.18), (4.23), and (4.24), one can calculate the evolution of the trajectory in closed algebraic form to find the exact trajectory of the ball as it heads toward the rosewood box. The solution is plotted in Figure 4.26. An alternative method is to plot the

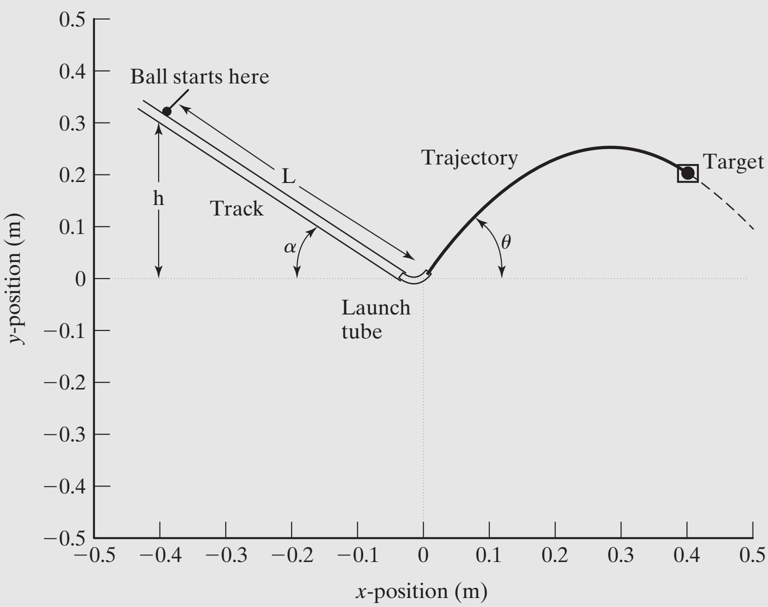


Figure 4.26
Desired parabolic trajectory and landing site for the ball. The parameters for this particular simulation are $L = 0.51$ m, $h = 0.33$ m, $\theta = 40°$, $\theta = 61°$. The target is placed at $x = 0.4$ m and $y = 0.2$ m relative to the point of launch.

ball's trajectory using a computer and observe whether or not it hits the box for various choices of track parameters. Although this second method will not provide as accurate an answer as a direct calculation, it has visual appeal and is well suited for implementation on a computer.

EXAMPLE 4.5

Plotting Trajectories Using MATLAB

The task of plotting the ball's trajectory can be performed using any of a number of software tools, including spreadsheets or such programming languages as C^{++}, Mathematica, or MATLAB. The latter is chosen for this example because it is a software tool used by many engineers.

MATLAB is a versatile and comprehensive programming environment particularly suited for engineering problems. MATLAB is similar in syntax to the programming language C, but it also provides simple commands that enable programmers to plot and organize data, manipulate matrices, observe variables, solve systems of linear equations, and solve differential equations. The strength of MATLAB lies in its ability to manipulate, plot, and graph large amounts of data. Tips on getting started in MATLAB can be found in any of several references.[2]

One possible version of the code in MATLAB is shown below. The program first prompts the user for values of launch tube length, launch tube angle, and the position of the rosewood box relative to the exit of the launch tube. It next computes the starting height of the ball and the x- and y-components of the exit velocity, then plots the trajectory of the ball. This last task is accomplished by incrementing t by a small time dt for each pass through the *while* loop. The looping continues as long as x and y remain within the boundaries of the solution space which is arbitrarily defined as $-0.5\text{ m} < x < 0.5\text{ m}$ and $-0.5\text{ m} < y < 0.5\text{ m}$. At the end of each loop, the program extends the trajectory plot from the most recently calculated (x, y) position to the newly calculated position. Visual inspection of the plot reveals whether the trajectory hits the rosewood box at the desired location.

The best values for the launch angle θ, track length L, and inclination angle α may be found by trial and error. Figure 4.26 illustrates the trajectory resulting from the launch parameters $L = 0.51$ m, $h = 0.33$ m, $\alpha = 40°$, and $\theta = 61°$. The target is placed at $x = 0.4$ m and $y = 0.2$ m relative to the point of launch. This solution was found by trial-and-error entry of the various parameter values.

```
%%%%% MATLAB PROGRAM CODE    %%%%%%%%
%%%%% Computes trajectory of ball traveling down track
%%%%% and exiting flexible launch tube at specific launch angle
%%%%% Assumes that launch point is at x=0 and y=0
%%%%% SET PARAMETERS:
xT=input('ENTER Target x-position in meters: ');
yT=input('ENTER Target y-position in meters: ');
L=input ('ENTER length of ball travel distance down track, in
meters: ');
```

[2]Etter, D., Kuncicky, D., and Moore, H. *Introduction to Matlab 7*, Upper Saddle River, NJ: Prentice Hall, 2005. Hanselman, D.C. and Littlefield, B. L. *Mastering Matlab 7*, Upper Saddle River, NJ: Prentice Hall, 2005.

```
alpha=input('ENTER ANGLE OF TRACK INCLINATION in DEGREES: ');
alpha=alpha*pi/180;       %convert angle to radians
theta=input('ENTER ANGLE OF LAUNCH in DEGREES: ');
theta=theta*pi/180;       %convert angle to radians
h=L*sin(alpha);           %Compute height of starting point
                          %relative to y=0
vo=sqrt(2*g*h);           %Compute total ball velocity at moment
                          %of launch
vxo=vo*cos(theta);        %Compute x-component of launch velocity
vyo=vo*sin(theta);        %Compute y-component of launch velocity
g=9.8;                    %gravitational acceleration in m/s^2
%PREPARE TO CALCULATE AND PLOT
%Set axes for making plot on screen
close                     %close any previously opened figures
S=0.5;                    %Arbitrary axis width
axis([-S S -S S]); hold on
plot(xT,yT,'ob')          %draw target point on screen
line([-L*cos(alpha) 0], [h 0])
                          %draw the track
line([-L*cos(alpha)+0.01 0.01], [h+0.01 0.01])  %draw the track
xo=0.001; x=xo            %set initial value of x
yo=0.001; y=yo            %set initial value of y
t=0;                      %set initial time to zero
dt=0.1*L/vo;              %set a time increment
%-----------------------------------------------------------------
while (x>S & y<0)         %calculate until trajectory goes out of
                          %bounds
t=t+dt;                   %increment time
xnew=vxo*t;               %compute new x-position
ynew=vyo*t-0.5*g*(t^2);   %compute new y-position
%plot latest segment of trajectory:
plot ( [x xnew] , [y ynew],'-r' ); hold on
drawnow;                  %put segment on the screen
x=xnew; y=ynew            %update values of x and y
end
%-----------------------------------------------------------------
```

Practice!

1. Use analytical calculations to compute the trajectory of Figure 4.26 for a launch angle of 40°, a track length of 1 m, and a track inclination angle of 40°. Determine the x-coordinate at which the rosewood box must be placed if its y-coordinate is at the same height as the launch tube exit.
2. Use analytical calculations to compute the trajectory of Figure 4.26 for a launch angle of 75°, a track length of 0.5 m, and a track inclination angle of 40°. Determine the y-coordinate at which the rosewood box must be placed if its x-coordinate relative to the launch tube exit is 25 cm.
3. Enter the program from Example 4.6 into a computer that can run MATLAB. (This code may be found at *http://people.bu.edu/mnh/*

design.) Situate the rosewood box target at $x = 25$ cm and $y = -10$ cm. For a track length of 65 cm and track inclination angle of 30°, determine the launch angle required if the ball is to hit its target.

4. What launch angle will result in a ball that travels the farthest horizontal distance in Example 4.6? Assume that only the portion of the trajectory for $y > 0$ is of interest.
5. What launch angle will result in a ball that travels the farthest horizontal distance in Example 4.6 if the target point is located 20 cm in height below the end of the launch tube?
6. Draw the flowchart of a program designed to compute the path of a tennis ball after it leaves a player's racquet.
7. Draw the flowchart of a program designed to compute the height of a helium-filled balloon after it has been released from sea level.
8. Draw the flowchart of a program designed to compute the trajectory of a pinball as it makes its way from the top if its launch arc through a maze of obstacle posts.

The following questions relate to an elastic device that obeys the force-elongation equation $F = -kx$.

9. What is the potential energy stored in a spring that has a restoring force of 1 kN/m and has been stretched by 1 cm?
10. Compute the initial velocity of a 100-gm projectile that is launched by stretching a rubber band by 10 cm. Assume the rubber band has an elastic constant of 50 N/m and obeys a $F = -kx$ law.
11. What is the potential energy stored in a spring that has a restoring force of 500 N/cm and has been compressed by 10 cm? What will be the initial velocity of a 250-gm pinball propelled by the compressed spring after release?
12. A spring has an elastic constant of 100 N/m. (a) How much force will be required to elongate the spring by 5 cm? (b) What will be the landing point of a 100-gm marble propelled from the ground by the spring at a launch angle of 30°?

Professional Success: The Role of Computers in Society

Computers have become so enmeshed in our lives that it's hard to imagine society without them. Computers are used in everything—science, engineering, business, commerce, government, education, finance, medicine, avionics, social service—you name it. Computers have even become a form of recreation. One can debate the merit of computers and their effect on human relationships. (Is an AOL chat better than a phone conversation? Is it better to buy online or from a real store?) But in the world of engineering, computers are indispensable. Like most people, engineers use computers for communication, information retrieval, data processing, word processing, electronic mail, and Web browsing. But the special value of the computer to the engineer lies in its ability to perform calculations extremely rapidly. A computer can be programmed to perform all sorts of numerical calculations. Commercial programs for simulation, spreadsheets, and graphing enable engineers to determine everything from the stresses on mechanical parts and the operation of complicated electronic circuits to the force loads on building frames and theoretical predictions of rocket launches. The availability of the computer and the abundance of software tools greatly enhance the productivity of engineers in all disciplines.

EXAMPLE 4.6

Method of Numerical Iteration by Computer

The field of micro-electromechanical systems, or MEMS, has become increasingly important over the past decade. MEMS devices are tiny microscale machines made from silicon, metals, and other materials. They are fabricated using tools borrowed from integrated-circuit manufacturing: photolithography, pattern masking, deposition, and etching. MEMS devices have found their way into mainstream engineering design solutions. The sensors used to deploy safety airbags in automobiles, for example, are built around tiny MEMS accelerometers that are about 1 square millimeter in size, and the nozzles of inkjet printing cartridges are microscale MEMS devices.

One technique for fabricating MEMS devices is called surface micromachining. The basic steps involved in surface micromachining are shown in Figure 4.27. A silicon substrate is patterned with alternating layers of polysilicon and oxide films that build up a desired mechanical structure. The oxide films serve as sacrificial layers that support the polysilicon layers during fabrication but are removed in the final steps of fabrication. This construction technique is analogous to the way that arches of stone buildings were made in ancient times. Sand was used to support stone pieces and was removed when the building could support itself, leaving the finished structure.

One simple MEMS device used in numerous applications is shown in Figure 4.28. This double-cantilevered actuator consists of a bridge supported on two ends and situated over an underlying, fixed activation electrode. A side view is shown in Figure 4.28. The bridge has a rectangular shape when viewed from the top. The bridge sits atop an insulating layer and silicon substrate. When a voltage is applied between the bridge and the substrate, the electrostatic force of attraction causes the bridge to bulge toward the substrate. This motion can be

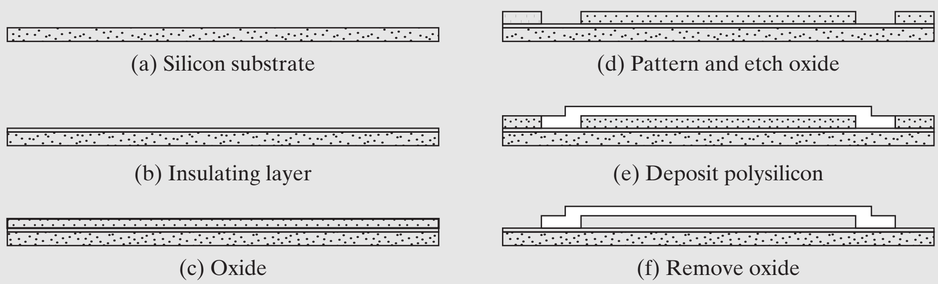


Figure 4.27
Fabrication sequence for a simple MEMS actuator. (a) Begin with a silicon wafer substrate; (b) deposit an insulating layer of silicon nitride; (c) deposit a thick layer of silicon dioxide ("oxide"); (d) pattern and etch the oxide using photolithography and masking techniques; (e) deposit a layer of polysilicon that will become the actuator bridge; (f) remove the oxide, leaving an air gap between the actuator and the substrate.

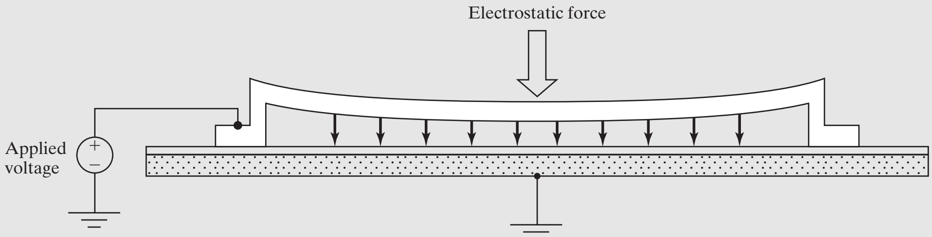


Figure 4.28
Applying a voltage between the actuator and the substrate causes deflection of the actuator bridge. This mechanical motion can be used to move other devices, change the direction of reflected light, pump liquids and gases, or perform other operations on a microscopic scale.

used to perform useful functions. For example, the deflecting bridge can open and close tiny valves, change the direction of reflected light, pump fluids, or mix chemicals in small micromixing chambers. A MEMS designer must know the relationship between the voltage applied to the bridge and its deflection. For a given applied voltage V, the electrostatic force F_e will be given approximately by the following equation:

$$F_e = \frac{\varepsilon_0 AV^2}{2(g - y)^2} \tag{4.25}$$

Here, y is the bridge deflection, A is the area of the bridge as seen from the top, and g is the gap spacing between the bridge and the electrode at zero deflection. The permittivity constant ε_0 is equal to 8.85×10^{-12} F/m (farads per meter) for air. Note that the electrostatic force increases with increasing deflection and becomes infinite for $y = g$ (i.e., when the net gap spacing becomes zero). This increase in force with deflection would cause the bridge to collapse completely when any voltage was applied were it not for the counteracting mechanical restoring force of the elastic material used to make the bridge. To first order, the restoring force F_m will be proportional to the bridge deflection and can be expressed by the simple equation:

$$F_m = -ky \tag{4.26}$$

This force is exactly analogous to that of a rubber band or spring: Its magnitude increases in proportion to the deflection. In the case of the MEMS device of Figure 4.30, the mechanical restoring force prevents the bridge from collapsing completely when a voltage is applied. As the deflection increases, the restoring force also increases. At some value of deflection, the mechanical force becomes equal to the electrostatic force, allowing no further deflection. A MEMS designer is extremely interested in this equilibrium point, because it determines the bridge deflection for a given applied voltage.

The equilibrium deflection point can be found, in principle, by equating the magnitudes of the electrostatic and mechanical forces given by Equations (4.25) and (4.26), yielding the following cubic equation:

$$ky = \frac{\varepsilon_0 AV^2}{2(g - y)^2} \tag{4.27}$$

Solving this force balance equation by hand is difficult. (Try it!) The calculation is well suited, however, for solution on a computer using the method of

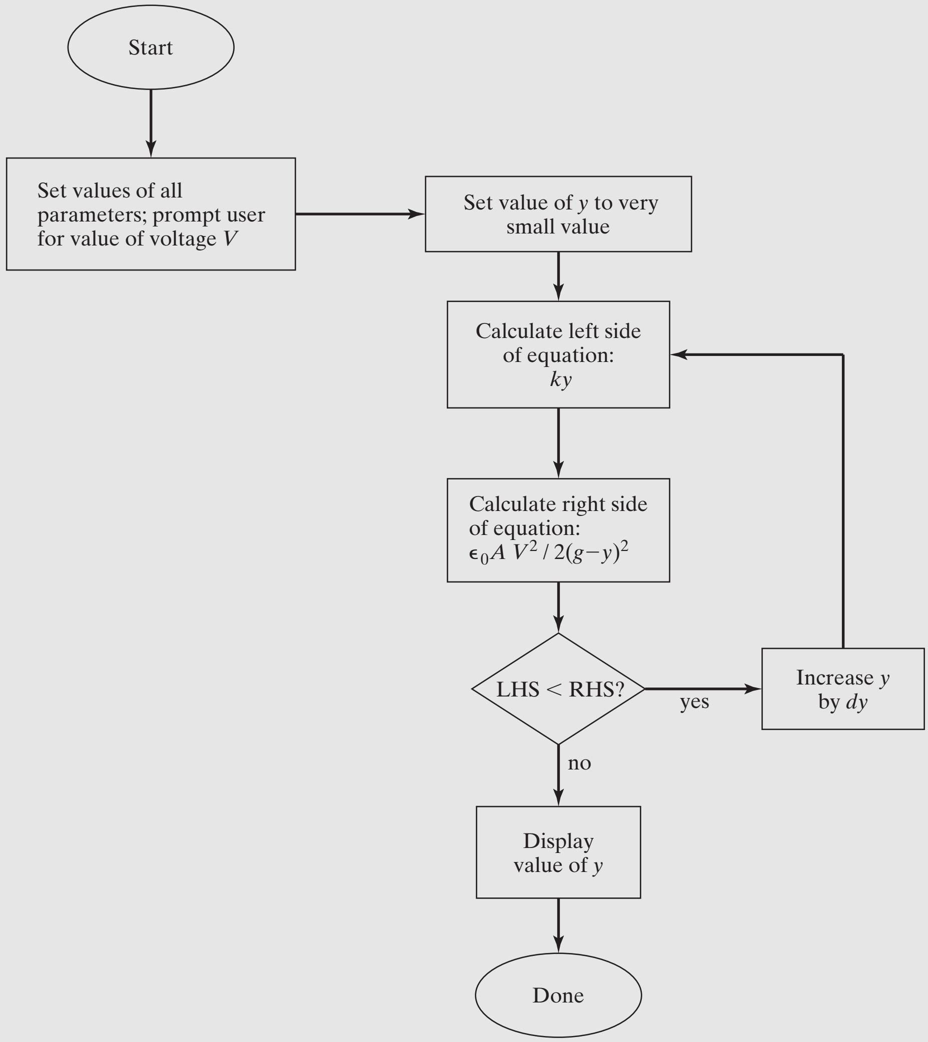


Figure 4.29
Flowchart for the iterative solution of Equation (4.23).

numerical iteration. In this latter method, the computer tries many different values of y until it finds one for which both sides of Equation (4.27) match. One can instruct the computer, for example, to begin with some very small value of y and then increase it by small amounts until the solution point is found. This iterative method is ideal for implementation on a computer, because it typically involves many repetitive calculations that would be time consuming if performed by hand.

The flowchart of Figure 4.29 illustrates the steps needed to find the equilibrium point by the method of iteration. The program begins with a small value of y, then successively increases y by dy until the left-hand and right-hand sides of Equation (4.27) agree within some residually small value set by the programmer.

The circles in Figure 4.30 show the results of the computation for several values of applied voltage and the parameters listed in Table 4.4. The dotted curve shows the complete analytical solution for comparison. The latter was plotted by solving Equation (4.27) for numerous values of y and V, storing the data points and then plotting them.

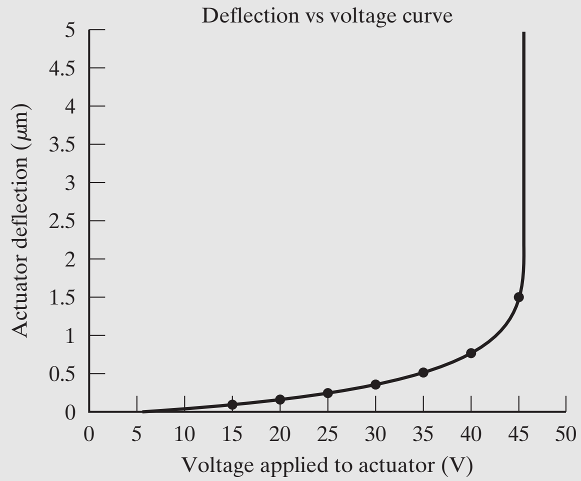


Figure 4.30
Deflection versus voltage curve resulting from the simulation of Figure 4.31.

Table 4.4 Parameters for the MEMS Simulation of Example 4.7

Symbol	Parameter	Value
k	Restoring force	30 N/m
s	Side of square actuator	250 μm
g	Zero-voltage gap spacing	5 μm
y	Bridge deflection	$0 < y < 5$ μm
dy	Deflection increment for iteration	0.05 μm

Above about 45 volts, the restoring force is no longer capable of holding back the electrostatic force, and the deflection becomes "infinite" (i.e., the bridge collapses all the way to its underlying electrode). This phenomenon is called *snap-through* in the world of MEMS. Snap-through commonly occurs at a deflection of about one-third of the zero-voltage gap spacing.

The iteration leading to Figure 4.30 can be performed using any number of available software programs. Here we choose MATLAB and C as representative of programming languages used by many engineers. Sample program code listings written in MATLAB and C that produce the desired results are provided below. The C program can be turned into a C++ program by simply changing the header files and the functions used for reading and writing variables. The programs prompt the user for an applied value of voltage, calculate the corresponding deflection *y*, and display the result.

Program Code Listing in MATLAB

```
%%% ----------------- %%%
%%% MATLAB PROGRAM CODE LISTING %%
% Lines preceded by a percent sign (%) are comment lines
% This program finds the deflection of a MEMS bridge actuator
% for a given applied voltage.
k = 30;  %elastic restoring force in N/m
eo = 8.85e-12;   %dielectric permittivity of air
side = 250e-6;   %dimension of each side of actuator
Area = side^2;   %compute area of actuator
```

```
gap = 5e-6;      %spacing between actuator and activation electrode
dy = gap/100;    %incremental deflection to be used in iteration
                 %Prompt user for value of voltage:
V=input('Enter value of voltage applied to actuator: ')
y=0;             %initialize deflection to zero
Fm = k*y;        %Compute magnitude of mechanical force
Fe = eo*Area*V^2/2*(gap-y)^2;
                 %Compute magnitude of
                 %electrostatic force
%-----------------------------------------------
while Fm
y = y + dy;      %Try a slightly larger deflection
Fm = k*y;        %Recompute magnitude of mechanical force
Fe = eo*Area*V^2/2* (gap-y)^2;
                 %Recompute magnitude of
                 %electrostatic force
end
                 %Display result:
disp ('Deflection in microns when Fe = Fm:'), y*1e6
```

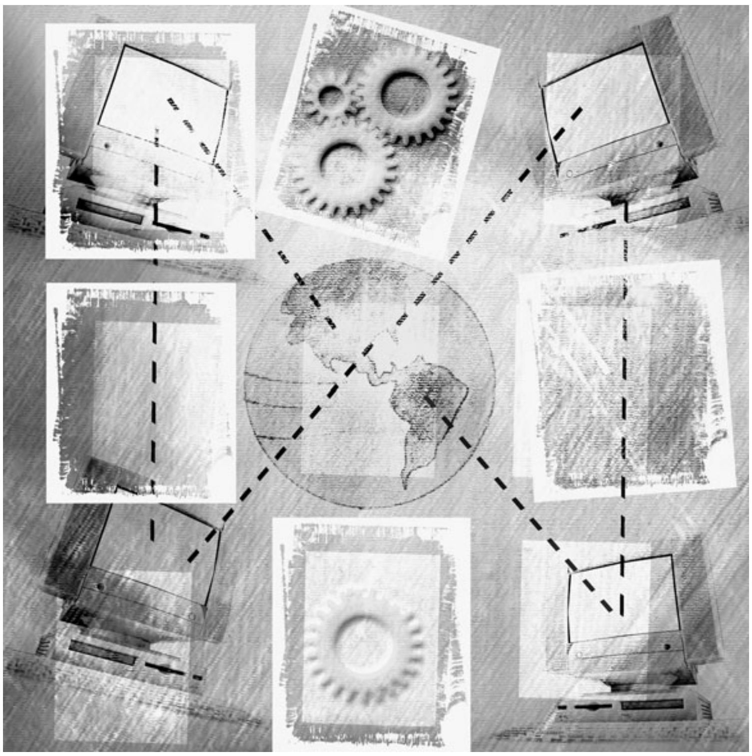
Program Code Listing in C

```
/*----------------------------------------------*/
/* C PROGRAM CODE LISTING */
/* Program to simulate MEMS actuator position versus voltage
curve */
#include<stdio.h>
#include<math.h>
int main() {
int k = 30;
float eo = 8.85e-12,
side = 250e-6,
area,
gap = 5e-6,
dy;
float v,
y,
Fm,
Fe;
/*Square "side" to get area (raise side to the power 2) */
area = pow(side,2);
dy = gap/100;
/* Prompt user for value of voltage */
cout << "Enter value of voltage applied to actuator: ";
cin >> v;
y = 0;
Fm = k * y;
Fe = (eo * area * pow(v,2)) / pow(gap y,2);
while(Fm < Fe) {
y = y + dy;
Fm = k * y;
Fe = (eo * area * pow(v, 2)) / pow(gap y, 2);
}
cout << "Deflection in microns when Fe=Fm: " << y*1e6 << endl;
return 0;
}
/*--------------------------------------------------------------*/
```

Professional Success: Garbage in, Garbage Out

The computer has become an indispensable tool for engineers because it can perform calculations much more rapidly than can a human. Its superb for storing and retrieving data and producing graphical images. But the computer is no substitute for thinking. A computer should be used to *enhance* the capabilities of an engineer, not replace them. A computer will faithfully follow its program code but is unable to pass judgment on the worth of the results. Its up to the engineer to provide the computer with information that is meaningful and relevant. If you program a computer to calculate the weight of structural steel for a bridge, it can do so flawlessly. But it can never tell you whether such a bridge is feasible, whether the stress–strain equations in its program are correct, or whether the bridge should be built at all. Only an engineer with experience and good judgment can make those determinations.

When a computer crunches numbers that have little meaning due to programmer error, or when it operates with faulty data that was erroneously entered, the computer operates in a "garbage in, garbage out" (GIGO) mode. GIGO refers to a situation in which bad input data or bad program code leads to a computationally correct but meaningless output. A GIGO condition can be prevented by testing a program on simple, well-known examples for which the solution can be easily computed by hand. If the computer can provide correct answers to numerous simple problems, then it's probably programmed correctly and is ready to be used on more complex problems.



Marine Receiver Specifications

Dimensions	1.49 in. x 5.42 in. x 8.47 in.
Power Requirements	10-30 VDC
System Connectors	D25, RS232 data and power
Antenna Connectors	TNCF

Marine Antenna Specifications

Dimensions	3 in. diameter, 3.5 in. high
Mounting	Standard marine 1-14 pole mount
Gain & Impedence	36db, 50ohm
Antenna Connectors	SMAF

Marine Software Requirements

Operating System	Microsoft Windows 98, 2000, NT, XP
Processor	300 MHz or greater
Memory	128MB RAM
Storage	60MB Free Hard Drive Space

Figure 4.31
A typical specification sheet. This particular set of specifications describes marine-grade radio receiver.

4.7 SPECIFICATION SHEETS

As a design effort progresses from the initial brainstorming stage, through the various iterations of the design cycle, to finally converging on a likely prototype, a point is reached where the designer has some level of confidence in the details of the product. At this latter stage of evolution, these details may be summarized in a one-page product specification sheet. The contents of this document will vary widely, depending on the discipline, but a representative version is shown in Figure 4.31. This particular set of specifications describes a marine-grade radio receiver for use on ships and boats. The salient information includes the dimensions of the unit, as well as its power connection, software requirements, and operating frequency. A specification sheet for an entirely different class of product—in this case, a protein purification device for chromatography applications—is shown in Figure 4.32. Note how very different is the information contained in this second example. In general, the format and content of a specification sheet is left up to the designer. The sheet will be adequate as long as

BD TALON™ Product Specifications

	BD TALON	BD TALON Superflow	BD TALON CellThru	BD TALON Spin Columns
Batch/Gravity Flow	Yes	Yes	Yes	No
FPLC	No	Yes	Yes	No
Scale	Analytical Preparative	Analytical Preparative Production	Preparitive	Analytical
Capacity (mg protein /ml absorbent)	5-10	5-14	5-10	2-4
Type of matrix	6% Cross-linked agarose	6% Cross-linked agarose	4% Cross-linked agarose	6% agarose
Bead size, μm	45-165	60-160	300-500	45-165
Maximum linear flow rate (cm/h)	75-l 50	3000	800	NA
Maximum volumetric flow rate (ml/min)	0.5	50	13	NA
Recommended volumetric flow rate* (ml/min)	0.3	1.0-5.0	1.0-5.0	0.3
Maximum pressure	2.8 psi 0.2 bar 0.02 MPa	140 psi 10 bar 0.97 MPa	9 psi 0.62 bar 0.06 MPa	NA
pH Stability	2−14 (< 2h) 3−14 (< 24h)	2−14 (< 2h) 3−14 (< 24h)	2−14 (< 2h) 3−14 (< 24h)	2−8.5 (< 2h) 2−7.5 (< 24 h)
Protein exclusion limit, D	>> 4×10^7	4×10^6	2×10^7	NA
Supplied as	50% suspension in 20% ethanol, precharged with Co^{2+} ions	50% suspension in 20% ethanol, precharged with Co^{2+} ions	50% suspension in 20% ethanol, precharged with Co^{2+} ions	50% suspension in 20% ethanol, precharged with Co^{2+} ions, packed in columns
Storage Conditions	RT or 4°C Do Not Freeze	RT or 4°C Do Not Freeze	RT or 4°C Do Not Freeze	RT or 4°C Do Not Freeze

* Determined on 5 × 1 cm HD (height & diameter) column

Superflow™ and CellThru™ are trademarks of Sterogene Bioseparations, Inc.

Figure 4.32
Specification sheet for a protein purification product for chromatography.

its purpose is fulfilled: It must convey all the information a user may need to determine the suitability of the product for use in a given application.

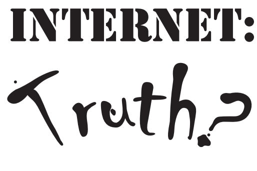
4.8 THE INTERNET

When the first edition of this book was written in 2000, the Internet was described as "an up-and-coming engineering design tool" that was "rapidly gaining popularity." Today, it's virtually impossible to imagine engineering (or any aspect of life, for that matter) without the Internet. Indeed, linking millions of Internet host sites has become vital not only for engineers, but also for individuals involved in business, government, the media, commerce, science, politics, the arts, education, and recreation. The widespread use of data sheets in PDF (portable document format) has made the printed technical data book practically obsolete. Parts and supplies are now more easily purchased from online stores than they are from "brick-and-mortar" vendors. Searching for obscure parts now takes minutes instead of days, and a plethora of information on any engineering topic can be found from a simple "Google" search. The first stop for any engineer seeking information about a particular type of product is likely to be the Internet.

Professional Success: "I Saw it on the Internet. It must be True."

While a comprehensive introduction to the Internet is beyond the mission of this text (and probably unnecessary for most students), a discussion of *when* to use the Internet as part of engineering design is most appropriate. When you access information from the Internet for an engineering project, be sure that it comes from a reliable source. Information is not necessarily accurate just because it has been posted on the Web. Information that comes from the websites of reputable companies and institutions is most likely reliable. Information from personal webpages, student project sites, the amateur press, lone information providers, "bloggers," and other sources outside the mainstream should be viewed with more skepticism. Before the Internet, it took a great deal of time for rumors and misinformation to propagate around the technical community. Now this process takes minutes. Information from one website can be copied to another, leading to the multiple propagation of errors. Although the Internet has provided instant access to limitless information, it has also eliminated an important filter provided by print media: webpages are inexpensive; hence, almost anyone can produce them. Before the Web, only serious companies could afford to disseminate information to the general public. In the print age, technical information seemed more grounded in legitimacy. Now, it's hard to distinguish worthless information from valued information obtained from serious providers. Choose your Internet sources with care.

One other word of caution: The World Wide Web has been around only since the early 1990s. Its growth has been explosive, but the information it can provide on a particular subject is only as complete as the time someone has taken to archive it. The vast majority of engineering data and knowledge existed long before the Internet came into being. As a source of information, the Web can only augment the hundreds of millions of books, reports, and periodicals available in the world's libraries. Although the Internet and its searching tools are important sources of information for your design projects, they should not be the only sources.



Practice!

1. Use the search feature of your Internet browser to perform a search on the term "oil platform." Record the number of listings. Now, narrow the search by adding, in succession, the following additional keywords: "photo," "north," "sea," and "terminal." Determine how many fewer listings are obtained each time the search is narrowed by an additional keyword.

2. Use the search feature of your browser to perform a search on the term "Lyle gun." Record the number of listings. Now, narrow the search by adding, in succession, the following additional keywords: "photo," "history," "rescue," and "reenactment." Determine how many fewer listings are obtained each time the search is narrowed by an additional keyword.
3. Use the search feature of your browser to perform a search on the term "space station." Record the number of listings. Now, narrow the search by adding, in succession, the following additional keywords: "photo," "NASA," "Russian," and "shuttle." Determine how many fewer listings are obtained each time the search is narrowed by an additional keyword.
4. Use the Internet to find a replacement hubcap for a 1994 Toyota Camry. How many different vendors stock this hard-to-find part?
5. The Internet can be a valuable source of technical news. Find everything you can on the subject of the "total artificial heart." What salient feature makes this invention superior to all previous attempts to design a similar device?
6. Use the Internet to find information on the proper design of a "red coachman" fishing lure. Specifically, what type of hackles are recommended for optimum fabrication?
7. The Internet can be the source of misinformation as well as information. Do a search on any of the following topics and find at least two references that contradict each other.

   a. Is there a link between artificial sweeteners and mental health?
   b. Should electrostatic charge decay be measured using the triboelectrification or corona method?
   c. What is the best defense against the winter moth?
   d. Can flexible intermediate bulk containers (FIBCs) be safely used without ground wires?
   e. What is the maximum permissible tolerance on the spacing between the wheels of a light-rail train vehicle?
   f. What is the recommended tread-to-riser ratio for a staircase?
   g. Should bottled water containers be refilled with water for later drinking?
   h. Is there a link between electric power lines and human health?
   i. Will tapping the side of a soda can prevent its contents from foaming over when you open it?
   j. How many spiders does the average person swallow each year?
   k. Can a penny placed on railroad tracks cause a train to derail?

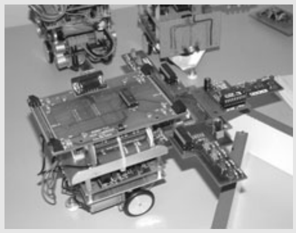
4.9 SPREADSHEETS IN ENGINEERING DESIGN

A spreadsheet is a programmable table in which each cell consists of text, fixed numerical data, or a formula that relies on other numbers in the spreadsheet for its value. The most popular spreadsheet program continues to be Microsoft Excel. Other types include Lotus 1-2-3, Open Office (a Linux program), Appleworks, Clarisworks, and Corel Quatro Pro. Engineers may use spreadsheets in all phases of the design process for tasks such as performing calculations, analyzing results, planning budgets, tracking parts lists, and performing simulations. A spreadsheet becomes particularly useful when a problem is complex and has many interrelated variables. By programming a spreadsheet to model a complex problem, an engineer can see the effect that changing a single variable has on the entire system. The next two examples illustrate the usefulness of spreadsheets in engineering design. The spreadsheet tables are meant to be generic in form but typical of most commercial spreadsheet software.

EXAMPLE 4.7

Calculating the Center of Mass

This example describes one phase in the design activities of students Freeda and Froda who have entered the annual "MicroMouse" competition sponsored by the Institute of Electrical and Electronic Engineers (IEEE). The objective of the competition is to design a self-contained, battery-powered mini-vehicle that can learn a maze on its own and then traverse it as rapidly as possible. (See *www.ieee.org*, and enter "micromouse" into the search field.) Because the mouse must make numerous high-speed turns as it negotiates the maze, one concern is the placement of components and the effect of their physical locations on the balance of the vehicle. The students determine that their mouse will perform best if its center of mass is located midway between its front and rear axles. Their simulations have shown that if the center of mass is too far forward, the rear wheels will not maintain enough traction to drive the mouse at high speed. Conversely, if the center of mass is too far toward the rear, the high torque of the motor and gears may cause the front of the mouse to lift up and temporarily lose its steering capability. The students must now determine where to mount the various components on the chassis of the mouse. The physical location of these components will determine the location of the vehicle's center of mass.



Freeda has weighed each component and recorded the values in her logbook, shown here as Figure 4.33. She's also entered the sketch of Figure 4.34 which outlines one possible layout for the components. She's calculated the center of mass of the bare frame (with none of the components yet installed) from basic principles and has found that it lies about 7 cm behind the midpoint between the two axles.

Froda's next step is to decide for certain where to place each of the components on the vehicle chassis. She's prepared a spreadsheet, shown in Table 4.5, to calculate the center of mass of the entire vehicle, including all its components. (Note that Table 4-5 shows the contents of each cell in the spreadsheet, not what appears on Froda's computer screen.) The discussion that follows focuses on the center of mass in the x-direction. A similar analysis must also be performed for the y-direction.

The location x of each part represents the position of its own individual center of mass relative to the center of mass of the frame. The latter is located at the midpoint between the two axles. The moment M_n of the nth part is equal to its position times its mass:

$$M_n = x_n \times m_n \tag{4.28}$$

2/14/09
Measurements of vehicle parts

ITEM	APPROX* WEIGHT [gm]	PROPOSED LOCATION
Chassis	1000	[defines center line]
Wedge frame	400	−7 cm
Battery	120	+8
Switch	10	+5
Motor	200	−7
Gearbox	50	−10
Launch tube	15	−12

*measured on pan balance

Figure 4.33
Logbook page showing weights of key vehicle components.

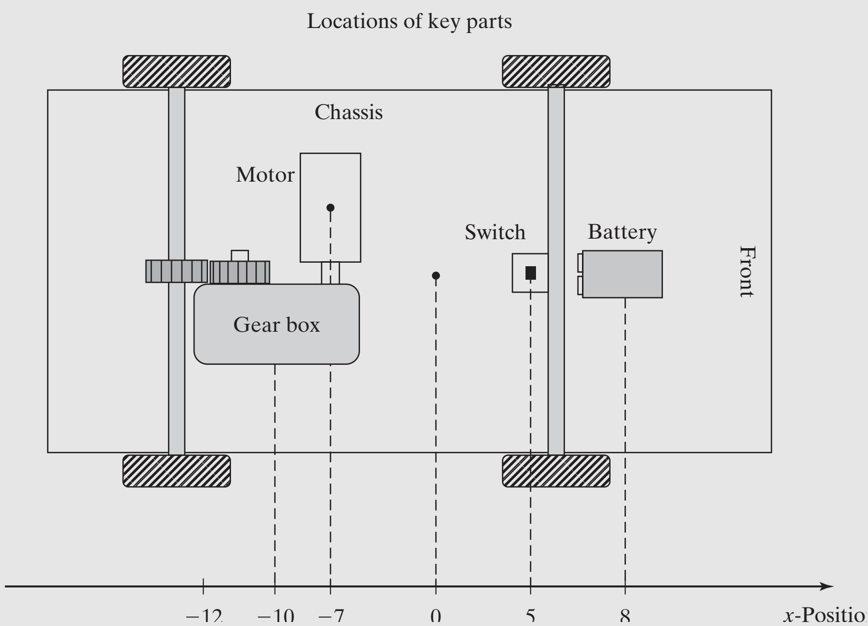


Figure 4.34
Possible layout of vehicle components.

Table 4.5 Cell Entries in Spreadsheet that Calculates Center of Mass

	Part Name	Mass *m* (gm)	Location *x* (cm)	Moment *m* (gm–cm)
1	Chassis	1000	0	= B2*C2
2	Wedge frame	400	−7	= B3*C3
3	Battery	120	8	= B4*C4
4	Switch	10	5	= B5*C5
5	Motor	200	−7	= B6*C6
6	Gear Box	50	−10	= B7*C7
7	Launch Tube	15	−12	= B8*C8
8	Total Weight	= SUM(B2:B8)		
9	Total Moment	= SUM(D2:D8)		
10	Net C.O.M.	= D10/B9		

The x-directed center of mass x_{CM} of the entire ensemble of parts is given by the sum of the moments divided by the sum of the masses:

$$x_{\mathrm{CM}} = \frac{\sum M_n}{\sum m_n} \tag{4.29}$$

The output of Froda's spreadsheet, as it appears on her computer screen, is shown in Table 4.6. The calculations show that the center of mass of the vehicle (Net C.O.M. in the spreadsheet table) lies at $x \approx -2.16$, or about 2 cm behind the geometrical center of the axle mounts. The force calculations that the students have previously performed indicate that the center of mass needs to lie within 1 cm of the vehicle's midpoint.

Table 4.6 Screen Output of the Spreadsheet of Table 4.5

	Part Name	Mass *m* (gm)	Location *x* (cm)	Moment *m* (gm–cm)
1	Chassis	1000	0	0
2	Wedge Frame	400	−7	−2800
3	Battery	120	8	960
4	Switch	10	5	50
5	Motor	200	−7	−1400
6	Gear Box	50	−10	−500
7	Launch Tube	15	−12	−180
8	Total Weight	1795		
9	Total Moment			3870
10	Net C.O.M.		2.16	

Table 4.7 Screen Output of Modified Spreadsheet

	Part Name	Mass *m* (gm)	Location *x* (cm)	Moment *m* (gm–cm)
1	Chassis	1000	0	0
2	Wedge frame	400	−7	−2840
3	Battery	120	8	960
4	Switch	10	5	50
5	Motor	200	−7	−1400
6	Gear box	50	−10	−500
7	Launch tube	15	−12	−180
8	**Counterweight**	**200**	**10**	**2000**
9	Total weight	1995		
10	Total moment		–	1870
11	Net C.O.M.		−0.94	

The students discuss possible alternative arrangements for the vehicle components. Freeda tries to simulate moving the battery forward by changing the entry for battery position on the spreadsheet. Because the battery is connected to the motor by wires of arbitrary length, this change is easy to implement. The change, however, shows that moving the battery all the way to the 15-cm forward position merely shifts the center of mass forward to the −1.7 cm position.

Froda suggests adding a counterweight somewhere between the midpoint of the vehicle and its front axle. She inserts a new row into the spreadsheet and enters data for the counterweight into the cells, as shown in Table 4.7. The students experiment with different values for the location and mass of the counterweight. The spreadsheet allows them to track changes in the center of mass as they go along. Competition rules specify a 2-kg mouse weight limit, including batteries. The spreadsheet allows the students to see how close they come to this limit as the mass of the counterweight is increased. The cells in Table 4.7 show the results of placing a 200-gm counterweight 10 cm forward of the vehicle midpoint. The center of mass has been shifted to −0.96 cm behind the midpoint, which lies just on the edge of the targeted range of ±1 cm. The total weight has increased to 1,995 gm, which is five grams below the maximum 2-kg limit. Freeda and Froda decide to stay with these parameters so that they will have a small safety margin with respect to weight; this margin will allow for adding small nuts, bolts, glue, or tape during the competition.

EXAMPLE 4.8

Keeping Track of Cost with a Spreadsheet

A spreadsheet also helps Freeda and Froda track the total cost of their mouse vehicle. The funds they have obtained to support their entry set the total cost limit at $100, including batteries. An accounting of the costs must be submitted to the Student Activities Office if they are to be reimbursed for their purchases. Froda has set

Table 4.8 Cost-Tracking Spreadsheet. The Unit Cost Column Indicates the Cost per Item, and the Extended Column is Equal to Quantity × Unit Cost

Item		Quantity	Unit Cost ($)	Extended ($)
1	Chassis	1	12.50	12.50
2	Wedge frame	1	15.00	15.00
3	Battery	12	2.19	26.28
4	Switch	3	2.29	6.87
5	Motor	1	3.49	3.49
6	Gearbox	1	5.99	5.99
7	Launch tube	1	0.67	0.67
8	Counterweight	1	0.85	0.85
9	Rubber bands	12	0.04	0.48
10	6-32 Screws	24	0.06	1.44
11	6-32 Nuts	24	0.05	1.20
12	6-32 Washers	24	0.02	0.48
13	Two-part epoxy	1	2.29	2.29
14	Wheels	4	1.59	6.36
15	Spool of wire	1	2.49	2.49
16	Tape	1	2.59	2.59
17	Metal brackets	6	1.19	7.14
18	Screw thread	1	0.99	0.99
19	Wing nut	2	0.25	0.50
20	TOTAL			$97.61

up a spreadsheet to track these costs. The output screen of the spreadsheet is shown in Table 4.8.

The Unit Cost column indicates the cost per item, while the Quantity column indicates the number of parts of that type that have gone into the vehicle. The Extended column, equal to the product Quantity × Unit Cost, shows the total cost for each part type. The Total entry at the bottom provides the sum of all the extended prices. As each part is added to the vehicle, the students update their spreadsheet. If the total cost exceeds $100, they can experiment by eliminating various parts, such as extra nuts and bolts, if the design allows it, until the total cost is in compliance. At first, they allot 16 batteries for use on competition day, but this quantity causes the total cost to exceed $100. By using the spreadsheet, they are able to determine by trial and error that reducing the battery allotment to 12 results in a total cost less than $100.

Practice!

1. Verify the calculated cells in the spreadsheet of Table 4.7.
2. Find the center of mass in the x-y plane of a set of objects positioned as follows (the numbers in parentheses indicate each object's x-y

coordinates): object 1, 1.2 kg (0.2 m, 0.4 m); object 2, 3.3 kg (1.3 m, 2.3 m); object 3, 0.9 kg (0.8 m, 0.4 m); object 4, 0.2 kg (0 m, 1.7 m).

3. Using published population data of the twenty most populous cities, find the approximate geographical "center-of-mass" of the country.
4. Using published results from the most recent national election, determine the political "center of mass" of the country; that is, find the geopolitical center that represents a balance between liberal and conservative views.
5. Use a spreadsheet to track your expenditures for one week. Then experiment with possible changes in your cash outflow to enable a budget reduction of 5%.
6. Write a spreadsheet to accurately compute your own grade point average (GPA). Does your result agree with your official transcript? Use your data to project your final graduation GPA. What grades must you get in future courses if you are to meet your GPA goal?
7. Write a spreadsheet to compute the estimated electrical energy use of an average household of four occupants over the course of one week. Include a range of typical electrical loads and their *duty cycles* (percentage of time each one is turned on).
8. Use a spreadsheet to calculate the cost of the entire wardrobe, including accessories, that you happen to have in your closet at this moment.
9. Use a spreadsheet to calculate the approximate center of mass, relative to home plate, of a nine-person baseball team with each player in position prior to a pitched ball.
10. Use a spreadsheet to estimate the surface area of a 747 airplane. From this information, estimate the volume of paint required to apply one coat of primer.

EXAMPLE 4.9

MEMS Actuator Revisited

The method of solution by computer iteration was illustrated in Example 4.7 using programs written in MATLAB and C. In Table 4.9, this same problem is solved using an Excel™ spreadsheet formulation for the case $V = 35$ V. Each cell in column 1 represents a "test" value of y and is greater than the value above it by the incremental *dy* entered into cell B6. When this variable is entered into cell formulas elsewhere in the spreadsheet, the Excel "dollar-sign" notation B6 is used, rather than the simple row–column notation B6. This ensures that any references to B6 will be preserved when cell contents are copied from one cell to another. Without the dollar sign notation, the cell coordinates B and 6 would be automatically incremented during copy operations. The dollar sign notation is similarly used to refer to each of the fixed quantities under the B column of the spreadsheet.

Columns 2 and 3 in Table 4.9 contain the computed values of the left-hand and right-hand sides of Equation 4.22, respectively. The entries in column 4, called the residual values, represent the difference between the column 2 and 3 entries. We seek the row for which the residual is zero, that is, the value of *y* at which the

Table 4.9 Solution to the MEMS Actuator Problem of Example 4.9

Voltage:		35	Val. No.	Column 1	Column 2	Column 3	Column 4
1	*k*	30		*y*	F_m	F_e	Difference
2	gap	= 5*10^ − 6	1	0	= B2*D3	= B7*B5*B1^2/(B3 − D3)^2	= E3 − F3
3	side	= 250*10^ − 6	= C3 + 1	= D3 + B6	= B2*D4	= B7*B5*B1^2/(B3 − D4)^2	= E4 − F4
4	area	= A4^2	= C4 + 1	= D4 + B6	= B2*D5	= B7*B5*B1^2/(B3 − D5)^2	= E5 − F5
5	*dy*	= B3/20	= C5 + 1	= D5 + B6	= B2*D6	= B7*B5*B1^2/(B3 − D6)^2	= E6 − F6
6	ε_0	= 8.85*10^ − 12	= C6 + 1	= D6 + B6	= B2*D7	= B7*B5*B1^2/(B3 − D7)^2	= E7 − F7
7			= C7 + 1	= D7 + B6	= B2*D8	= B7*B5*B1^2/(B3 − D8)^2	= E8 − F8
8			= C8 + 1	= D8 + B6	= B2*D9	= B7*B5*B1^2/(B3 − D9)^2	= E9 − F9
9			= C9 + 1	= D9 + B6	= B2*D10	= B7*B5*B1^2/(B3 − D10)^2	= E10 − F10
10			= C10 + 1	= D10 + B6	= B2*D11	= B7*B5*B1^2/(B3 − D11)^2	= E11 − F11
11			= C11 + 1	= D11 + B6	= B2*D12	= B7*B5*B1^2/(B3 − D12)^2	= E12 − F12
12			= C12 + 1	= D12 + B6	= B2*D13	= B7*B5*B1^2/(B3 − D13)^2	= E13 − F13
13			= C13 + 1	= D13 + B6	= B2*D14	= B7*B5*B1^2/(B3 − D14)^2	= E14 − F14

Table 4.10 Output of the Spreadsheet of Table 4.9. Solution lies between *y*-values shown in columns (5) and (6)

	A	B	C	D	E	F	G	H
1	voltage	35	Val.No.	Column 1	Column 2	Column 3	Column 4	
2	k	60		y	F_m	F_e	Difference	
3	gap	5.00E-06	1	0	0.00E01	2.71E-05	−2.71E-05	
4	side	2.50E-04	2	2.50E-07	1.50E-05	3.00E-05	−1.50E-05	
5	area	6.25E-08	3	5.00E-07	3.00E-05	3.35E-05	−3.46E-06	← SOLUTION
6	dy	2.50E-07	4	7.50E-07	4.50E-05	3.75E-05	7.49E-06	← RANGE
7	ε_0	8.85E-12	5	1.00E-06	6.00E-05	4.23E-05	1.77E-05	
8			6	1.25E-06	7.50E-05	4.82E-05	2.68E-05	
9			7	1.50E-06	9.00E-05	5.53E-05	3.47E-05	
10			8	1.75E-06	1.05E-04	6.41E-05	4.09E-05	
11			9	2.00E-06	1.20E-04	7.53E-05	4.47E-05	
12			10	2.25E-06	1.35E-04	8.96E-05	4.54E-05	
13			11	2.50E-06	1.50E-04	1.08E-04	4.16E-05	
14			12	2.75E-06	1.65E-04	1.34E-04	3.12E-05	

Table 4.11 Expansion of Spreadsheet of Table 4.10 Starting with Value (3) from Table 4.10 and Smaller *dy*

	A	B	C	D	E	F	G	H
1	voltage:	35	Val. No.	Column 1	Column 2	Column 3	Column 4	
2	k	30		y	F_m	F_e	Difference	
3	gap	5.00E-06	1	5.00E-07	3.00E-05	3.35E-05	−3.46E-06	
4	side	2.50E-04	2	5.10E-07	3.06E-05	3.36E-05	−3.01E-06	
5	area	6.25E-08	3	5.20E-07	3.12E-05	3.38E-05	−2.56E-06	
6	dy	1.00E-08	4	5.30E-07	3.18E-05	3.39E-05	−2.11E-06	
7	ε_0	8.85E-12	5	5.40E-07	3.24E-05	3.41E-05	−1.66E-06	
8			6	5.50E-07	3.30E-05	3.42E-05	−1.22E-06	
9			7	5.60E-07	3.36E-05	3.44E-05	−7.71E-07	
10			8	5.70E-07	3.42E-05	3.45E-05	−3.26E-07	← SOLUTION
11			9	5.80E-07	3.48E-05	3.47E-05	1.17E-07	← RANGE
12			10	5.90E-07	3.54E-05	3.48E-05	5.60E-07	
13			11	6.00E-07	3.60E-05	3.50E-05	1.00E-06	
14			12	6.10E-07	3.66E-05	3.52E-05	1.44E-06	

mechanical force F_m balances the electrostatic force F_e. The actual output of this spreadsheet is shown in Table 4.10. No single value of y shown in the table yields a precise residual of zero, but the values $y \approx 0.5\ \mu$m and $y \approx 0.75\ \mu$m bracket the correct answer, because the residual in column 4 changes from a negative to a positive value between these two rows.

Table 4.11 shows a second spreadsheet, identical to the first, except that the upper and lower bounds of y values tested are chosen as 0.55 μm and 0.61 μm, and the increment dy is reduced to 0.01 μm, or about a tenth as large as the dy used in Table 4.8. The results of this second spreadsheet show that the actual equilibrium point lies somewhere between $y \approx 0.57$ μm and $y \approx 0.58$ μm. If an even more precise answer is desired, then these y values could be set as new upper and lower bounds and dy could be reduced to an even smaller value.

4.10 SOLID MODELING AND COMPUTER-AIDED DRAFTING

When the ultimate goal of a design effort is a real physical product, formal drawings of the object must augment estimations and rough sketches. Formal drawings form a key link between design engineers and technicians, fabricators, marketing specialists, customers, and other individuals. Pictorial documentation may appear in one of several forms at various stages of the design process. These forms include isometric views, orthographic projections, exploded views, and solid models. Each of these graphic formats serves a particular design need.

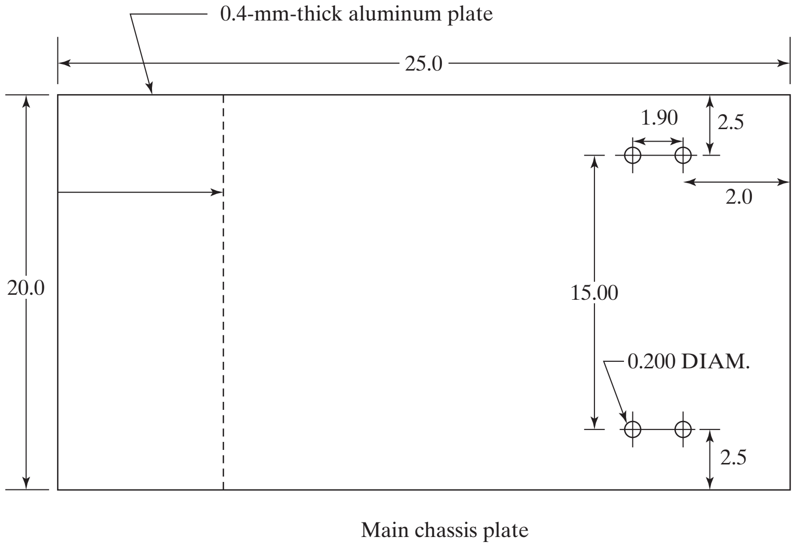
Various methods for generating engineering drawings have evolved over the years. Before computers, the skill of manual drafting (sometimes called "technical drawing") was taught to engineers and technicians in all disciplines. Courses on drafting were common in high school and college curricula, and all self-respecting engineering students owned a complete set of drafting tools. A typical engineer's drafting kit included T-squares, triangular rules, mechanical pencils, erasers, inking pens, and drawing templates. Drafting skills learned in school carried over to the workplace, as the practice of manual drafting was a mainstream activity in most engineering companies. In any given engineering firm, entire rooms would be filled with drafting tables and engineers at work.

Nowadays, computers have virtually eliminated the need for manual drafting skills. Much as the typewriter replaced manual penmanship, and the word processor replaced the manual typewriter, so have numerous computer-aided design (CAD) software tools replaced the need for engineers with manual drafting skills. Popular CAD software packages, including ProEngineer™ and SolidWorks™, are used by engineering companies everywhere. This section reviews the key steps involved in using these types of CAD tools for generating engineering drawings.

4.10.1 Why an Engineering Drawing?

Consider the engineering drawing of the chassis plate shown in Figure 4.35. For the purpose of this discussion, its end use does not matter. This object might be used, for example, as part of a vehicle for the MicroMouse competition mentioned in Example 4.7. Contrast the detailed engineering drawing of the figure with the following written fabrication instructions:

> The plate should be made from 0.4-cm-thick aluminum stock and should be a rectangle 25-cm long by 20-cm wide. It should be drilled with four holes. The first should be located 2.0 cm from the right-hand, 20-cm edge of the plate, and 2.5 cm from the upper 25-cm edge. These dimensions should be held to a tolerance of 0.1 cm. The second hole should be located 1.9 cm to the left of the first, to within 0.05 cm. Both holes should be drilled to a diameter of 0.2 cm with a tolerance of 0.001 cm. These holes should be duplicated using the same dimensions at the other corner of the plate, but located 2.0 cm from the right-hand, 20-cm edge of the plate, and 2.5 cm from the lower 25-cm edge.



Tolerance table All dimensions in cm	
X	±0.5
X.X	±0.1
X.XX	±0.05
X.XXX	±0.001

Figure 4.35
Drawing of a chassis plate to be sent to a machinist for fabrication.

For most people, the diagram conveys the information much more succinctly than does the written version. The human brain is an extremely efficient image processor, and drawings will almost always surpass written prose as a means for conveying information. The superiority of human imaging power motivates the well-known saying, "A picture is worth a thousand words."

4.10.2 Types of Drawings

As noted previously, engineering drawings come in several widely accepted forms. Categories include hand sketches, isometric projections, orthographic projections, exploded views, and solid models. Each type of drawing has its own particular use in the engineering design process. During the idea-generation phase, hand sketches can be extremely useful. By quickly drawing things on paper, an engineer can rapidly convey a design concept to other team members. The very act of producing a hand sketch can serve as a catalyst for ideas. Hand sketches also are the method of choice for entering ideas into engineering logbooks.

When a commitment has been made to pursue a particular design concept, more formal types of drawings are in order. The drawing of Figure 4.36 shows the isometric view of a simple part. An isometric view is a three-dimensional rendition in which the parallel sides of the actual object are drawn as parallel lines on the page. Isometric views differ from perspective drawings as taught in art and advertising graphics, in which parallel lines point to a distant "vanishing point." An isometric projection becomes a slightly distorted rendition of the object, but if the part is small and distances are short, the differences will be minor. The isometric view of Figure 4.36, for

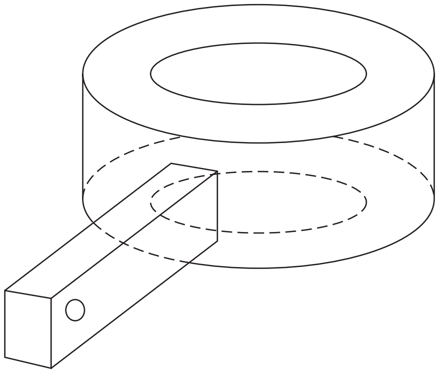


Figure 4.36
Isometric view of cylindrical collar with rectangular tab and pin hole.

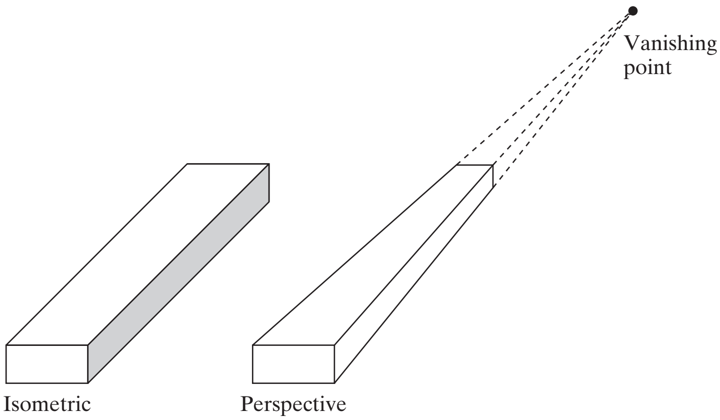


Figure 4.37
Isometric and perspective views of a long narrow box. In the isometric view, all parallel lines on the physical object are drawn parallel to each other on the page. In the perspective view, parallel lines on the physical object are drawn so that their extensions intersect at some distant vanishing point.

example, differs little from its equivalent perspective drawing, whereas the isometric and perspective views of a long narrow box, shown in Figure 4.37, differ significantly. The principal advantage of the isometric view is that it is much easier to draw than a perspective drawing. Also, compared with its related counterpart, the orthographic projection, the isometric drawing provides a "birds-eye view" of the object that conveys many of its features at a single glance.

The two-dimensional orthographic projections of an object shows its front, side, and end views. In some cases, a fourth view may be necessary. Figure 4.38 shows an orthographic projection of the same part described by the isometric view of Figure 4.36. Orthographic projections are principally used by machinists for whom such drawings provide all the information needed to fabricate the actual part. Dimensions, tolerances, and machining details are very easy to convey on an orthographic projection. Compared with other types of drawings, orthographic projections are exceptionally easy to draw but require more interpretation on the part of the person trying to read the drawing.

An exploded view, or assembly drawing, is used to describe how multiple parts are to be assembled to form the working whole. Dotted lines convey paths to connection or attachment. The diagram in Figure 4.39, for example, shows how the part of Figure 4.38 is to be assembled with other related parts. Although exploded views sometimes can be difficult to draw, they are very useful for conveying information about complex structures.

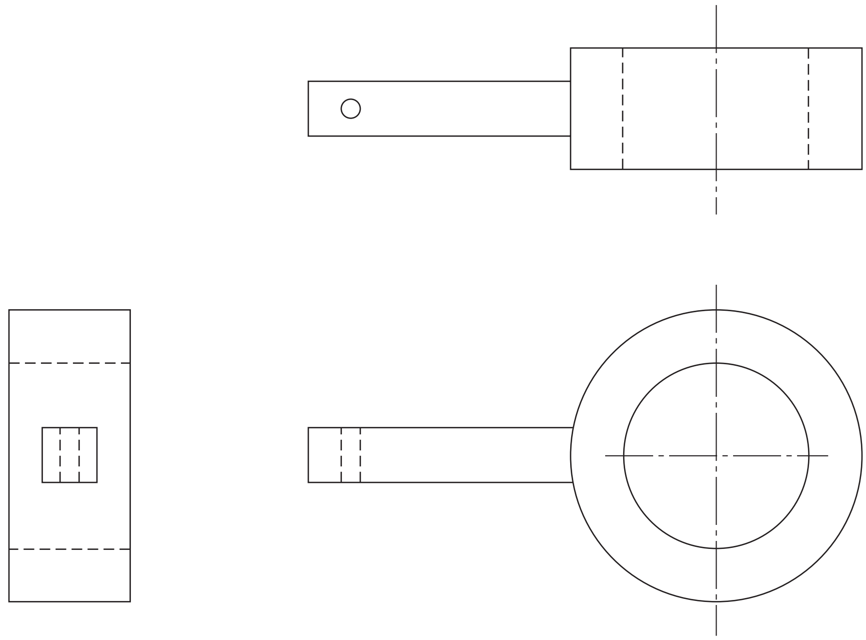


Figure 4.38
Orthographic projection of the part of Figure 4.38.

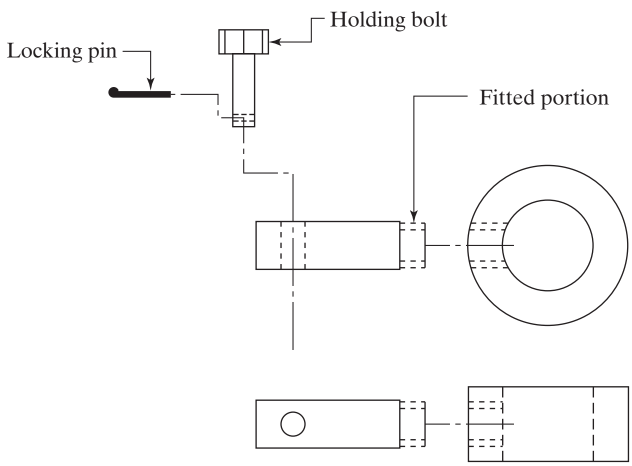


Figure 4.39
Exploded view of several parts shows the way in which they are to be assembled.

The most computationally sophisticated type of drawing produced by a CAD system is called a *solid model*. Unlike isometric and orthographic projections, which depict just the surfaces of an object, a solid model rendition includes information about the surfaces and the interior details of the object. A solid model is much more than a simple visualization. It contains a complete mathematical description of the object's material properties as well as its interior and exterior dimensions. This additional information makes the solid model useful for many applications besides viewing. For example, the solid model can be used to predict the object's deformation under applied stress, its reaction to temperature changes, and its interaction with other parts in the system. A solid model of a part is invaluable for rendering the sort of animations associated with computer graphics. A solid model allows the user to view an object's hidden features, as well as view the object as its rotation is simulated.

At the core of solid modeling lies a computational method known as finite element analysis (FEA), in which an object is represented by a large number of interconnected cells, or *elements*. A finite element analysis keeps track of the mutual interaction between each cell and its neighbors and computes the behavior of each cell in response to internal and external stimuli. The popular CAD tools ProEngineer and SolidWorks, for example, incorporate finite-element analyses into the solid models of parts and objects.

When an object has been rendered in CAD software as a solid model, the latter becomes invaluable when the part is ready for manufacturing. Sophisticated software linked to computer-guided machining tools—lathes and milling machines, for example—can be instructed to fabricate the part directly from its solid model representation. The language used by this class of machines is called *computer numeric control*, or CNC. The CNC system enables an engineer to design a part on the computer screen, then send its CNC code directly to a computer-controlled machine for fabrication from metal, plastic, or other machinable materials. Another method for fabricating things directly from solid models is called *rapid prototyping*. In this technique, a rendition of the part suitable for prototype needs is produced using a laser beam that shapes the part from very thin cross sections of plastic resins or paper. The prototype part is assembled, literally layer by layer, by stacking its cross sections.

EXAMPLE 4.10

Producing a Simple Part

This example illustrates the steps involved in producing the solid model of the part shown in Figures 4.36 and 4.38. The steps for producing the solid model drawing are summarized here in a generic way, but they are similar to those one would follow when using specific CAD tools such as ProEngineer and SolidWorks.

Step 1 *Open a new drawing screen.* Open a new part screen in the CAD software by choosing NEW from the software's FILE pull-down menu. A blank screen appears on which the part description will be drawn.

Step 2 *Sketch the principal cross section* (Figure 4.40). Using the mouse and keyboard cursors, sketch the part's basic cross section on the screen. Even though the part may have features in all three dimensions, only its principal cross section (e.g., its top view) need be drawn at this stage. The other views of the part will be generated automatically in a later step. This initial cross section of the part can include some of its machined features. For example, the part in Figure 4.38 includes a drilled hole in its center whose location and dimensions are specified in the initial cross section. The radii of corners and bends in the cross section also can be specified at this stage. This step is sometimes desirable because no machining process can produce perfect angles from solid materials.

Step 3 *Dimension the sketch* (Figure 4.41). Major features of the part—lines, circles, and arcs, for example—are selected on the screen and their dimensions are specified in the units chosen for the drawing (e.g., mm, cm, or in). This step also provides a reference scale for all the other lines and curves that will make up the finished drawing.

Step 4 *Extrude the cross section* (Figure 4.42). The defined and dimensioned cross section from the previous step is extruded, or "stretched," in the direction

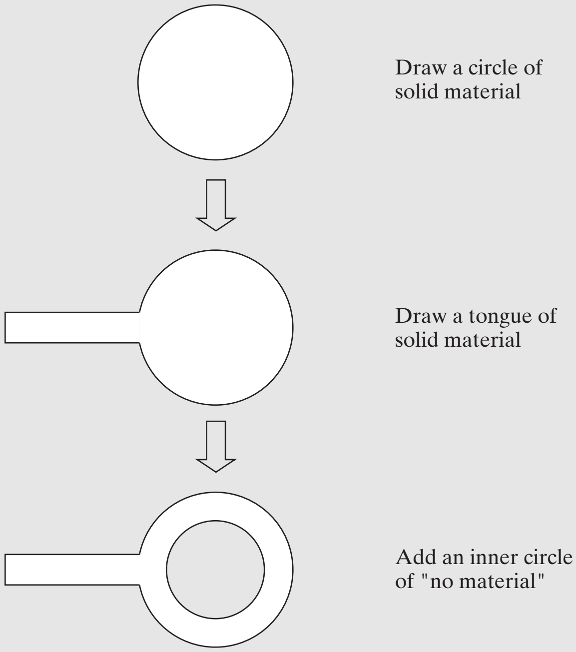


Figure 4.40
The principal cross section of the part of Figure 4.40 is drawn on the computer screen.

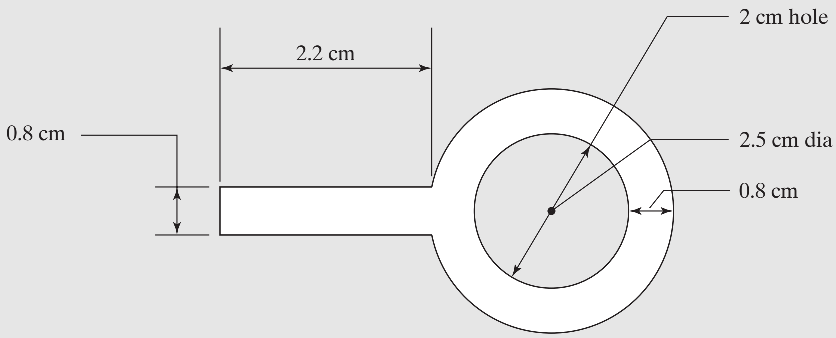


Figure 4.41
Dimensions are added to the cross-sectional sketch.

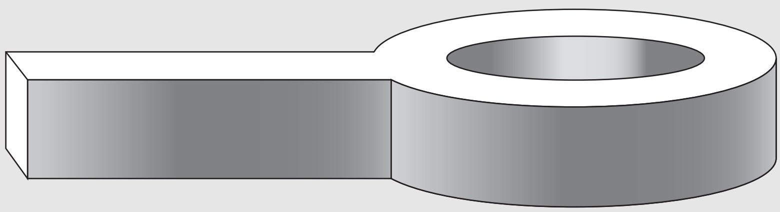


Figure 4.42
The cross section is extruded to form a solid model.

perpendicular to the drawing plane to form a three-dimensional version of the part. The extrusion of a circle produces a cylinder, while the extrusion of a rectangle produces a rectangular solid. The extrusion operation leading to Figure 4.42 thus results in a cylindrical solid with a hole in its center; it also has a rectangular appendage called a tab.

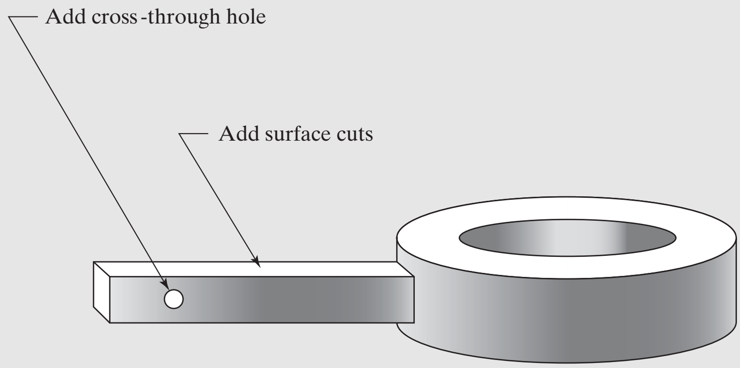


Figure 4.43
Other features are added to the extruded model that were not created during the first extrusion. In this case, a hole whose axis is parallel to the cross-sectional plane is drawn through the rectangular tab, and the top and bottom faces of the tab are trimmed.

Step 5 *Add features to the extruded part* (Figure 4.43). Once the cross section has been extruded to form a three-dimensional solid model, the three orthographic projections of the part will be available to the designer. Features that are not part of the principal cross section, including perpendicular holes, material cuts, and rounded corners, are added to the object at this stage using the appropriate orthographic view. In this case, a hole whose axis is parallel to the cross-sectional plane is drawn through the rectangular tab, and the top and bottom faces of the tab are trimmed.

Step 6 *Save the file.* The file is saved for future use, printing, and so forth. The solid model rendition of the part is now complete and can be sent as a drawing to other engineers for review in either hard copy or electronic form. Additionally, it can be sent to a CNC-equipped machine tool or to a rapid prototyping machine for computer-controlled fabrication.

4.11 SYSTEM SIMULATION

Sometimes, engineers must model the dynamic behavior of a system, that is, the way in which the various parts of the system interact over time. A dynamic analysis differs from the finite element analyses provided by simulation tools such as ProEngineer and SolidWorks in that the various parts of the system are represented mathematically in block diagram form, rather than as dimensioned objects having physical properties such as density and elasticity. System simulation is useful for analyzing physical objects such as machinery, but it also is invaluable for analyzing intangible entities such as transportation systems, manufacturing processes, or even financial systems. Dynamic simulation tools are useful whenever the system can be mathematically described by *differential equations* in which the value of a variable depends on its own derivative or that of other variables. A simple pendulum or a guitar string, for example, can each be described by a differential equation.

One popular dynamic system simulation tool that runs as an appendage to MATLAB is called Simulink®. The programmer uses Simulink to draw a block diagram that represents the dynamic system to be simulated. The program then determines the relevant differential equations and sends them to MATLAB for solution and display. This layering of software shells, wherein one program produces code that can be solved by another, is common in software engineering.

EXAMPLE 4.11

Thermostat Control

The concept for the following example is derived from an example found in the instruction manual that comes with the student version of Simulink. These block diagrams are more generic than those actually used within Simulink, but they illustrate the concepts involved. Suppose that you were given the task of designing a temperature control system for a small building heated by a furnace. Because the building has thermal memory, that is, it retains heat for some time when the furnace goes off and requires time to heat up when the furnace is turned on, the furnace-building combination constitutes a dynamic system. The variables of the system include the desired temperature (the setting of the thermostat) and the actual indoor temperature. The program determines the difference between the two temperatures and turns on the switch if $T_{\text{actual}} < T_{\text{thermostat}}$. Turning on the switch causes the furnace to produce heat that increases indoor temperature, but with a time delay τ_1 (sometimes called a time constant). In the meantime, regardless of the status of the furnace, heat continually flows out of the building in proportion to the difference between the indoor and outdoor temperatures. The time constant governing this outward heat flow is τ_2.

A block diagram description of the system is shown in Figure 4.44. The output of the system, produced by Simulink for the parameters $T_{\text{thermostat}} \approx 68°\text{F}$, $T_{\text{outdoor}} \approx 32°\text{F}$, $\tau_1 \approx 4$ min, and $\tau_2 \approx 12$ min, is shown in Figure 4.45. This plot indicates that the temperature falls slowly until T_{actual} falls below $T_{\text{thermostat}}$. At that point in time, the furnace turns on and raises the temperature until $T_{\text{actual}} \approx T_{\text{thermostat}}$. Note that the building temperature continues to rise for some time after the furnace is turned off. This phenomenon occurs because of the nonzero time delays in the system. Although the thermostat recognizes that T_{actual} has reached $T_{\text{thermostat}}$, the time delay governing the transfer of heat from the furnace and the building causes additional heat to flow from the former to the latter.

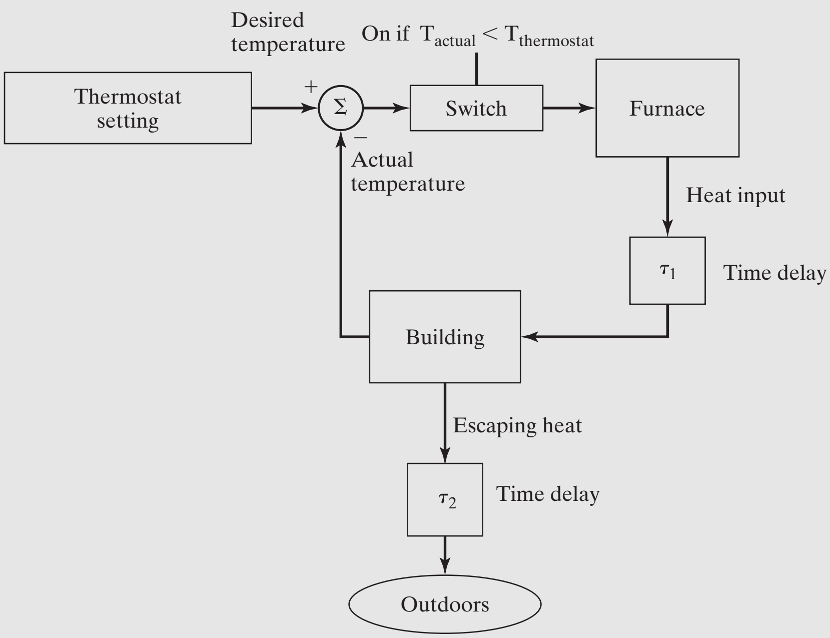


Figure 4.44
Block diagram description of the dynamic system of a building and its heating furnace.

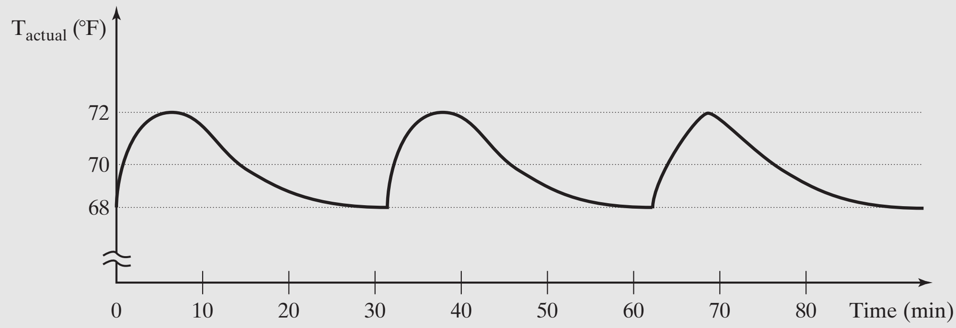


Figure 4.45
Results of the simulation with $T_{thermostat} = 68°F$, $T_{outdoor} = 32°F$, $\tau_1 = 4$ min, and $\tau_2 = 12$ min.

4.12 ELECTRONIC CIRCUIT SIMULATION

Circuits involving electricity can take many forms. A circuit that delivers energy from batteries, generators, or fuel cells is commonly called an *electrical* circuit. Examples of electrical circuits include flashlights, motor drives for electric subway cars, power lines that deliver electricity to homes, and wiring systems inside automobiles and trucks. These systems typically involve only a few basic component types that might include batteries, generators, wires and switches, plus loads that can be modeled as simple resistors. A device such as a resistor is linear and obeys Ohm's law: $v = iR$, where v is the voltage applied to the resistor, i is current that flows in response, and R is the resistance value.

In contrast to resistors, semiconductor devices are usually nonlinear. Their voltage-current equations are not simple linear equations; rather, they take on more complex forms. For example, the current–voltage equation for a simple diode is given by the exponential equation:

$$i = I_S\,(e^{v/nV_T} - 1) \tag{4.30}$$

where n, I_S, and V_T are constants.[3]

The transistor, a three-terminal device, has an even more complicated set of governing equations. Other nonlinear devices include the light-emitting diode (LED), and the integrated circuit. When a circuit contains nonlinear devices, it is usually called an *electronic* circuit, rather than an "electrical" circuit.

Calculating the voltages and currents in electronic circuits, particularly those with multiple semiconductor devices, can be a daunting task. Even the simple circuit shown in Figure 4.46 cannot be solved by simple algebra. Circuits that contain

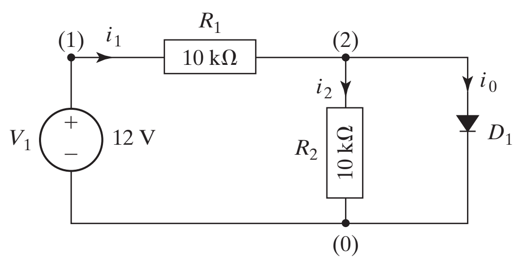


Figure 4.46
Circuit to be simulated using PSPICE. Each node of the circuit has been assigned a unique number. The common "ground" node at the bottom is assigned the number 0.

[3]For $v > V_T$, the equation is sometimes approximated as $i = I_S e^{v/nV_T}$.

multiple diodes, transistors, or integrated circuits are readily solved using a circuit simulation tool called SPICE. Several derivatives of this program, including PSPICE and ORCAD, all use the original core SPICE calculation program, developed for large mainframe computers in the 1970s at the University of California at Berkeley.

SPICE can model voltage sources (e.g., batteries, the output of dc power cubes, and ac transformers); resistors; other linear circuit elements called capacitors and inductors; and all sorts of semiconductors, including diodes, transistors, and operational amplifiers. It also enables the entry of devices with user-specified characteristics. SPICE can perform steady-state analyses, simulate circuit behavior over time, and model the effects of temperature, thermal noise, and random component variations. Output is provided in several forms, including text-based listings of the circuit's various voltage, current, and power dissipation values, as well as plots versus time of selected circuit variables. The internal core program within SPICE relies on text-based entry of the circuit description. This entry mode stems from the origins of SPICE, which was developed as public-domain software for implementation on mainframe computers with punched cards and line printer output. More modern versions of SPICE, such as PSPICE-A/D and ORCAD, provide powerful graphical interfaces and pull-down lists of predefined commercial parts from which to build the circuit. Ultimately, however, these higher end programs translate circuit information entered graphically into traditional text-based SPICE code. Student evaluation versions of SPICE are available for download on the Internet. (See, for example, *www.orcad.com*).

In text-based SPICE code, the circuit is described by a set of program statements stored in a file named FILENAME.CIR, where FILENAME is chosen by the user. This data file is retrieved by SPICE during program execution. Each line of the input file contains one program statement that either describes a single part or instructs SPICE with a command. Comment lines are preceded by an asterisk (*) or a semicolon (;).

The typical input file consists of a required title line, a set of element statements that describe the circuit, and a set of control statements that instruct SPICE during program execution. Control statements always begin with a period. The entire file is terminated by the control statement .END. In order to simulate a circuit in SPICE, its various nodes must be assigned numbers. One node (usually the most common node, or "ground") must be assigned the number zero.

EXAMPLE 4.12

Nonlinear Circuit Simulation

The circuit of Figure 4.46 is easily solved using SPICE. Following is a program listing that instructs SPICE to calculate the voltage across, current through, and power dissipated in each circuit component. Each node has been numbered, and the bottom common node has been assigned the number 0:

```
SPICE SIMULATION OF CIRCUIT OF Figure 4.48
*Specify the elements in the circuit.
V1 1 0 dc 12V           ;12-V dc voltage source between nodes 1
```

```
                           ;and 0 (+ side of source at node 1)
R1 1 2 10000               ; A 10-kΩ resistor between nodes 1 and 2
R2 2 0 10000               ; A 10-kΩ resistor between nodes 2 and 0
D1 2 0 diode               ; A diode pointing from node 2 to node 0
.MODEL diode D(Is=1e-5m n=2)   ;A statement that identifies the
                               ;parameters of the diode
.OP                        ;Calculate the operating point (voltage
                              ;and current) of every device
.END
```

Here is a portion of the text output that results from running this simulation:

```
********SMALL SIGNAL BIAS SOLUTION TEMPERATURE = 27.000 DEG C
NODE   VOLTAGE   NODE   VOLTAGE
 (1)    12.00     (2)    0.5995
VOLTAGE SOURCE CURRENTS
NAME CURRENT
V1 −1.140E-03
TOTAL POWER DISSIPATION 1.37E-02 WATTS
JOB CONCLUDED
TOTAL JOB TIME .65
*************************************************************
```

This output indicates that the diode voltage will be equal to about 0.6 V, and the source current will be equal to about 1.1 mA. The entire circuit will dissipate 13.7 mW (i.e., it will convert 13.7 milliwatts of electrical power to heat).

4.13 GRAPHICAL PROGRAMMING

One category of software tool that is extremely useful for certain design tasks is called graphical programming. Marketed under commercial software packages that include LabVIEW™, HP-VEE, and Softwire, graphical programming languages enable engineers to create programs simply by connecting together visual objects on the computer screen. An object can be a formula, a data source, a display, or a logical function. Objects are tied together much like the boxes of a flowchart that describe a computer program. Some graphical programming languages enable the user to interface directly with benchtop instruments, such as multimeters, function generators, and oscilloscopes. Interconnections are made using digital control links, such as the IEEE-488 bus or GPIB (general purpose instrument bus). Data can be sent to and from the instruments via graphical program objects. Connections can also be made to analog-to-digital (A/D) and digital-to-analog (D/A) plug-in cards directly from the computer bus. This environment is ideal for creating automated industrial systems consisting of analog-to-digital and digital-to-analog conversion boards plus a graphical programming interface run from a desktop PC.

An example of a typical graphical program is shown in Figure 4.47. This program is designed to measure the voltage across and current through a motor being tested under load. The mechanical load, expressed in terms of the number of weights applied to a frictional brake, is entered into the program by the user.

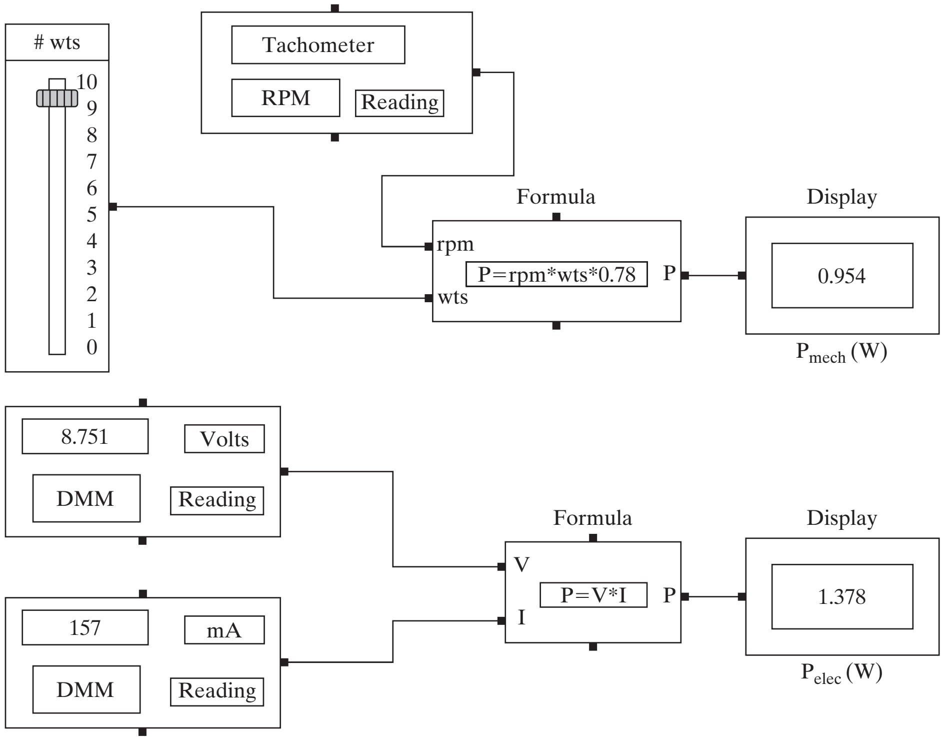


Figure 4.47
Graphical interface program designed to measure the voltage across and current through a motor under test. The mechanical load, expressed in terms of the number of weights, is entered into the program by the user.

Professional Success: When are Computers Really Necessary?

Computers play an important role in solving engineering problems. Their use in virtually all technical disciplines has come to be expected, and the use of computers has become a mandatory part of educational programs in engineering. Despite the highly beneficial symbiosis between design and the computer, a danger exists when use of the computer supersedes human creativity and judgment in the design process. This phenomenon is sometimes called the "can-do" trap. All too often, we spend time doing things on a computer simply because we *can* do them. We simulate mechanical structures or circuits and blindly accept the results without verifying the fundamental principles behind the simulations. We assume a commercial software package will produce genuine results without comparing its output with real physical tests. We create documents that lack real substance but are visually perfect composites of embedded graphics, color printing, and fancy fonts. We create laptop slide presentations with moving arrows, sound, and video, but do an inferior job of conveying any real information. A good engineer learns to harness the power of the computer without falling into the can-do trap. The computer is a precision tool that should be used like a fine instrument, and not as a heavy hammer. In engineering design, computers should become an adjunct to our own creative process, not our preoccupation. The examples of this chapter illustrate several ways in which the computer can rightfully be used as a meaningful part of the design process.

4.14 MICROPROCESSORS: THE "OTHER" COMPUTER

We usually associate the term "computer" with the desktop PC or networked workstation. In truth, these integrated computational machines represent but a small fraction of all the computers in use today. The most prolific computer, the microprocessor, far exceeds in numbers the desktop PC. A microprocessor is a single-chip computer that performs digital functions at the fundamental logic level. Microprocessors are excellent choices for solving many design problems, especially those involving real-time control by computer. These applications are sometimes referred to as *embedded computing*.

In its most basic form, a microprocessor is a computer with no disk drive, keyboard, monitor, or external memory chips. It simply consists of a silicon microcircuit housed in a plastic or ceramic package. A microprocessor lies at the heart of just about every appliance or piece of equipment that requires intelligent control. Microprocessors can be found inside automobiles, microwave ovens, washing machines, children's toys, cellular telephones, fax machines, printers, and, of course, personal computers. The Pentium® chip made by Intel and the Athlon™ chip made by AMD are examples of high-performance microprocessors that are connected to peripheral devices to create desktop PCs. The more numerous microprocessors found inside appliances and machines are usually much simpler devices than Pentium or Athlon chips, but their operating principles are the same. Microprocessors operate in a base 2 arithmetic system of logic rules known as *Boolean algebra*. The rules of Boolean algebra allow a microprocessor to make decisions based on the status of stored or incoming digital data.

EXAMPLE 4.13

Microprocessor Speed Control

This example illustrates the use of a microprocessor for a timing and speed control operation. The application involves the design of a crane that must lift an object for a predetermined distance. The crane works by winding a flexible steel cable around a rotating drum. A sensor, depicted in Figure 4.48, provides information about the net distance that the crane has lifted the object. A transparent disk with opaque radial lines passes between the arms of an optical detector. The disk is connected to the drum of the crane. After each increment of rotation of the transparent disk, a line passes between the arms of the optical sensor and causes it to send a pulse to the microprocessor. Because the circumference of the drum and the number of pulses per complete rotation is known, the total retraction of the cable, and hence the change in height of the object, can be found. By simply counting pulses, the microprocessor can compute the total cable intake and issue a "stop" command

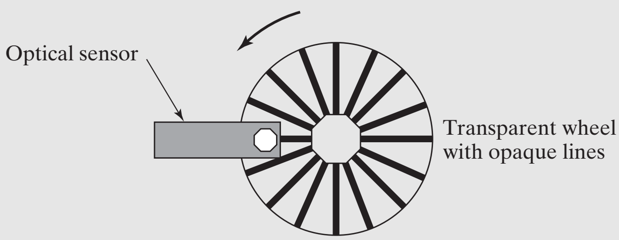


Figure 4.48
Optical encoder wheel produces a digital pulse every 22.5° of rotation.

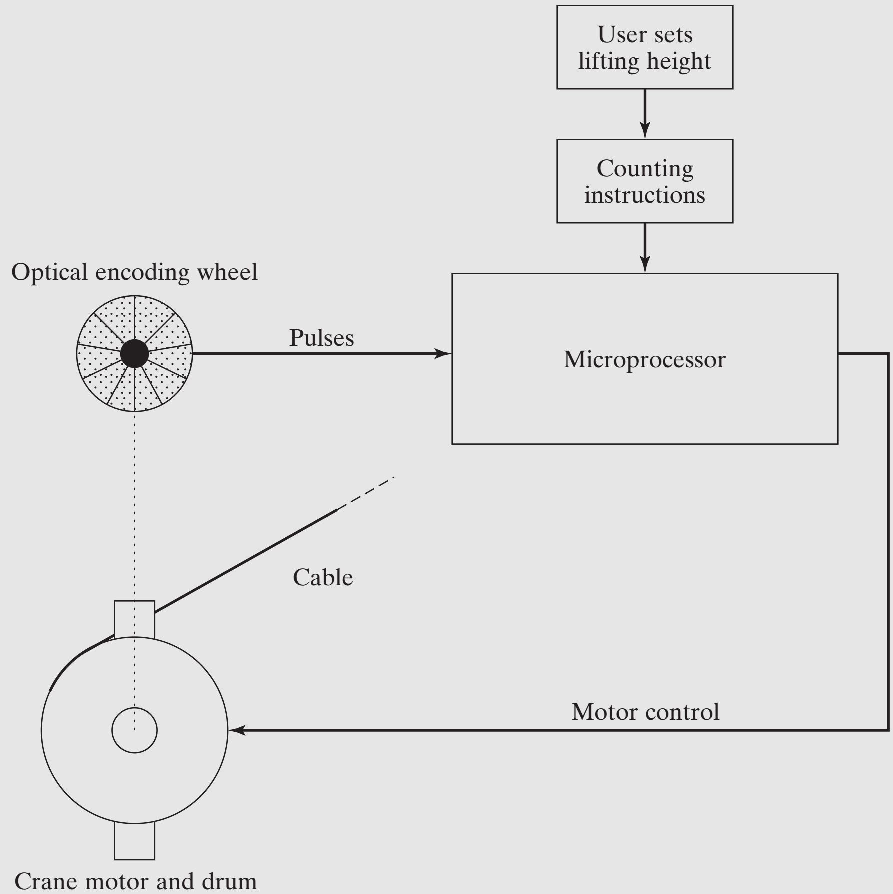


Figure 4.49
Block diagram of system consisting of optical encoding wheel, microprocessor, crane motor, and cable drum.

when the desired lift height has been reached. A block diagram of the complete system consisting of the optical encoder, microprocessor, crane motor, and cable drum, is shown in Figure 4.49.

Practice!

1. Discuss the way in which a microprocessor might be used to automatically produce timing pulses for a traffic light sequencer.
2. Discuss the way in which a microprocessor might be used to build a digital alarm clock.
3. Identify ten appliances or machines that utilize a microprocessor.
4. A cellular telephone contains a microprocessor that provides its operational functions. If you have a cell phone, make a map or flow chart of all functions performed by its microprocessor.
5. A microprocessor uses internal binary code (a digital system of ones and zeros) to perform its various functions. People who program microprocessors sometimes use *hex code* to represent binary numbers. What is the relationship between binary code and hex code?

6. Do some research and determine the various ways in which microprocessors are used in automobiles.
7. Draw a flowchart and block diagram of the way in which a microprocessor might be used in a vending machine.
8. Your computer printer contains its own internal microprocessor. Discuss why it needs one and the functions that it must perform.
9. Draw the flowchart for a microprocessor program that might be used to make a four-function calculator.
10. What is the difference between a microprocessor and an embedded microcontroller?

KEY TERMS

Dimensioning
Estimation
Microprocessor
Prototype
Reverse Engineering
SI Units
Significant Figures
Simulation
Solid Model
Specification Sheet
Spreadsheet
Tolerance
Unit Reconciliation

PROBLEMS

Estimation

4.1 This problem relates to a design competition in which a 1-kg battery-powered vehicle must be propelled up a 0.9-m tall ramp within a 15-second time interval.

(a) For a run time of 9 seconds, how much power must the battery supply to the vehicle? What would be a reasonable estimate of the average power flow over a 15-second run time?

(b) Suppose that batteries are chosen that can supply only 50 mA of peak current. Such a decision might be made to reduce battery weight and produce a lighter vehicle. If vehicle weight is reduced to 0.5 kg, what power flow can be expected? What will be the peak battery current?

(c) If motors are chosen that have 95% efficiency and mechanical losses are 60%, what will be the required battery current?

The following four problems involve vector addition. Vector manipulation is an important skill for estimating forces in mechanical systems. When adding forces or other quantities represented as vectors, the principles of vector addition must be followed. Vectors to be added are first decomposed into their respective x, y, and z components. These components are added together separately, then recombined to form the total resultant vector. Sometimes, it's convenient to decompose vectors into components lying on axes other than rectilinear x-, y-, and z-axes.

4.2 Two guy wires securing a radio antenna are connected to an eye bolt. One exerts a force of magnitude 3000 N at an angle of 10° to the vertical. The other exerts a force of 2000 N at an angle of 75° to the vertical. Find the magnitude and direction of the total force acting on the eye bolt.

4.3 A guy wire exerts a force on an eye bolt that is screwed into a wooden roof angled at 30° to the horizontal. The guy wire is inclined at 40° to the horizontal. If the eye bolt is rated at a maximum force of 1000 N perpendicular to the roof, how much tension can safely be applied to the guy wire?

4.4 A large helium-filled caricature balloon featured in a local parade is steadied by two ropes tied to its midpoint. One rope extending on one side of the balloon is inclined at 20° to the vertical. A second rope located on the other side of the balloon is inclined at 30° to the vertical. If the balloon has a buoyancy of 200 kN, what will be the tension in each of the ropes?

4.5 An eye bolt is fixed to a roof that is inclined at 45° relative to the x-axis. The eye bolt holds three guy wires inclined at 45°, 150°, and 195°, respectively, measured clockwise from the x-axis. These wires carry forces of 300 N, 400 N, and 225 N, respectively. What is the magnitude and direction of the total resultant force? What are the components of force measured perpendicular and parallel to the roof line?

Problems 6 through 22 can help you develop your design-estimation skills. Discuss them with your friends, and see if you arrive at the same approximate answers.

4.6 Estimate by hand the amount of paint required to paint a Boeing 767 airplane.

4.7 Estimate the cost of allowing a gasoline-powered car to idle for 10 minutes.

4.8 Estimate the daily consumption of electrical energy by your dormitory, residence, apartment building, or home. (Check your estimate against real electric bills if any are available.)

4.9 Estimate the cost of leaving your computer running 24 hours per day.

4.10 Estimate the cost savings of installing storm windows on an average-sized four-unit apartment building.

4.11 Estimate the gross weight of a fully loaded 18-wheel tractor trailer.

4.12 Estimate the number of single-family houses in your home state.

4.13 Estimate the number of bolts required to assemble the Golden Gate Bridge.

4.14 Estimate the number of bricks in an average-sized house chimney.

4.15 Compute the surface area of all the windows in your dorm, apartment building, or house where you live.

4.16 Estimate the amount of carpet that it would take to cover the playing field at Chicago's Wrigley Field.

4.17 Estimate the total mass of air that passes through your lungs each day.

4.18 Estimate the time required for a stone to fall from sea level to the bottom of Marianas Trench, the lowest point in the Earth's oceans.

4.19 Estimate the cost of running a medium-sized refrigerator for a year.

(a) Estimate the weight of a layer of shingles needed to cover a single-family ranch-style house that has a flat roof.

(b) Now revise your calculations for a pitched roof.

4.20 Estimate the physical length of a standard 120-minute VHS videocassette tape.

4.21 Estimate the number of microscopic pits on 2-hour-long digital video disk (DVD).

4.22 Estimate the number of books checked out of your school library each week.

Significant Figures

4.23 When calculations are performed, the answer will only be as accurate as the least accurate step in the chain. An answer should be expressed with the same number of significant figures as the least accurate factor in the computation.

(a) Express the result of each of the following computations with an appropriate number of significant figures.

(b) Express the result in the appropriate SI unit.

$$V = (12.9\ \text{mA})(1500\ \Omega)$$
$$F = 2.69\ \text{kg} \times 9.8\ \text{m/s}^2$$

$$F = -3.41 \text{ N/mm} \times 6.34 \text{ mm}$$
$$i = \frac{1.29 \text{ mA}}{100}$$
$$Q = (6.891 \times 10^{-12} \text{ F})(2.34 \times 10^{3} \text{ V})$$

4.24 **(a)** Evaluate each of the following numerical computations, expressing the result with an appropriate number of significant figures.
(b) Express the result in the appropriate SI unit.

$$F = 1221 \text{ kg} \times 0.098 \text{ m/s}^2$$
$$V = 56 \text{ A} \times 1200 \text{ ohms } (\Omega)$$
$$x = 76.8 \text{ m/s} \times 1.000 \text{ s}$$
$$m = 56.1 \text{ lb} + 45 \text{ lb} + 98.2 \text{ lb}$$
$$i = \frac{91.4 \text{ V}}{1.0\ \Omega}$$
$$P = \frac{(5.1 \text{ V})^2)}{1.0\ \Omega}$$

Dimensioning

4.25 Measure the dimensions of an ordinary coat button. Prepare a dimensioned sketch of the button, complete with a tolerance table.
4.26 Prepare a dimensioned sketch of a common coffee cup.
4.27 Measure the dimensions of a bicycle and prepare a dimensioned sketch of it.
4.28 Make a dimensioned sketch of this textbook.

Prototyping

4.29 Suppose that 100 mA of steady current flows from a 9-V battery via a timer circuit to a motor. If the controller circuit is 92% efficient and the motor is 95% efficient, how much mechanical power is transferred to the motor wheels (neglecting bearing friction)?
4.30 Ohm's law states that the voltage across a resistor is equal to the current flowing through it times the resistor value ($V = IR$). Calculate the current flowing through the following resistors if each has a measured voltage of 24 V across it:

$$1\ \Omega, 330\ \Omega, 1\ \text{k}\Omega, 560\ \text{k}\Omega, 1.2\ \text{M}\Omega\ (\textit{Note}: 1\ \text{k}\Omega \equiv 10^3\ \Omega; 1\ \text{M}\Omega \equiv 10^6\ \Omega).$$

4.31 Ohm's law states that the current flowing through a resistor is equal to the voltage across it divided by the resistor value ($I = V/R$). Calculate the voltage across each of the following resistors if each has a measured current of 10 mA: 1.2 kΩ, 4.7 kΩ, 9.1 k Ω, 560 kΩ, 1.2 MΩ. (*Note*: 1 k$\Omega \equiv 10^3\ \Omega$; 1 M$\Omega \equiv 10^6\ \Omega$).
4.32 Kirchhoff's current law states that the algebraic sum of currents flowing into a common connection, or node, must sum to zero. Suppose that currents of 1.2 A, −5.4 A, and 3.0 A flow on wires that enter a four-wire node. What current must flow into the fourth node?
4.33 Kirchhoff's voltage law states that the sum of voltages around a closed path must sum to zero. Three resistors are connected in series with a 9-V battery. The measured voltages across two of the resistors are 5 V and 2.5 V, respectively.
(a) What is the voltage across the third resistor?
(b) The first two resistors have values of 100 Ω and 50 Ω, respectively. What is the current flowing through the third resistor?

4.34 A heat sink enhances the thermal contact between a hot surface and the surrounding air, leading to a cooler device and a larger power-dissipation capability. Heat removal is important, because excess heat can cause failure in many types of devices. A heat sink is characterized by a heat-transfer coefficient, or thermal resistance, θ (capital Greek theta), which describes the flow of heat from the hotter sink to the cooler ambient air. The ambient air is assumed to remain at a constant temperature. This thermal flow can be described by the equation $P_{\text{therm}} = (T_{\text{sink}} - T_{\text{air}})/\theta$, where P_{therm} is the thermal power flow out of the device, T_{sink} is the temperature of the heat sink, and T_{air} is the temperature of the air.

(a) A power device is mounted on a heat sink for which $\theta = 4.5$ °C/W. A total of 10 W is dissipated in the device. What is the device temperature if the ambient air temperature is 25°C?

(b) A device rated at 200°C maximum operating temperature is mounted on a heat sink. If the ambient air is 25°C and 25 W of power must be dissipated in the device, what is the largest thermal coefficient θ that the heat sink can have?

4.35 A switch is a mechanical device that allows the user to convert its two electrical terminals from an open circuit (no connection) to a short circuit (perfect connection) by moving a lever or sliding arm. A switch pole refers to a set of contacts that can be closed or opened by the mechanical action of the switch. A single-pole, double-throw (SPDT) switch has three terminals: a center terminal that functions as the common connection point, and two outer terminals that are alternately connected to the center terminal as the position of the switch lever is changed. When one of the outer terminals is connected to the center terminal, the remaining outer terminal is disconnected from the center terminal.

(a) Imagine that you must wire the light in the stairway of a two-storey house. Ideally, the occupants should be able to turn the light on or off using one of two switches. One switch is located at the top of the stairs, and the other is located at the bottom. Toggling either switch lever should make the light change state. Draw the diagram of a circuit that illustrates the stairway lighting system.

(b) Now imagine a three-storey house in which the lights in the stairwell are to be turned on or off by moving the lever of any one of three switches (one located on each floor). Design an appropriate switching network using two single-pole switches and one double-pole switch. (A DPDT switch has six terminals and can be thought of as two SPDT switches in tandem, with both levers engaged simultaneously.)

4.36 A dc motor consists of a multipole electromagnet coil, called the *armature*, or sometimes the rotor, that spins inside a constant magnetic field called the *stator field*. In the small dc motors typically found in model electric cars and toys, permanent magnets are used to create the stator magnetic field. In larger, industrial-type motors, such as an automobile starter or windshield-wiper motors, the stator field is produced by a second coil winding.

Current is sent through the rotating armature coil via a set of contact pads and stationary brushes called the *commutator*. Each set of commutator pads on the rotor connects to a different portion of the armature coil winding. As the rotor rotates, brush contact is made to different pairs of commutator pads so that the portion of the armature coil receiving current from the brushes is constantly changed. In this way, the magnetic field produced by the rotating armature coil remains stationary and is always at right angles to the stationary stator field. The north and south poles of these fields constantly seek each other; because they are always kept at right angles by the action of the commutator, the armature experiences a perpetual torque (rotational force). The strength of the force is proportional to the value of armature current; hence, the speed of the motor under constant mechanical load is also proportional to armature current.

(a) Obtain a small dc motor from a hobby or electronic parts store. Connect two D-cell batteries in series with the motor without regard to polarity. Observe the direction of rotation, and then reverse the polarity of the battery connections. Observe the results.
(b) Using a double-pole double-throw switch like the one described in the previous problem, design a circuit that can reverse the direction of the motor using a single switch.

Reverse Engineering:

4.37 Take apart a retractable ballpoint pen (the kind that has a push button on top to extend and retract the writing tip). Draw a sketch of its internal mechanism, and write a short description of how the pen mechanism operates.
4.38 Take apart a common plastic CD case. Make a sketch of its inner construction, and write a short summary of its various components.
4.39 Take apart a standard desktop telephone. Use your investigative methods to develop a block diagram of how the phone works and connects to the outside world.
4.40 Suppose that you have been given the assignment to design a desktop stapler. Dissect an existing model from a competitor, draw a sketch of its mechanical construction, and create a parts list for the stapler.
4.41 Take apart a common flashlight, draw a sketch of its mechanical construction, and create a parts list from which you could reproduce another.
4.42 Imagine that you have discovered an errant unoccupied space vehicle in a remote field. Write a report in which you reverse engineer the spacecraft to discover elements of its technology. Examine the vehicle's propulsion system, telemetry, and sensor systems.

The Computer as an Analysis Tool:

4.43 Write a computer program in the language of your choice to calculate the trajectory of a pebble that falls from an airplane traveling at 200 kph. Include the effects of air resistance.
4.44 Consider a snapping mousetrap bale. Write a computer program in the language of your choice to plot its angle θ as a function of time from $t = 0$ and $\theta = \pi$ until the time when the bale makes contact with the base at $\theta = 0$. Assume that the bale has a moment of inertia 0.01 kg-m and that the spring exerts a torque of value 0.5 θ/π N-m, where θ is in radians.
4.45 A capacitor is a device that stores electrical energy. The degree to which a capacitor is charged at any given moment is indicated by how much voltage appears across its terminals. If a resistor is connected across a charged capacitor, then the current i flowing out of the capacitor and into the resistor will be given by the equation $i = v/R$, where v is the capacitor's voltage and R the value of the resistor. The capacitor will respond to the flow of current by reducing its voltage according the equation $dv/dt = i/C$. Write a

computer program in the language of your choice to plot $v(t)$ for the case $v(t = 0) = 10$ V, $R = 10\ \text{k}\Omega$, and $C = 100\ \mu\text{F}$.

(*Note:* $10\ \text{k}\Omega \equiv 10{,}000$ ohms, $100\ \mu\text{F} \equiv 10^{-4}$ farads.)

4.46 Draw a flowchart for a computer program that could be used to control the traffic at a busy intersection where two streets cross. Traffic should be allowed to flow over the east–west route, unless a car stops at the north- or south-bound streets entering the intersection. Write this program in the language of your choice. Include an input mechanism for indicating the number of cars at each sector of the intersection.

4.47 Draw a flowchart for a computer program that could be used to control the traffic at a busy intersection where two streets cross. Traffic should be allowed to flow over the east–west route until three cars are stopped at the north street entering the intersection, but only if no car is stopped at the south entrance. If more than three cars become stopped along the east–west route, it should be open to traffic flow, regardless of the number of cars stopped at the north–south streets. Write this program in the language of your choice. Include an input mechanism for indicating the number of cars at each sector of the intersection.

4.48 Draw the flowchart for a computer program that can serve as a three-digit password decoder for an alarm system. Each of the digits (0–9) entered into the alarm should be represented in binary form. Choose the last three digits of your birthday year as the password. Write this program in the language of your choice. Include an input mechanism for each of the entered digits.

4.49 Draw the flowchart for a computer program that can tally the voting of a 10-person city council. The output should indicate the majority of "aye" or "nay" votes with a logic high (1) or logic low (0) output. Include a provision for a tie vote. Write this program in the language of your choice. Include an input mechanism for each of the 10 city-council votes.

4.50 Draw the flowchart and block diagram of a sensor system that can turn on a garden watering system if the temperature rises above 30°C, the sun is not shining on the plants, and the time is not before noon of the same day.

4.51 Draw the flowchart for a computer program that can be used by a scientific investigator to assess the probability of various events. The system should accept five input signals and provide an output that corresponds to the status of the majority of inputs.

4.52 Draw the flowchart of a microprocessor program that can be used to sound an alarm in a four-passenger automobile if the ignition is energized but the driver has not put on a safety belt. The alarm also should sound if a passenger is seated but has not put on a safety belt.

4.53 This problem illustrates the concept of amplitude modulation. Suppose that the function $c(t)$ is equal to a triangular waveform that has peak values of 1 and -1 and frequency f_1. Similarly, $m(t)$ is a square wave function that varies between $+1$ and -1 and has frequency f_2. Write a computer program that plots the amplitude-modulated waveform described by the equation

$$v(t) = c(t)[1 + am(t)]$$

for the case $f_1 = 10$ Hz, $f_2 = 1$ Hz, and $a = 0.4$. The factor a is called the *modulation index*, and hertz (Hz) has the units of cycles per second.

4.54 Draw a flowchart that will implement the system described in the following memo:

To: Xebec Design Team
From: Harry Vigil, Project Manager
Subject: ATM Simulator

Our client for this project has requested that we develop a machine that can simulate the functions of an automatic teller machine (ATM) such as one might find at any local bank. Your task is to design and build such a simulator using the components and materials of your choice. Here is a list of specifications that you can use as a guide in preparing your initial project proposal and technical plan:

- The simulator should be self-contained with no actual contact with the outside world.
- It should realistically simulate such features as user inquiry, prompting for password, type of transaction, and dollar amounts.
- The simulator should include its own set of entry keys or buttons, display device, printer, and dispenser for (simulated) money.
- The simulator should be triggered into operation by the insertion of an ATM-type bank card. The decoding and interpretation of information stored on the inserted cards is not a necessary feature of the system. An acceptable solution could instead involve storing passwords (possibly as an updatable list) inside the simulator; this list would be activated by the insertion of any card of the appropriate size.

Spreadsheets

4.55 Write a spreadsheet program that computes the trajectory of a rubber-band-launched projectile. Your spreadsheet calculations should have cells in which you can enter key parameters of the problem such as dimensions, launch angle, and amount of rubber-band stretch. Use an array of cells to indicate the position of the projectile at various points along its trajectory. Choose any appropriate values for the projectile mass m and spring constant k.

4.56 Suppose that you are trying to come up with a budget for an engineering design project. Your salary is about \$6,000 per month, and the technician with whom you work earns about \$3,500 per month. You need \$5,000 for materials and supplies, \$1,200 for traveling to a sales meeting, and you have to contribute 8% of the direct dollars you spend to support clerical staff. In addition, you have to pay 80% of the entire contract cost, including the 8% clerical charges, to overhead that supports the general operation of the company. Write a spreadsheet program that can help determine the maximum number of person-months that you'll be able to charge to the project if the total budget must not exceed \$100,000. You'd like your technician to work at least half time on the project.

4.57 Write a spreadsheet program that will help you determine the center of gravity of all the passengers on a small commuter airplane. The airplane has ten rows of four seats each, with two seats on either side of the aisle, for a total of forty seats. The centers of the aisle seats are located 0.5 m from the aircraft centerline, and the centers of the window seats are located 1.2 m from the aircraft centerline. The rows are spaced 1 m apart. Your program should compute the center of gravity measured relative to the first row of seats (y-coordinate). Assume that you know the weight of each passenger. Feel free to do your analysis in either kilograms or pounds.

4.58 A film-manufacturing plant produces standard 35-mm photographic film for cameras. The film is produced on large rolls between 500 m and 2,000 m long. Each large roll might have a width ranging from 0.5 m to 2.0 m in steps of 0.5 m. That is, there are four possible values for the width. The large rolls are sliced into 35-mm strips and packaged into consumer-sized canisters for 12, 24, or 36 pictures per strip. Assume that each picture requires 35 mm of strip length, and that the 35-mm wide strip inside each canister must allocate 10% of its length to a trailer and leader (i.e., unexposed film at the start and end of each roll). Write a spreadsheet program that will allow you to compute the total number of film canisters of each size obtainable from a large roll for various percentage allocations of the three values of shots per canister. Your spreadsheet should have the following user entries: width of large roll, length of large roll, percent each of 12-, 24-, and 36-shot canisters desired from the entire roll. Assume that the slicing process generates no wasted film.

4.59 Suppose that the owner of a ferryboat has asked you to design a system to help load cars and freight in the most balanced way. Write a spreadsheet program that will help you determine the moment of inertia about the center of gravity of the ferry due to all the passengers and freight on the ferry. The ferry is to have 40 parking spaces, each 2.7 m $\times$ 4 m, and it should accommodate as many 2.7 m $\times$ 8 m shipping containers as possible. The total cargo area for the ferry is 50 m $\times$ 100 m. Assume a weight of 1,000 kg per vehicle, 6,000 kg per shipping container, and 60 kg per person.

Microprocessors

4.60 Write the flowchart of a microprocessor program needed to run a desktop telephone with the following features: tone dial, redial button, flash button, memory (8 registers), and hold.

4.61 Microprocessors communicate with computers and peripherals using either serial or parallel data links. When a parallel link is used, the connection consists of one wire for each of the bits in the digital word, a common return ground wire, plus additional wires for sending synchronizing signals. The latter are needed so that the receiving device will know when to read each digital word sent by the transmitting device.

When a serial link is used, data bits are sent one at a time. In a synchronous link system, one wire is used by the transmitting device to send the data bits in sequence, one wire is used for return ground, and a third wire is used to send a synchronizing signal. The latter is used by the receiving device to determine the timing between each data bit. In an asynchronous link system, typical of the type used to communicate over telephone modems, wireless networks, and the Internet, only one wire pair is available for signal transmission. Data-bit synchronization requires that the sending device and receiving device both be set to the same BAUD (for bits audio), or bit timing rate. Such timing is never perfect, however; if left uncorrected, the BAUD timing of the receiving device will drift apart from the BAUD timing of the sending device. To ensure that the bit-timing sequences will match, the receiving device resets its timer after each digital word. It knows when the received word ends, because the transmitting word appends a stop-bit sequence to each one. After the stop bits are sent, the transmitting device sets the data line to the value 1 as a prelude to sending its next word. It also adds a start bit of value 0 to the beginning of each word so that its arrival will be unambiguous.

- A particular microprocessor sends data in eight-bit packets, or bytes. Determine the content of the two bytes represented by the data sequence shown in Figure 4.50. The start bit, from which you can determine the time interval per bit, precedes a second 1 bit. The stop-bit sequence consists of two data bits held high.
- Draw the serial data stream for the byte sequence (1001 1100) (0001 1111) (1010 1010).

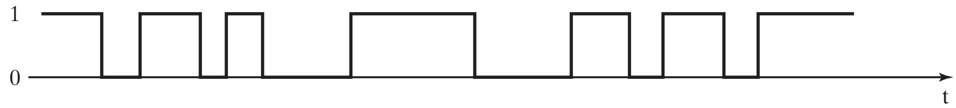


Figure 4.50
Asynchronous serial data stream.

4.62 A pulse-width modulation motor drive system applies voltage to a motor while adjusting the duty cycle, or time interval, over which full voltage is applied. The current that flows when voltage is applied will be determined by the motor speed and internal resistance. The average power consumed by the motor will be equal to the time average of the voltage–current product. The pulse-width modulated waveform is produced in response to a digital data signal from a computer module. Draw the microprocessor flowchart for a program that can produce the required voltage waveform. Your program should accept a binary or decimal number between 0 and 255 and then produce an output that is high (logic 1) for an amount of time proportional to the input value.

4.63 Analog-to-digital interfacing is an important part of many microprocessor-controlled engineering systems. Although most physical measurement and control involves analog variables, most data collection, information transmission, and data analyses are performed digitally. A/D and D/A circuits provide the interfaces between analog and digital worlds. A D/A converter produces a single analog output signal, usually a voltage, from a multibit digital input. One common conversion algorithm produces an analog output proportional to a fixed reference voltage as determined by the equation

$$v_{\text{OUT}} = \frac{nV_{\text{REF}}}{2^N - 1}$$

where N is the number of bits in the digital input word, n is the decimal value of the binary number represented by all the input bits that are set to **1** in the digital input word, and V_{REF} is a reference voltage. When n is equal to $2^N - 1$, v_{OUT} is equal to V_{REF}.

- Suppose that the input to an 8-bit D/A converter is **0010 1111** with $V_{\text{REF}} = 5$ V. Find the resulting value of v_{OUT}.
- A 10-bit D/A converter is fed the input word **00 1001 0001** and is given a reference voltage of 5 V. What is the output of the converter?
- What is the smallest increment of analog output voltage that can be produced by a 12-bit D/A converter with a reference voltage of 10 V if the algorithm previously shown is used?
- What is the largest analog output that can be produced by an 8-bit D/A converter if $V_{\text{REF}} = 12$ V?

4.64 An A/D converter compares its analog input voltage to a fixed reference voltage and then provides a digital output word B given by

$$B = \frac{\text{rnd}(v_{\text{IN}})(2^N - 1)}{V_{\text{REF}}}$$

where the operator rnd() means "round to the nearest integer." This encoding operation is called *binary-weighted* encoding. A full-scale binary output (all bits set to **1**) occurs when $v_{\text{IN}} = V_{\text{REF}}$.

- An 8-bit binary-weighted A/D converter has a reference voltage of 5 V. Find the analog input corresponding to the binary outputs **1111 1110** and **0001 0000**.
- Find the binary output if $v_{\text{IN}} = 1.1$ V.

- Find the resolution of the converter.
- Find the additional voltage that must be added to a 1-V analog input if the digital output is to be incremented by one bit.

4.65 Boolean algebra is a system of logic used by many computers. In Boolean algebra, variables take on one of two values only: TRUE (logic 1) or FALSE (logic 0). Boolean operators include AND, OR, and NOT. The AND operator is represented by a dot between variables, (e.g., $Y = A \cdot B \cdot C$ means that Y is true if A, B, and C are all true). The OR operator is represented by plus signs (e.g., $Y = A + B + C$ means that Y is true if one or more of A, B, or C is true). The NOT operator, represented by an overbar, simply reverses the state of the variable (e.g., $\overline{A} = 0$ if $A = 1$).

- Verify the following equations in Boolean algebra:

$$A \cdot B + A \cdot \overline{B} = A$$
$$(A + B) \cdot (B + C) = B + A \cdot C$$
$$\overline{(A + B) \cdot C} = \overline{A + B} + \overline{C}$$

- DeMorgan's theorem states that the Boolean expression $\overline{A \cdot B \cdot C}$ is equivalent to $\overline{A} + \overline{B} + \overline{C}$. Similarly, $\overline{A + B + C}$ is equivalent to $\overline{A} \cdot \overline{B} \cdot \overline{C}$. Verify both forms of DeMorgan's laws.

Use of Computers:

4.66 Discuss the way in which a computer or microprocessor (single-chip computer) might improve your approach to designing the following products:

- an all-electronic telephone answering machine
- a tachometer and an odometer for a bicycle
- an energy-saving light switch
- a smart clothes iron that shuts off after 1 hour without use
- a data logger for measuring part weight in a quality-control system
- a voice-synthesized device for a speech-impaired person
- a digital alarm clock
- a system for producing Gantt charts for homework assignments

4.67 Identify a system or entity in your school, home, or place of work that would benefit greatly from the introduction of a computer system. Write a short summary explaining why.

4.68 Identify a system or entity in your school, home, or place of work that suffers because one or more computers were introduced inappropriately. Write a short summary explaining why.

4.69 Take a survey of a select group of people who use computers. (The people you choose could be those who live on your dorm floor, attend one of your classes, or are in your extended family, for example.) Make a list of how many hours per day each person uses a computer and the approximate percentage of time spent at various tasks on the computer. Examples of tasks include word processing, spreadsheet use, CAD drafting, computation, and e-mail.

4.70 Make a list of at least 10 appliances or machines that you encounter on a regular basis, exclusive of desktop computers, that utilize the power of a microprocessor. Now make a list of at least five appliances or machines that you encounter on a regular basis whose function could be greatly improved by the use of a microprocessor.

CHAPTER 5

The Human–Machine Interface

Objectives

In this chapter, you will

- Learn how people interact with machines.
- Understand the importance of the human–machine interface.
- Examine case studies of good and bad human–machine interfaces.

Have you ever noticed how some machines are very easy to use? Some products appeal to your touch and sight, while others are awkward to use. Similarly, some software programs are extremely user friendly, while using others is painful. Things that are easy to use share one attribute: an excellent human–machine interface. The human–machine interface defines the way in which a person interacts with an engineered product. It evokes the senses of touch, sight, and hearing. A good product just simply "feels" right. It becomes an extension of the user's hands and eyes. Its features are included not just because they can be, but because the product has been developed from the start with the end user in mind. The designer of a good product worries about *how* it will be used as well as *what* the product must do. A good product is one that has been designed in concert with both the function and purpose of the device.

Experienced engineers know that the human–machine interface is one of the first things that should be addressed during the initial stages of product development. In this chapter, we examine the role of the human–machine interface in engineering design. Throughout this chapter, the word "machine" is defined to mean any device, be it a mechanical, electrical, industrial, structural, biomedical, or software entity designed by an engineer.

5.1 HOW PEOPLE INTERACT WITH MACHINES

The pages of engineering history are littered with tales of products that fulfilled a useful function but were hopelessly inept at providing an adequate human–machine interface. One canonical example of this principle is the now extinct VCR machine. In a television commercial that aired in the early 1990s, a satisfied user of an infomercial-marketed device for programming a VHS video player (VCR) via voice command proudly proclaimed, "Hey, even I don't know how to program my VCR, and *I* have a *Master's* degree!" Indeed, much humor was been derived from the notion that seemingly intelligent people were content to let their VCR displays blink at 12:00 rather than tackle an intricate maze of programming functions.

The problem with underutilized features of consumer electronic devices is seldom the intelligence of the user. Rather, most of us simply do not have the time to master hard-to-learn features provided by the manufacturer. Examples include various versions of the digital watch, microwave ovens, programmable music players, cell phones, and word processors. Even the latest automobiles are laden with features that elude the owner who is usually intent on simply driving the car. Without a simple, easy-to-remember sequence of programming steps, the features of the most intricate and complex machines will lay idle most of the time.

5.2 ERGONOMICS

The human–machine interface influences our attitude toward the most mundane of devices. Take doors, for example. Some doors require less effort to open; others require gargantuan effort. Various tableware sets are more appealing to diners; a favorite chair becomes one's sanctuary at home. The best of these products were designed with careful attention given to *ergonomics*, the science of how the body interacts with machines. Ergonomics focuses on the size, weight, and placement of objects and control devices that interact with the human body. The average length of the human arm, the arm's swing frequency, the height of the eyes above a tabletop, the spacing between fingertips—these are all examples of things that must be considered when designing the physical layout of a product. Consider the case of the driver's position in the automobile, a product that has been fine-tuned for over 100 years. Auto makers carefully consider the placement of the steering wheel, gearshift lever, brake and accelerator pedals, heat and air-conditioning controls, radio knobs, rear view mirrors, windshield aperture, etc. Cars are designed for the average human body while maximizing the range of physical attributes that can be accommodated. By how much should the position and height of a seat be adjustable? Will a tiltable steering wheel gain more market share because drivers on the fringe of the ergonomic range will find the car appealing to drive?

This approach to vehicle design has served the driving public for most of the history of the automobile, although occasionally unforeseen problems occur. The concern over airbags that surfaced in the mid 1990s, for example, illustrates a design principle run amok. Automobile airbags have saved countless lives, but like all devices in the automobile cockpit, it was designed with the average driver in mind. It inflates at a "chest level" defined for a person of average height. The first airbags exposed children and short adults to a potentially lethal blow to the head. This unforeseen problem led to the revised recommendation that children be confined to the rear seats of all automobiles having passenger-side airbags. While this advice provides a temporary solution, the hazard remains a problem for short adult drivers and front-seat passengers and has led to redesigned air bags of the so-called "stage II" (SR-2) variety. Modern cars include passenger seat sensors which arm the airbag only when a person of sufficient weight sits in the seat.

The study of ergonomics has produced a body of anthropometric data that can be used in designing anything that involves the interaction of a human and a machine. Tables of statistics on arm length, arm span, joint location, limb bending angles, and turning radii can be found in numerous references in the literature, including those listed at the end of this chapter. These data can be used to choose the size of knobs, location of openings, spacing of push buttons, and location of display devices. One goal should be to avoid awkward positions or physical actions on the part of the user. Awkwardness was purposefully designed into the layout of the ubiquitous QWERTY keyboard. This very odd distribution of letters requires finger extensions to key some of the most frequently used letters. This feature was embodied in the layout, because the very first mechanical typewriters (circa 1880) could become jammed if insufficient delay occurred between keystrokes. The fact that the QWERTY layout has persisted to this day, solely by tradition, is a quirk of history.

5.2.1 Putting Ergonomics to Work

The basic rules of ergonomics are easy to master. Although some of the more esoteric guidelines are the province of experts, most involve simple common sense. Button controls should be kept within a finger span unless they are intended for occasional use only. Knobs and valves should be kept within an arm's reach, and those linked to a common function should be grouped together. Visual information should be kept within line of sight. Display devices should be located so that the user does not need to constantly turn or bob the head. Command sequences or operations should follow a logical order and should be easy to remember. Some of these design principles are so ingrained in our subconscious that we notice them only when they are violated. If you sat down behind the wheel of a car, for example, and found the ignition key to the left of the steering wheel, you'd note that the car's layout did not feel right. If you opened a new software program and found the FILE pull-down menu in the upper right-hand corner of the screen instead of the upper left-hand corner, you might think it strange. The principles of ergonomics share a unique symbiosis with the shape of our bodies, the dimensions of our limbs, our shared expectations, and even elements of our culture.

Practice!

1. Measure the shoulder-to-fingertip arm span of your own body. Compare it with the height of your desk and distance from its edge to your computer keyboard. Is there a correlation?
2. The standard desk height in the U.S. is 76 cm (30 in). Measure the height of your waist above the floor. Is there any correlation?
3. Measure your own floor-to-shoulder height and compare to the standard 106 cm (42 in) height at which electrical wall switches are installed.

4. Measure the span of your hand with the fingers curled. Compare it to the distance between a bicycle brake lever and its associated handlebar grip. Is there any relationship?
5. Sit in a car, and measure the distance between the bottom of your foot and the accelerator pedal as the seat is moved from its extreme forward and backward positions. What range of driver leg length do you think the car can accommodate?
6. Examine the FILE pull-down menus of up to 10 computer programs, and write down the order in which the menu items appear. Compare and contrast the differences in a simple table.
7. Examine the distance between the upper and lower buttons located on the control panels of several elevators. Compare these numbers with the range of the human arm span.
8. Measure the height-to-depth ratio of the steps on several staircases. Do you observe a pattern?
9. Find the height of the standard entry door. Look up the range of human heights by percentage population. What fraction of the adult population will not fit under a standard doorway opening without stooping?
10. Measure the distance between buttons on your cell phone. Look up the range of width of the human of index finger, and compare.
11. Do a traffic study at several city intersections. Record the time allotted pedestrians who cross by the "walk" cycle of the traffic light. Also measured the curb-to-curb distance at the crosswalk. Look up the range of the adult human gait, and determine what fraction of the adult population will have insufficient time to cross. For the purpose of this exercise, do not consider individuals walking with canes or riding in wheelchairs.
12. Devise a simple force measuring instrument using one or more rubber bands and a ruler. You can calibrate your device using weights of known mass. Now go to a large number of buildings and measure the force needed to open the entry door. Is there any standard value for opening force?
13. Go to several buildings that have human-activated revolving doors (not the type that automatically rotate). Devise a simple experiment to measure the force needed to initiate door rotation. Your measuring instrument could consist of one or more rubber bands and a ruler calibrated using weights of know value. How closely is this force matched from door to door?
14. Look up data on the diameter of the "fleshy" part of the human ear canal.
15. Lightly curl your fingers, then measure the diameter of the ensuing circular space. Go online and look up the diameter of about 20 different types of drinking glasses. How many of the latter correlate to the former?
16. Find online data concerning the distribution of head diameters in the general population. Now measure the minimum and maximum

diameters of a "one-size-fits-all" baseball cap. (It may be easier to measure the hat's circumference, then divide by pi. Alternatively, you may find anthropomorphic data on head circumference, rather than diameter.) For what percentage of the population will the hat not fit?

17. Do some research and find the distribution of shoe sizes in the general population for the gender of your choice. Organize the data into a simple bin histogram in which the horizontal axis represents shoe size, and the vertical axis shows the percentage of the population who need that size. Now go to the website of any popular online clothing vendor. For each of the shoe-size bins in your histogram, determine if the vendor carries shoes of that size. What conclusions can you draw concerning the extent of inventory of the vendor.
18. Do some research and determine the barrel diameter of a large number of writing instruments (pens and/or pencils). Now plot a percentage size distribution in the form of a bin histogram. A sample size of 50 to 100 writing instruments is necessary for this task.
19. Get each member of your class to contribute backpacks for the following experiment. Hang the backpack by its shoulder strap, then measure the distance from the point of suspension to the point where the strap attaches to the bottom of the back. This distance will provide a fair measure of the body size to which the backpack's straps are set. Record data for all your classmates. What are the mean, minimum, maximum, and standard-deviation values?
20. Get each member of your class to contribute backpacks for the following experiment. Measure the total length of one of the backpack shoulder straps. This distance provides some measure of the maximum body that the backpack will accommodate. Is there an industry standard?

5.3 COGNITION

Nearly every engineered device requires the user to learn its features before it can be operated. The typical user wants to have control over a product and fully understand its use. *Cognition* refers to the way in which a user learns about the device and masters its features. A well-engineered device affords a short learning curve and a consistent set of operating rules. As an example of this principle, consider the now-standard graphical user interface (GUI) embodied by most software programs. In most, the FILE and EDIT pull-down menus are always located in the upper left-hand corner of the screen. They are placed in this location because the user *expects* to find them there. Their menu items are rather standard also, including such items as OPEN and SAVE. A user will consider a program easy to use when it builds upon features learned from prior use of similar products.

Another example of this principle can be found in the automobile. The gearshift, directional signal lever, ignition key, and horn are placed in standard locations. Every driver learns to operate these controls and expects them to always be in the same place. One aspect of car operation that has no consistency is the location and operation of the headlight switch. Have you ever driven a strange car only to fumble momentarily while trying to figure out how to turn on the headlights?

In designing a product or system, care should taken to make its operation easy to learn. As you design a new device, mimic the operating principles of similar devices. Borrow functional sequences, structural details, or command sequences. Place controls where they are likely to be found on similar machines, or, at the very least, in logical places. We expect a light switch to be located along a room's interior wall, just inside the unhinged edge of the door. This location is logical, given the way one enters a room. If the switch is placed anywhere else, it contradicts our learned behavior. The same can be said for the direction of the volume control on a music system. We subconsciously expect the volume to be increased by turning a knob clockwise, moving a slider to the right, or pressing an up-arrow button. There is no hard logic to this choice, but it resonates with our learned notion that the rotational direction of an analog clock corresponds to marching forward; the progression of sound volume should follow the progress of printed words on the page; and an up arrow associates a height increase with an increase in volume. Acknowledging the importance of cognition in engineering design requires that we design products and systems whose operation is easy to learn, easy to remember, and consistent in operation with other, similar products.

One prominent product that exemplifies the failure of product developers to address cognition is the ubiquitous TV remote control. No one standard exists with regard to type, placement, or function of buttons. Indeed, the different types of remote control devices numbers in the hundreds – so much so that it's impossible for a user to pick up any one device and operate it without thinking. The status of the omnipotent ATM provides another example of the failure of an entire industry to arrive at a single cognition standard. The layout of the user screens, the sequence of buttons pushed, and even the location of the buttons themselves, seem to vary at random. These variations can challenge even the most cognizant of ATM users.

5.4 THE HUMAN–MACHINE INTERFACE: CASE STUDIES

Engineers can learn a great deal about design by studying the successes and failures of other engineers. While grand large-scale failures, such as falling bridges and collapsing roofs, have gained much notoriety in the press, small-scale failures, particularly in the arena of the human–machine interface, are equally worthy of study. Such studies illustrate the impact of the small design decisions that engineers make every day. This section cites several case studies of both well-designed and poorly designed human–machine interfaces.

In the discussions that follow, the happy-face symbol ☺ denotes an example of a good human–machine interface. The sad-face symbol ☹ denotes a bad interface, and the neutral-face symbol 😐 denotes a "mixed bag."

EXAMPLE 5.1

The Hand-Set Telephone Dial ☹

Until the mid-1970s, almost all telephones had a rotary dial of the type shown in Figure 5.1. The integrated-circuit technology needed to integrate DTMF (dual-tone, multiple-frequency, or Touch-Tone™) capability into telephones was neither economical nor practical. Rotating the dial from the chosen digit to the hook and releasing it caused the device to send the proper number of electrical current pulses to the central telephone station. The main problem with the rotary dial was that it was mechanical; therefore, it was more prone to failure. It also was much slower than its soon-to-appear Touch-Tone replacement.

Today, the standard for cellular, cordless, and many table-top phones is to place the keypad within the headset. This approach to keypad location, however, violates an important principle of ergonomic design. It makes the product much more difficult to use. In the typical scenario involving voice mail or automated telephone functions, the user first listens to an announcement, then presses the appropriate key selection. For most people, the latter operation requires looking at the keypad while pressing the selected key. The user must repeatedly hold the headset to the ear, remove it from the ear, hold it in front of the face to press keys, and then return the headset to the ear to listen for the results or the next automated instruction. It is much easier to handle automated telephone dialing or voice-mail instructions when the keypad is located in front of the user, as it is in a conventional desktop phone.

The latest technology circumvents the deficiencies of the keypad-in-headset phone by responding to spoken numerals and voice commands. These systems are getting better year after year and will eventually supplant the deficiencies brought about by misplaced keypads.

Figure 5.1
The rotary telephone dial from years past.

EXAMPLE 5.2

The Hard-to-Open Cell Phone ☹

Cell phones come in a wide variety of physical configurations, but most adhere to the flip-phone design reminiscent of the communicator used by Captain Kirk of Star Trek. Those who choose this type of phone recognize one of its advantages: it can be opened with one hand. This feature is invaluable for folks on the go, for example to students who receive calls while walking from class to class.[1] It's similarly convenient to be able to reach into your pocket to retrieve a phone, and to then flip it open with the same hand. This action is invariably performed by the users thumb. (Try it on your own phone if you wish.)

The manufacturer of the flip-phone of Figure 5.2 has erred in its ergonomic design. In order for the user to perform the single-handed thumb flip, the phone

Figure 5.2
Cell phone design that is difficult to open with one hand. There is very little separation between the cover and the phone's body at the location of the user's thumb.

Figure 5.3
Cell phone design that facilitates opening with one hand. There is ample space between the cover and the phone's body at the location of the user's thumb.

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[1]While the single-handed flip opening is valuable to drivers who need to answer calls while underway, the author is adamantly against the use of cell phones while driving.

needs to have sufficient space between its cover and main body to permit entry of the edge of the thumb. The cover of the phone in Figure 5.2a closes flush with the main body. Some users need two hands in order to open this phone.

Interestingly, the phone of Figure 5.3a is an updated model, made by the same manufacturer, of the phone of Figure 5.2b. The latter, as shown, does include a space for insertion of the user's thumb tip, thereby facilitating one-handed opening.

EXAMPLE 5.3

The Evolution to the Mountain Bike ☺

The mountain bike shown in Figure 5.4, sometimes called a "street bike," became the choice of recreational bike riders sometime in the 1990s. Riders were drawn to its comfort, durability, and ease of use. Its evolution to prominence provides an example of good ergonomic design. Prior to the 1960s, the bicycle of choice by serious riders was a three-speed model that had a single gearshift lever mounted on the handlebars. This bicycle, of British design, was dubbed the "English bike" by Americans; it replaced the balloon-tired "coaster brake" models which were soon relegated to kids-only status. A decade later, the 10-speed bicycle dominated the bikeways. With its lightweight frame, large choice of gear ratios, and thin tires, and dubbed the "racing bike", the 10-speed was built for speed and efficiency. Dubbed the "racing bike," it soon became the standard for a host of riders. Its design was cloned from the bicycles that had been used for years by professional racers. As illustrated in Figure 5.5, the brake levers were mounted on the front of curved handlebars, and the gearshift levers were mounted on the foremost strut of the bicycle frame. The placement of these controls required the rider to assume a hunched over, albeit aerodynamically efficient, position. In order to change gears, the rider had to let go of the handlebars with one hand in order the reach the gear levers. Although the hunched-over position is very efficient for racing and extended cross-country riding, most casual users found it cumbersome. Minor solutions, such as placing the gearshift levers on the handlebar post and adding brake-lever extensions, became available toward the end of the 10-speed's heyday.

Sometime in the late 1980s to early 1990s, the mountain bicycle appeared on the scene. It had straight handlebars, brake levers within easy reach of an upright rider, and gearshift levers integrated right into the hand grips. The rider no longer had to let go of the handlebars to shift gears. By the mid 1990s, the mountain bike had become the bike of choice by all but serious cross-country riders and racers. Its

Figure 5.4
A rack of mountain bikes.

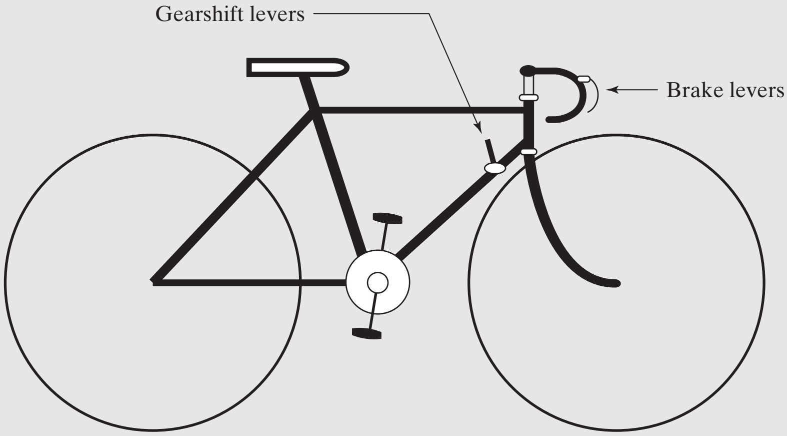


Figure 5.5
The classic 10-speed bicycle.

strong frame and rugged tires, designed to assault mountain paths, also proved worthy of bumpy city streets. As the bike progressed into the 2000s, front-fork shock absorbers were introduced. These are now standard on all new bikes. The success of the mountain bicycle can be attributed to its designers' careful attention to ergonomics and their willingness to consider the riding functions and needs of the end users.

EXAMPLE 5.4

Mountain Bike Gearshift Levers ☹

Consumer success of the mountain bike aside, the ergonomics of the gear-shifting mechanisms of some bikes leaves much to be desired. This example pertains to those bikes equipped with shifting mechanisms that rotate around the handlebars, as in Figure 5.6. The standard bike has one such shifter for each of its two derailleurs.[2] These shifters can be set by the rider to different numbered positions wherein the higher the number, the higher the number of wheel rotations per turn of the pedals. Thus if the rider sets a shifter to a higher number, all other things being equal, the bike

(a) (b)

Figure 5.6
Bicycle gearshift levers. Increasing the difficulty number requires the user to turn the controls in opposite directions.

[2]The derailleur is the device that allows the rider to move the chain between gear sprockets of different diameters.

can go faster, but the rider must apply a greater force to the pedals. The protocol is clear: higher numbers for faster, harder riding; lower numbers for slower, easier riding.

The problem with the arrangement of most shifters is that the right-hand shifter must be turned toward the rider to reach its lower numbers, while the left-hand shifter must be turned away from the rider to reach its lower numbers. This opposite-turning arrangement is conducive to trouble-free gear changing which necessitates the pulling of a connection to shift to a higher-toothed gear. Nevertheless, the standard shifter arrangement can be very confusing to new, young, or dyslexic riders. From the point of view of ergonomics, it would be a better to require both shifters to be turned one way for lower numbers, and the other way for higher numbers.

EXAMPLE 5.5

The Toggle Light Switch ☺

Electricity first came into use at the end of the 19th century. Early methods of wiring were primitive, because the plastics that prevail today were not readily available. Indeed, most of them had not yet been invented. The first wall switches were bulky rotational devices. The user turned a light on and off by turning a ceramic knob. These early pioneers of electrical switching had one major drawback. It was impossible to tell if the switch was "on" or "off" simply by looking at it. Later designs added a pointer to the rotary knob, but determining the switch position still required careful examination. The much improved toggle switch came into use sometime in the late 1930s to early 1940s. Its simple up–down design has persisted to this day. Its cognitive function is second nature to us all: "up" means "on" and "down" means "off." (The only exception to this rule occurs in the three-way switches used for hallway lighting.) If you've ever encountered a room light switch that is mounted upside down, you've probably experienced a momentary sense that something was wrong as you tried to flip on the light.

The toggle motion of today's light switches provides another important ergonomic benefit. Unlike its rotary predecessor, it can be switched with no hands at all. An elbow, knee, hip, stick, or even well-placed nose can do the job. This feature is helpful to users carrying shopping bags, individuals with special needs, small children, or the adults that carry them.

EXAMPLE 5.6

The Rearview Mirror and the Sun Visor ☹

One model of a popular car incorporates a simple but significant design flaw. When the driver attempts to turn down the sun visor, it collides with the rearview mirror. This incongruity is illustrated in Figure 5.7). Either the sun visor must remain only partially down, or the rearview mirror must be pushed out of adjustment to accommodate the visor. This example underscores the need to test even the simplest ergonomic aspects of any new design before bringing it to market.

Figure 5.7
The sun visor in this car hits the rear-view mirror.

EXAMPLE 5.7

The Badly Placed Phone Button ☹

A FLASH button is provided on many phones so that the user can, in preparation for making another call, initiate a so-called "switch hook" (momentary hang up) without physically returning the phone to its cradle or reaching for the phone's cradle. This button is also very useful for phone services equipped with caller ID.

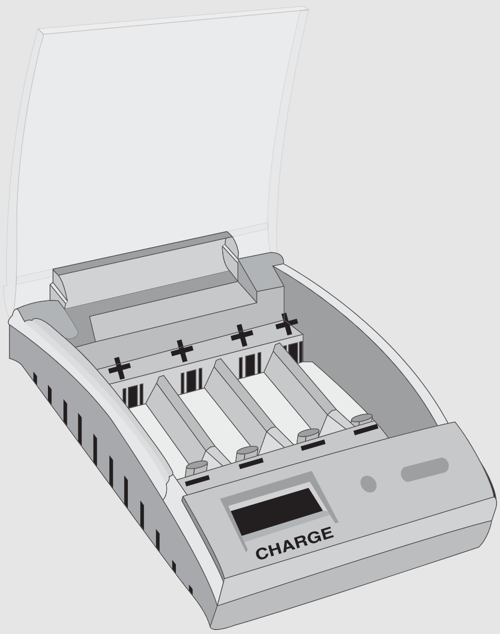
Figure 5.8
The "flash" button is very close to the user's chin. The button is easily pushed accidentally, especially when the user cradles the phone between chin and shoulder.

A very popular cordless (land-based) phone places the "flash" button as the leftmost of a row at the bottom of the phone's front face. If a user cradles the phone between the head and shoulder, as shown in Figure 5.8, it's easy for the user to accidentally press the FLASH with the chin. This ergonomic anomaly can lead to annoying and undesired call terminations.

EXAMPLE 5.8

The Battery Charger ☺

In most devices that use multiple batteries, the direction of insertion (that is, which end is plus and which minus) alternates from battery to battery. The user must stop and think about the orientation of each one as it is being inserted. The battery charger shown in Figure 5.9 accommodates four rechargeable batteries that power a digital camera. Unlike many similar products, in which adjacent batteries must be inserted in alternating directions, the four batteries on this charger are all inserted with the plus (+) side all facing in the same direction. This example of good cognitive design greatly simplifies the use of the product.



Battery charger

Figure 5.9 The batteries in this charger are all inserted in the same direction.

EXAMPLE 5.9

Operating System Start Menu ☹

This example will *not* be a discussion of the pros and cons of the Windows™ operating system. As of the 2009 writing of this book edition, the jury is still out as to whether Microsoft shot itself in the foot with its ill-fated Vista. The "Hi, I'm a

Mac . . . and I'm a PC" advertisements (e.g., *www.apple.com/getamac/ads*) have provided the public with a constant stream of entertainment. The focus of this example is a major change to Microsoft's operating system that first appeared in Windows 2000. Specifically, the START menu was moved to the lower left-hand corner of the screen. This change was counterintuitive to all prior software programs of the day, where the user initiated a program at the upper left-hand corner. While this change is well understood by present day Windows aficionados, it was a shock to users when it first appeared. As a side note, one wonders why the user of Windows must click on the START menu in order to shut down (i.e., stop) the computer.

EXAMPLE 5.10

The Digital Clock ☹

Digital clocks pervade our society. Display technologies have progressed to the point where economical electronic time pieces are sometimes less expensive than the batteries that power them. This was not always the case, however. The earliest models of the digital clock incorporated power-hungry light-emitting diode (LED) displays into plug-in table clocks. Soon thereafter, power-miserly liquid crystal displays were developed along with single-chip clock circuits, opening the door to cheap, reliable wristwatches and other timing devices. The attractiveness and robustness of electronic time-keeping technology has caused digital time to replace the mechanical timekeeping devices that served us well for over 500 years.

Engineers who study cognitive principles have come to realize that digital clocks have a fundamental disadvantage when compared with their analog counterparts. Although a digital clock allows you to know the exact time instantly, most people are more interested in how much time *remains* before some critical event. Examples include, "How much time is left before my class is over?" or "How many minutes do I have left to get to my appointment?" Viewing time from a digital clock

requires that you do the necessary arithmetic in your head. This mental exercise can take a few extra seconds when time is provided to the nearest minute, for example, subtracting 9:48 from 10:00 to determine that you have 12 minutes left to arrive at your 10 o'clock destination.

While your brain can readily do serial math, it functions much better as an image processor than as a calculator. In this task, the human brain is incredibly fast. No machine has yet been invented that can beat the human brain at general pattern recognition. Viewing the time 9:48 on an analog clock hands enables you to estimate and subtract all in one glance as you instantly determine that you have about 10 minutes left to get to your appointment. The contrast between digital and analog clocks provides an example of the often-ignored discord between technological progress and human cognition.

EXAMPLE 5.11

The Gymnasium Lighting System ☹

A town near the author's home renovated its high-school gymnasium. The new facility included dual-use seating to accommodate assemblies as well as phys-ed classes and sporting events. As part of an overall energy-saving strategy, the overhead lights were equipped with motion detectors. In the absence of motion on the central gym floor, the lights would gradually dim and turn off.

The new gym was a huge success. The first time the room was used for a general assembly, however, a critical design flaw was discovered. A very famous speaker had been invited to address the student body on an important social issue. The speaker's podium was set up at one end of the room, and students and faculty sat on the sides in bleachers and chairs. Ten minutes into his speech, the lights began to dim, eventually leaving the entire assembly in darkness. The motion detectors, sensing no movement in the center of the gym, proceeded to turn off the lights under the mistaken conclusion that the room was empty. By the way, the design engineers had failed to provide a manual override for the motion detectors. The assembly continued in darkness.

EXAMPLE 5.12

The Beeping Digital Thermometer ☺

Digital thermometers for measuring human body temperature, like the one in Figure 5.10, arrived on the scene sometime during the 1980s. Originally too expensive for home use, their price has become so low that digital thermometers have largely replaced their older (and more dangerous) mercury and glass counterparts. Some brands include an extremely useful feature that embodies good cognitive design. If the thermometer has not been turned off after being removed from the patient's mouth and set aside, it will begin to beep after a few minutes. The device does not turn off automatically in case the user has left it on intentionally, so as to be able to refer to the reading at a later time. Much like the beeping of a phone left off the hook, the beeping thermometer reminds the user to turn it off so that its battery will not discharge. Were this simple feature not incorporated into the device, it might be discharged and useless the next time a family member had a fever in need of monitoring.

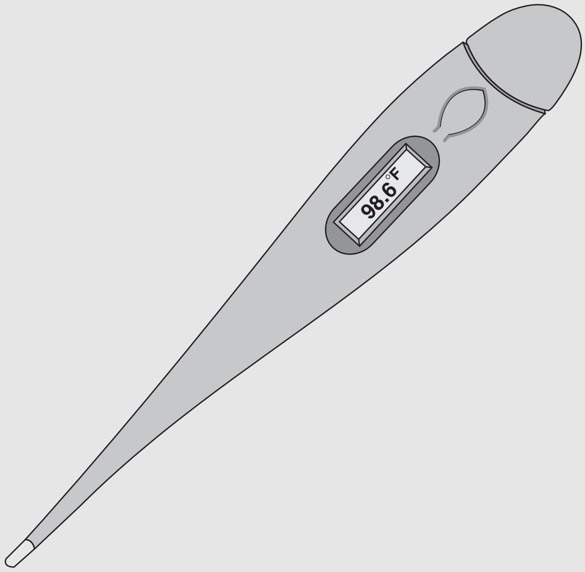


Figure 5.10
Digital thermometer for measuring human body temperature.

EXAMPLE 5.13

The Designer Lavatory Faucet ☹

A famous maker of decorative plumbing fixtures has marketed the designer lavatory faucet shown in Figure 5.11. This fixture is a captivating composite of chrome and brass that adds to the décor of any well-appointed bathroom. The straight, cylindrical handles rise cleanly above the curved, inlaid base. This visually appealing faucet has but one problem: When the smooth, cylindrical handles become the slightest bit wet, they are nearly impossible to turn. The faucet handles provide a good example of form taking needless precedence over user function.

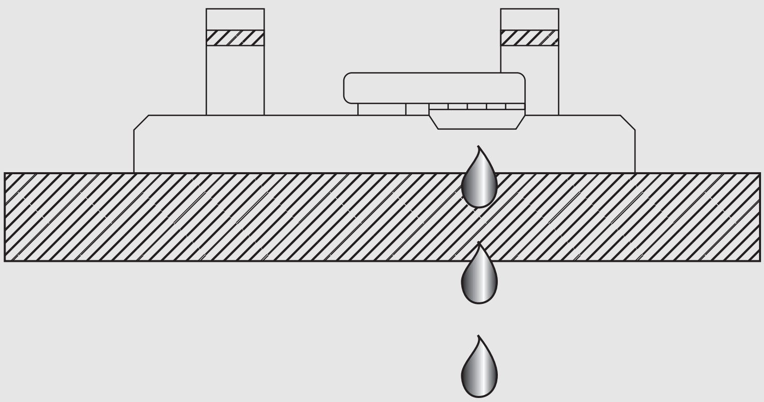
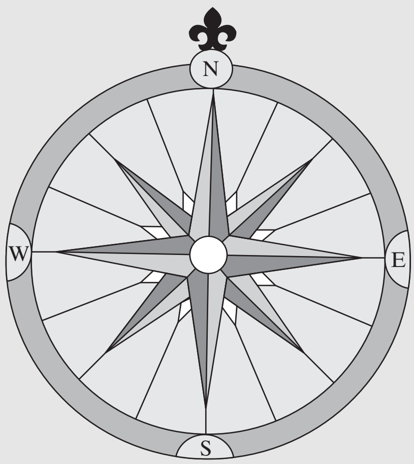


Figure 5.11
The designer laboratory faucet.

EXAMPLE 5.14

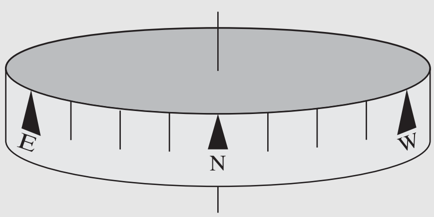
The Mariner's Compass ☺

Good ergonomic design need not be limited to the world of high tech. The simple mariner's compass, used by sailors for centuries, provides an example of bad ergonomic design turned good. The first compasses were made by floating pieces of lodestone, a naturally occurring magnetized rock, in water or other liquids. Free to turn in any direction, the lodestone unfailingly pointed in the north-south direction, providing an important navigational aide to sailors. As technology progressed over the centuries, the hard-to-find lodestone was replaced by magnetized iron and steel, eventually evolving into the floating compass rose design shown in Figure 5.12(a). This basic form of the compass, with its horizontally floating disk and glass bubble top, persists in many ships to this day. The problem with this design is that the disk can be viewed only from the top, because the printed surface of the compass is horizontal. The helmsman must look away from the horizon to glance down at the compass, leading to fatigue on long ocean voyages. Adding a mirror inclined at 45° to allow viewing from a horizontal line of sight does not help, because it reverses the apparent rotational direction of the compass and confuses the helmsman. The solution to this problem is a simple one. A much-improved, redesigned compass is shown in Figure 5.12(b). It replaces the floating disk with a cylindrical shell mounted on a jeweled pivot. The compass markings are printed on the vertical edge of the cylinder, allowing the entire compass to be mounted on a vertical wall of the cockpit. Mounted in a proper location, it can be viewed with only a slight downturn of the helmsman's eyes, rather than a complete lowering of the head. Fatigue during long voyages is greatly reduced.



Top view

(a)



Side view

(b)

Figure 5.12
(a) The original horizontal design of the mariner's compass; (b) Revised version with vertical wall design.

EXAMPLE 5.15

The Squeeze Ketchup Container ☺

While not glamorous, the lowly squeeze ketchup container (Figure 5.13) is an example of superb ergonomic design. It's easy on the hand because its compliant walls are just the right thickness to make squeezing effortless. Its translucent walls let the user see just how much ketchup is left inside. Its small pointed spout always dispenses the ketchup exactly where it's needed. Its glass bottle counterpart requires that the user pour ketchup by madly thumping on the base of the upturned bottle. Whoever invented the plastic squeeze ketchup container deserves recognition for a superior design.

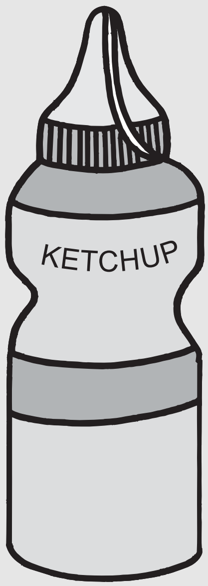


Figure 5.13
The squeeze ketchup container.

EXAMPLE 5.16

The Cereal Dispenser ☹

The large container shown in Figure 5.14 was made for storing breakfast cereal and other dry goods. The body of the container is much larger than the span of a typical hand grip, but the item is well designed and includes a recessed edge that is easily gripped for pouring. Its top includes a sealing flap that permits easy opening without requiring removal of the tight-fitting lid. The profile of the container as seen from the sides and top, including the lid, is shown in Figure 5.14. The design of this container has one major ergonomic flaw: The user can fill the container and put on the lid in either direction. No mechanism exists for forcing the user to put the opening flap on the side opposite the hand grip. An unfamiliar user may position the lid on the wrong side of the container, leading to an awkward situation at pouring time.

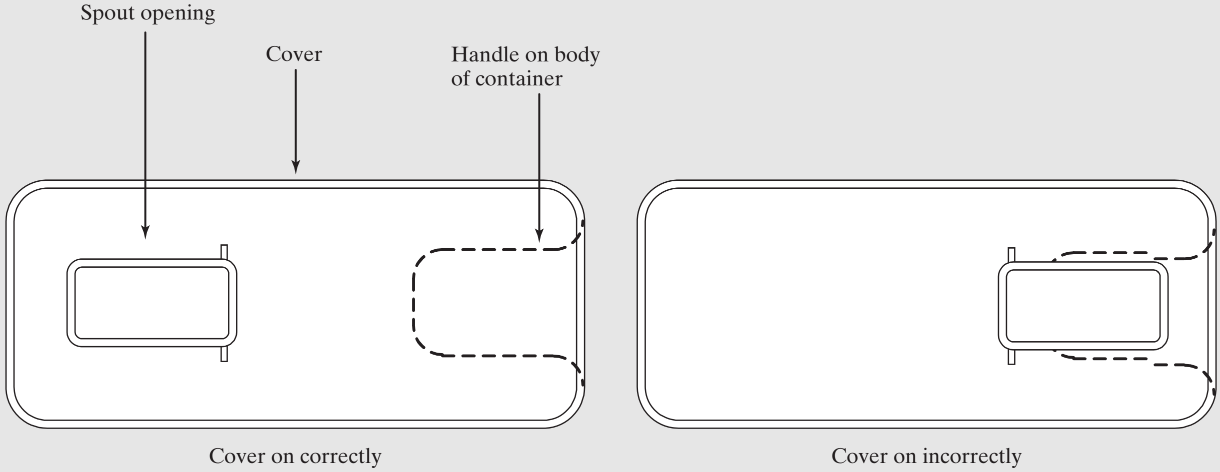


Figure 5.14
The cereal dispenser. Top right: Lid flap placed on the correct side, opposite the handle. Bottom right: Lid flap placed incorrectly on the same side as the handle.

EXAMPLE 5.17

The Hospital Revolving Door ☺

A large hospital recently renovated its main lobby. The previous building design had included revolving doors as a way to save energy by limiting air exchange during pedestrian traffic flow. Entering or leaving the hospital by wheelchair required use of large swinging doors located beside the bank of revolving doors. The problem with this arrangement is that many wheelchairs passed through the hospital each day. The hospital has a policy of requiring all released patients to be delivered to their cars by wheelchair. In addition, many incoming patients are wheelchair-bound,

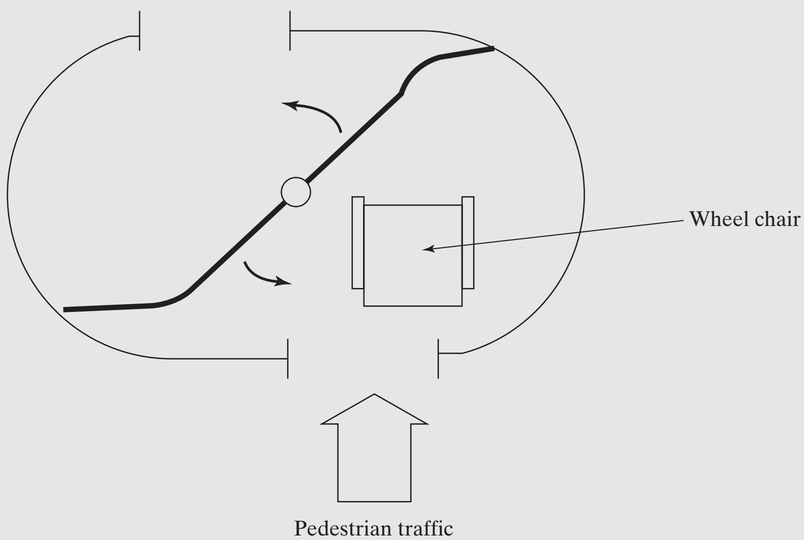


Figure 5.15
The hospital revolving door.

and many parents enter the hospital wheeling baby strollers. All these individuals were forced to use the swinging doors, bypassing the energy-saving feature of the revolving door.

The design of Figure 5.15 solved the problem. By designing a revolving-door cavity as an elongated rectangle with semicircular ends, and by designing an articulated door with outer wings, the architects were able to produce a revolving door that accommodates wheelchairs, baby strollers, and regular pedestrian traffic. The new design expedites traffic flow and saves energy at the same time.

EXAMPLE 5.18

The Paper Clip ☺

The simple office paper clip is a marvel of good ergonomic design. First patented around 1900 (and attributed, most say, to the Norwegian scientist, mathematician, and engineer Johan Vaaler), the basic paper clip of Figure 5.16 has survived virtually unchanged for over 100 years. The different lengths of its long and short tongues make it extremely easy to clip over several pages using only one hand, and the different widths of its two tongues—one fits inside the other—gives it added clasping strength. Although manufacturers have attempted to come up with numerous improved designs for the paper clip, none has succeeded in displacing the popularity of this indispensable office item.

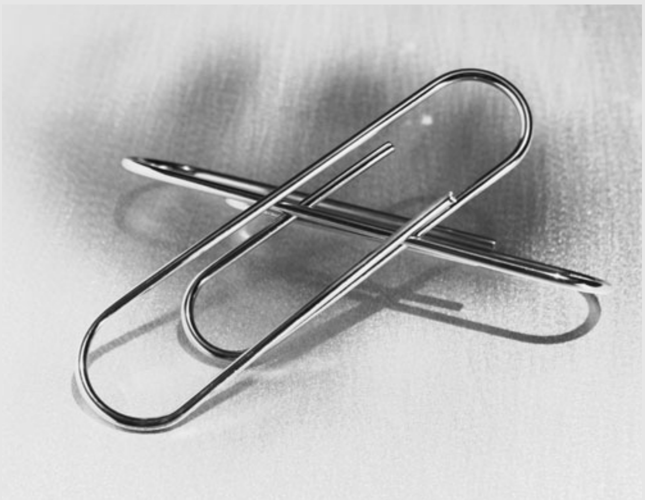


Figure 5.16
The common paper clip.

EXAMPLE 5.19

The Confusing Toaster

The common electric toaster invariably has a control to allow the user to adjust the lightness or darkness of the toast. The toaster control section shown in Figure 5.17 has white printing on a black background. Can you tell which direction produces darker toast: clockwise or counterclockwise? On the one hand, one might think the

Figure 5.17
Toaster control knob with confusing markings. Which icon suggests darker toast, the all white or the all black?

black toast icon means "darker". On the other hand, because the printing is white, the white toast icon might mean "fully colored in", hence darker toast. You'll have to buy one of these toasters to unlock the puzzle.

EXAMPLE 5.20

Web Frames—An Organizational Paradigm ☺

The first Internet Web pages were of very simple design. All were written directly in HTML (hypertext markup language) and may have included a picture or two. Navigating though a lengthy page meant a lot of vertical scrolling and was difficult at best. The onset of the "frames" mode of page design has greatly improved both the ergonomic and cognitive efficacy of Web pages. In the frames mode, information can be retrieved with precision and minimal scrolling. The contrast between single page and Web frame design is analogous to the relationship between music on tape, which must be accessed serially, and music on a CD, which can be accessed randomly. The simple software design change embodied in frames capability has made information on the Web ever more assessible to a broad spectrum of computer users.

Practice!

1. Consider two telephones, one with the keypad in the headset, and one with the keypad on its desktop base. Imagine that you are trying to access an automated flight arrival system for a major airline. Estimate the extra time per call required to enter the numbers from a headset keypad.
2. Measure the longest span between two keys on a typical desktop telephone. Measure the index-to-middle finger span on your own hand. Which is larger?
3. Do a survey of 10 or more toll-free customer service call-back lines. Before the main menu is finished, dial "0" for "Operator." Determine the number of sites for which prematurely dialing 0 (versus some other digit) actually brings a live person to the phone.

4. Call the toll-free information line of several commercial airlines. How many keys must you press, in addition to the toll-free number, in order to find out the arrival time of a flight?
5. Compare the locations of the digits 0 to 9 on a cell phone keypad with the locations of these digits on a calculator keypad. Is there a correlation?
6. Consider the lavatory faucet shown in Figure 5.13. Draw a revised design that would be easier to use but would retain the modern lines of the unit shown.
7. Consider the cereal dispenser of Figure 5.14. Draw a modification to the product that would ensure that the cover is put on correctly each time.
8. Sketch the design of a digital clock that eliminates the cognition problem discussed in Example 5.7.
9. Specify the details of an energy-saving lighting system that would allow the gymnasium described in Example 5.8 to be used for minimal-movement assemblies.
10. Do some online research and determine how many different types of paper clip designs you can find.
11. Consider the toaster of Example 5.19. Design a set of icons that will make the setting unambiguous.

Professional Success: Become Aware of the Human/Machine Interface

Formal study can help you learn about the human/machine interface, but direct observation in your own life is equally valuable. Be observant. If something seems difficult to use, try to figure out why. Think about how you might redesign the product to make it easier to use. Devise, in your own mind, modifications that will improve the product. By becoming aware of the machines and technology around you and identifying the design flaws of others, you'll become more skilled at designing your own human/machine interfaces.

KEY TERMS

Ergonomics   Case Studies   Cognition

PROBLEMS

5.1 Compile a list of five objects or devices that illustrate good ergonomic design. For every entry on your list, come up with a counterexample of poor ergonomic design.

5.2 Prepare a case study of an example of good or improved ergonomic design.

5.3 Prepare a case study of an example of poor ergonomic design.

5.4 Perform a telephone survey of 50 adults at random. Of those who own and use a programmable DVD player, ask how many regularly make use of its programmable features.

5.5 Survey people who use computers. Divide the list into those who use a conventional mouse, those who use a trackball, and those who use another pointing device. Of those in the first two categories, determine how many are happy with their pointing device and how many wish there existed something "better."

5.6 Design an experiment in which you draw a facsimile of the view as seen from the driver's seat of an automobile. Change the location of one feature of the layout (e.g., the location of the ignition key or gear shift lever). Show your drawing to a collection of test subjects. Record the amount of time that it takes each test subject to identify what is out of place.

5.7 Draw a diagram of a room with doors, windows, and furniture. Place the door handle on the same side as the hinges. Show your diagram to a number of test subjects. Record the amount of time that it takes each test subject to identify what is out of place.

Ergonomic Measurements

5.8 Measure a typical classroom chair in your school. Record the following dimensions: front-seat lip to floor; front-to-rear length of seat surface; front-seat edge to backrest; rear-seat edge to middle of backrest. Compare these dimensions to their corresponding body measurements on 10 individuals and compile your data.

5.9 Find light switches in 20 different buildings (not just different rooms in the same building). Measure the height of the switch above the floor, and find the average value and the standard deviation. Now measure the elbow-to-ground height of 30 different people. Also determine the average value and the standard deviation, and compare to the light switch measurements.

5.10 Measure the shoulder-to-fingertip arm span of 20 adults. Determine the average length, the minimum, the maximum, and the standard deviation. Do 20 people provide a large enough sample? Should you obtain measurements of more people?

5.11 Measure the floor-to-eye height of 10 seated people who work regularly at a computer. Compare their measured height to that of the center of the monitor screen on their computer. Ask each individual to estimate how long he or she can work at the computer before needing a break. See if there is any correlation between fatigue and monitor placement.

5.12 Find 25 or more volunteers who are willing to walk a fixed distance of approximately 30 m (about 100 ft). Count the total number of paces that each person requires to span the distance. Determine the average value and the standard deviation.

5.13 Measure the head circumference of 30 or more individuals. Determine the average, minimum, maximum, and most frequent head circumference measured to the nearest half centimeter.

Histograms

The following set of problems involves the use of the *bin histogram.* A histogram is a graphical plot that shows the number of members of an ensemble of data in various categories. For example, the histogram of Figure 5.18 shows the total number of occurrences of each letter of the alphabet in the text of this problem up to and including the end of this sentence. Similarly, the histogram of Figure 5.19 shows the distribution of end-of-semester grades in a particular engineering class. Engineers often use histograms to display data and sort information.

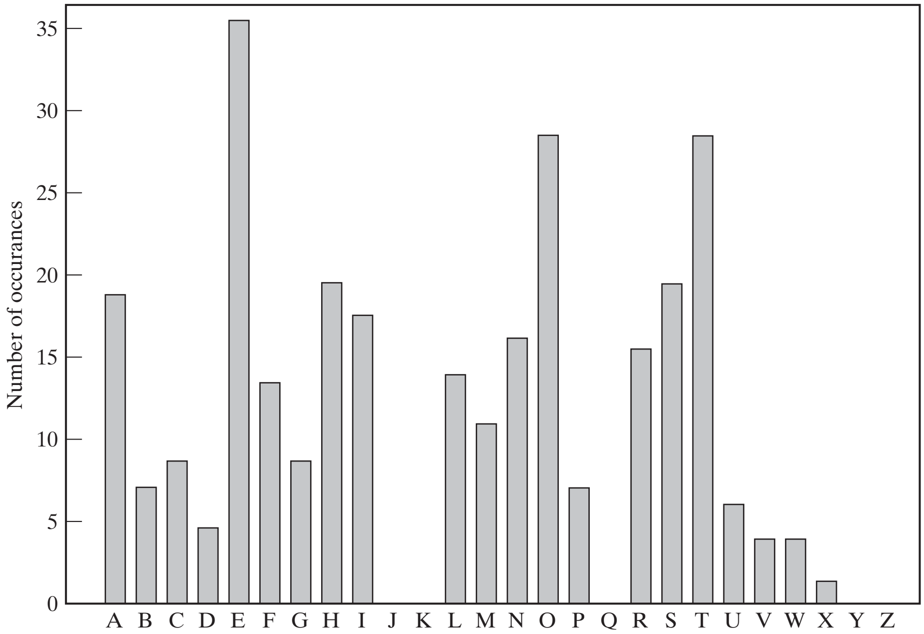


Figure 5.18
Bin histogram showing the frequency of the letters of the alphabet appearing in paragraph text.

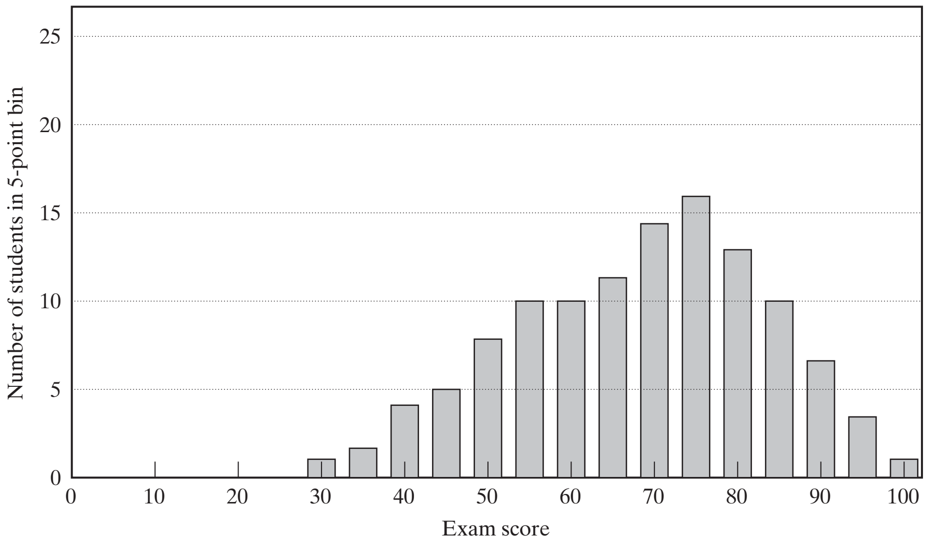


Figure 5.19
Bin histogram showing the distribution of grades in an engineering class.

5.14 Ask 100 full-grown people to tell you their height. Create a bin histogram that shows the distribution of heights in your sample pool.

5.15 Ask 100 adults to tell you their weight. Create a bin histogram that shows the distribution of weights in your sample pool.

5.16 Measure the exact height and width of 30 different desks. Plot your data in bin histogram form.

5.17 Measure the length and width of at least 50 marked parking spaces in your community. Exclude parking spaces for individuals with handicaps. Create two histograms, one for the length and one for the width, that show the distribution of parking space sizes.

5.18 Write a computer program to determine the keystroke frequency of each of the letters A–Z by someone typing The Gettysburg Address (or any similar document of your choice). Plot your results using a bin histogram.

5.19 Find 25 people who ride bicycles. Measure the length of their legs from hip joint to the bottom of the foot with shoes on. Now measure the height of their bicycle seats above the ground. Plot a histogram of the ratio of seat height to leg length. Is there any obvious pattern? Is there any gender correlation?

5.20 The objective of this problem is to determine the most common choices of color for personal passenger cars. Find a location along a highway or busy road. Record the color of at least 100 passing cars. Display your data, from most to least popular color, in bin histogram form.

Reaction Time

5.21 Write a computer program to track the keystrokes of someone typing a document of your choice into the computer. Find and record the average time that it takes the typist to activate each key after the entry of the preceding letter.

5.22 Perform the following test on several classmates. Prepare a card of simulated pushbuttons with the printed commands ON, OFF, LEFT, RIGHT, UP, DOWN, TURN LEFT, TURN RIGHT, and STOP. Prepare a second card in which the location and size of the buttons are the same, but the printed words have been replaced with the visual symbols shown in Figure 5.20.

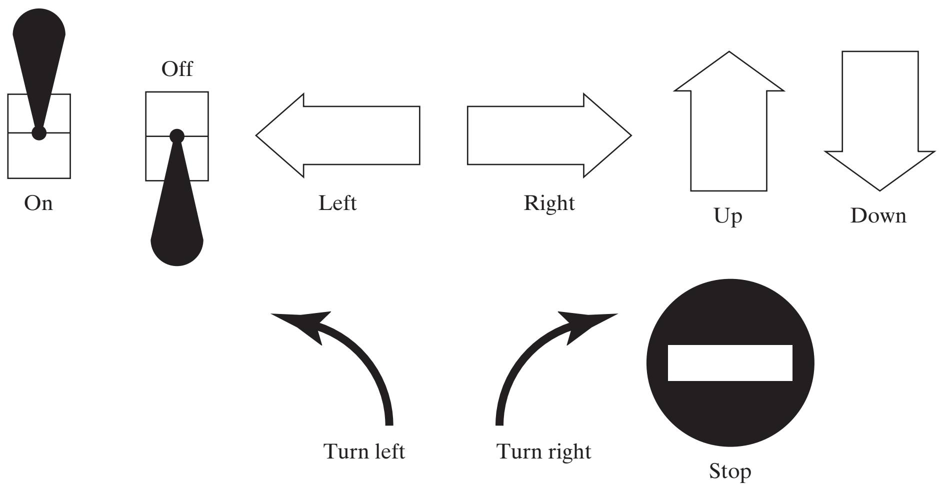


Figure 5.20
Visual commands for up, down, etc.

Now devise a set of keystroke sequences that simulate the navigation of a remote-control robot around a fictitious maze. Ask 10 or more friends to press the simulated buttons upon your verbal commands. Keep track of how much time it takes each person to complete the sequence. Which do you think will lead to a faster reaction time: the printed keys or the graphically labeled keys?

5.23 As you dictate the following passage, compare the time required for each of 20 people to write it on paper in longhand against the time required to type it into a computer: *Six saws saw six cypresses.* (Translate this sentence into French and it comes out sounding like, *"See see see see see prey."*)

5.24 Write a game on your computer that displays time from a made-up clock. For some participants, the time should be shown in analog form with hands. For others, it should be shown in digital form. As you repeatedly flash times on the screen, ask participants to press a key to stop the flashing when the displayed time is 12 (or whatever) minutes before another time that you've specified. For example, if you specified 5 minutes before 11:20, the correct answer would be 11:15. Have your computer program keep track of how much time elapses between the display of the correct answer and the pressing of the stop button. On average, is there a difference between reaction times to analog versus digital displays?

CHAPTER 6

Engineers and the Real World

Objectives

In this chapter, you will

- Examine society's view of the engineer.
- Learn about the role of failure in engineering design.
- Discuss classic design failures as case studies.
- Learn how to accept and utilize failure along the path to engineering success.

6.1 SOCIETY'S VIEW OF ENGINEERING

Now that you've decided upon engineering as a career and have gotten this far in the book, it's time for the bad news: If you become an engineer, you will be equipped to change the world, but will also be destined to oblivion. Think about it. The press and the broadcast media rarely cover the lives of engineers. The individual exploits of politicians, criminals, actors, financiers, glamour models, and sports figures all receive coverage in the press, but one seldom hears about the personal details of any important engineer. The only time that engineers do receive detailed coverage is when a major failure causes some public catastrophe. Few TV shows or movies highlight engineers as main characters. Rather, engineers are frequently portrayed as either the brains behind some villain's master plot or the nerd who provides technical support as the hero saves the day.

In truth, society at large depends on the work of engineers every day. The public expects devices and systems designed by engineers to work flawlessly—all the time—and only thinks about engineers when things fail. Most people take for granted the national power grid that magically causes electricity to appear from ubiquitous wall sockets. Only when those sockets go dead during blackouts does the public cry that "something must be done," implying that the blackout has occurred because of the incompetence of the engineers who supply electricity.

What is the reason for this stilted view of engineers? Is it because engineers are robotic people with flat personalities and no imagination? Is it because only high school nerds become engineers? Is it because engineers are incapable of being leaders? Far from it. In truth, engineering is a glamorous profession that attracts countless creative individuals. Engineers have changed the world and improved the quality of life in more ways than can be counted. It's been said in many forums that engineers have had a greater impact in increasing human life span than all medical doctors combined.

The reason the public views engineers with apprehension may be due to the following fact: *Engineers do the seemingly impossible as a matter of routine.*

What engineers accomplish is so amazing that it can't be understood by the general public. Consider the debut of the original television series *Star Trek* in the late 1960s. The notion that Captain Kirk could take a small box off his belt, flip open the cover, and talk to anyone in the world was pure science fiction. Now this scenario is a reality. Today you can buy a tiny, inexpensive cell phone that fits in your pocket, and you can call anyone in the world. Science fiction has come to fruition in a few short decades.

In the first half of the 1900s, much of science fiction focused on imaginary trips to the moon. Flash Gordon and Ming the Merciless captivated the minds of youngsters and adults. During the 1960s, engineers made it possible for the United States to *actually* land on the moon. Although the movie *Apollo 13* highlighted the trying ordeal of brave astronauts in the face of an unexpected mishap, in truth it was the NASA engineers on the ground who safely brought the astronauts safely back to earth. Indeed, it was the engineers who were responsible for an amazingly short decade of achievements leading to the first visit by a human to another celestial body.

As an engineer-to-be, you have a great responsibility to keep the public on track when it comes to popular misconceptions about engineering. When a public works project comes before your city government, it will be the engineers who will be able to discuss its impact on a sound technical basis. When the cell phone company wants to place a tower inside a church steeple, an engineer will be able to intelligently discuss the safety questions raised by the public. When the local school district needs help defining its strategic goal for information technology in the classroom, it will be the engineers who will guide the planning with intelligence.

These insights do not come easily. The public harbors numerous misconceptions about the technical world that surrounds us. The following true events highlight the discord between the errant notions of the nontechnical public and the knowledge of the engineer.

Cell Phone Use

A Midwestern newspaper reported that a father was locked out of a tornado shelter during a storm. He had run out of the shelter to retrieve his cell phone from his truck so that his family would have communication if the phone lines went down.

Misconception

Although cell phones themselves are wireless, the signals are sent to nearby cell-phone towers where they are routed to the telephone network by wires. In rural communities, these wires are most certainly overhead wires. Thus both the towers and interconnecting wires of a cell-phone network are vulnerable to a tornado.

Magnetic Resonance Imaging

The official name of magnetic resonance imaging (MRI) used to be nuclear magnetic resonance (NMR), having been named after the basic physical principle that lies at the core of this indispensable medical diagnostic tool. The name was changed to MRI because too many people were uncomfortable with anything involving nuclear technology.

Misconception

The "nuclear" in NMR refers to the nucleus of the atom being probed, which resonates in the presence of a magnetic field. The physics has nothing whatsoever to do with radioactivity of any kind.

The Debate Over Napster

The year 2001 saw a great public debate over the legality and morality of the free music download website *napster.com*. Amidst the discussion, an editorial appeared in a newspaper noting that Napster aficionados obviously preferred the sound of MP3 digital music available over the Web to the sound of regular music available on CDs.

Misconception

CD and MP3 recordings are both stored in digital format. The only difference is the storage medium. When played over the same sound system, the two formats are indistinguishable. The writer perhaps confused these digital storage media with audio cassette tapes, which are analog and often inferior in sound quality.

Radio Advertisement for a PDA

An advertisement that aired in 2001 featured a wayward soul who gets locked in a meat freezer and uses his wireless personal digital assistant (PDA) to send an e-mail message asking for help.

Misconception

The meat locker was made with stainless steel (metal) walls and doors. It would be impossible for the wireless signals to enter or leave the meat locker.

Making a Good Hot Cup of Tea

A TV sitcom featured a grandmother who kept her teapot boiling on the stove because she wanted it "extra hot."

Misconception

Water boils at 100°C. Once it boils, it can become no hotter without turning to steam and escaping the pot.

Crash of Cell-Phone System

A charitable organization holds an annual, a three-day fund-raising walk. The last leg of the 60-mile walk is paced so that participants arrive together at the end point in a large closing ceremony. After the ceremony, participants must find their families or friends for transportation home. At the 2000 event, which included about 2,500 walkers, the entire local cell network crashed after several hundred walkers and several hundred friends attempted to reach each other by cell phone.

Misconception

The traffic volume of any cell-phone network is finite. Cell phones do not call directly from one to the other, but must be routed via a cell-phone tower to land-based links. The system has a finite number of channels available from any one tower.

Electric Wiring

A homeowner called an electrician complaining about a light that had a "short" and flickered from time to time.

Misconception

The lighting circuit most certainly had an intermittent *open* circuit, and not a *short*, or closed, circuit. As any engineering student would know, a short circuit formed by two opposite wires accidentally touching each other would provide an unobstructed path to electricity that would instantly trip a circuit breaker or fuse rather than allow the light to flicker.

Thermostat Control

A rapid response help line (911) advised a parent who had found a young child lost in the snow to turn up the cabin thermostat very high so that the room would heat up "very fast" while the family waited for a distant ambulance to arrive.

Misconception

Most heating systems have just two states: "on" and "off." The heater will turn on when the inside temperature falls below the thermostat temperature, but the *rate* at which the room heats up will depend solely on the furnace output and will be independent of the thermostat setting.

Laser Printer

Many people think that the common laser printer works by burning the letters in the page with a laser.

Misconception

The sole role of the laser in a laser printer is to condition a light-sensitive roller so that it will hold electrostatically-charged toner particles where printing is desired. These toner particles are then transferred to the paper and fused to it by a heated roller. The laser beam never makes contact with the paper. This process is the same one used in photocopiers ("copy" machines), except that in the latter, a broad flash of bright light is used to condition the drum to hold toner particles in the desired places.

Hydrogen Fuel

Many people view hydrogen fuel as a replacement for oil.

Misconception

Hydrogen is an energy transport medium. It is not found naturally in large deposits, as are oil and coal. Rather, it must be produced, typically from electricity.[1] The latter comes from conventional power plants: oil, coal, natural gas, nuclear, or hydroelectric.

Cell Phones

Many people believe that calls between cell phones go directly from one phone to another, much like a pair of "walkie-talkies." Thus, during natural disasters, when regular phone lines are down, cell phones provide a reliable form of communication.

Misconception

The only radio links in a cellular telephone system are between individual cell phones and the nearest, land-based transceiver towers ("cell phone towers"). The remaining portions of the call connection are made via conventional, land-based telephone lines.

The cellular phone gets its name from the "cells" of radio space provided by a vast array of transceiver towers easily visible in populated areas. The cells of coverage

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[1]Current research seeks to produce hydrogen directly from sunlight. In this scenario, hydrogen would be a means for storing solar energy.

of adjacent towers just border on each other. A person on a call moving through different cells will be handed off between adjacent transceiver towers.

Fluorescent Lights

Many people have been told by well-meaning but misinformed individuals that a fluorescent lamp uses more electricity when it's turned on than during a long period of normal operation. (The author has heard numbers ranging from ten minutes to six hours, sometimes from licensed electricians.)

Misconception

The ballasts needed to make fluorescent lights operation results in a *very* short spike of current when first turned on, but most of the related energy is simply stored in the magnetic windings of the ballast. Moreover, the energy involved in this "spike" is minute compared to the energy needed to illuminate the bulbs. There is absolutely no basis for keeping unused fluorescent lights on as a means to "save" energy. Turning lights on and off does result in some deteriation of the bulbs, but this effect is minor compared to the energy wasted by leaving lights on all the time.

6.2 HOW ENGINEERS LEARN FROM MISTAKES

Consider the following scenario that describes the experience of two students working on the design of a battery-powered vehicle for a design competition:

- The students had been working on their vehicle for almost a week. They directed their efforts towards the design of an articulated arm that would pick up the opposing vehicle and throw it off the track. They first outlined their design on paper and then tested it using computer-aided design (CAD) software available in the computer lab. They built all the parts in the school machine shop, using their CAD drawings as a guide. A sketch of their design is shown in Figure 6.1. The students had just finished putting together all 58 machined pieces and were delighted to find that the arm worked perfectly on the very first try!

Wouldn't it be nice if engineering were so simple and foolproof as the scenario depicted in the preceding paragraph? In the real world, almost nothing works correctly the first time. Getting things to work perfectly almost always takes longer than expected. Fabricated parts do not fit together, circuits have wiring errors, software modules have incompatibilities, and structural elements are incorrectly sized. Experienced engineers know that designs seldom work the first time and are never discouraged by initial failure.

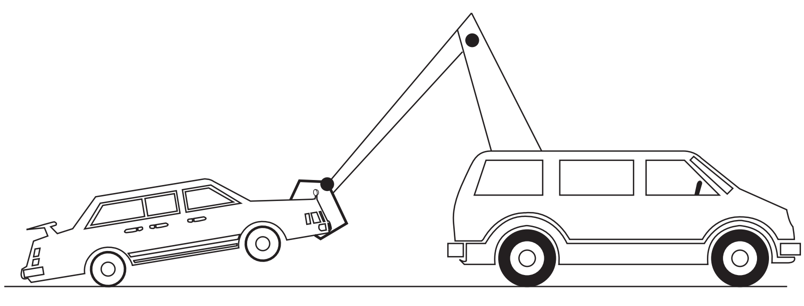


Figure 6.1
Hypothetical impractical car design includes an articulated arm.

Engineering tasks take longer than expected, because *failure* is an inevitable part of the design process. It's unreasonable to expect a new design to work the first time. When a device does not work as planned, it's a sure sign that something important has been overlooked. Perhaps two moving parts hit each other unexpectedly. Perhaps a circuit or machine doesn't work because secondary effects were not included in the design model. A software program may fail because an unforeseen set of keystrokes leads to a logical dead end. A scale model of a bridge may reveal an overstressed support beam because a support pillar was omitted. A biomedical implant may be rejected because a tissue interaction was underestimated. Whatever the failure mode, it's better for a defect to appear *during* the design process than after it, when the device is in the field. Redesign following failure provides an important path to optimizing the final product and gives engineers needed time to correct deficiencies and fix bugs in the system.

A more realistic version of the design scenario might proceed as follows:

- The students had been working on their design competition vehicle for almost a month. Their first version of the car included an articulated arm designed to pick up the opposing vehicle and throw it off the track. After much trial and error, they succeeded in building an arm capable of lifting objects. At first, the students attempted to power the arm using the spring force from a single mousetrap, but after much testing, the students discovered that they had ignored frictional effects. Two mousetraps were required for adequate mechanical power. After numerous tests, they learned that powering the arm from a small electric motor and gear set provided much finer control of its movements. Their first attempt at assembly required them to redrill several holes they had put in the wrong places. Although the final version of the arm worked well on paper and also on a CAD program, the arm failed miserably when mounted on the car. When an opposing program vehicle was lifted into the air, the center of gravity fell outside the maximum allowed wheelbase of the vehicle, causing *both* vehicles to topple over and fall off the track. The students had to abandon their arm design and eventually settled on the battering ram shown in Figure 6.2 for their offensive strategy.

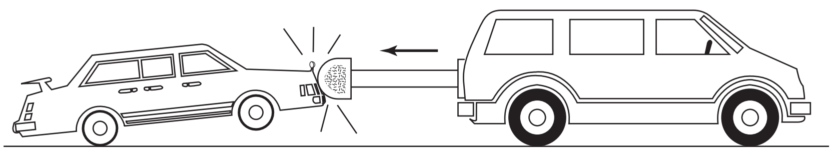


Figure 6.2
More realistic battering ram design as an offensive strategy.

6.3 THE ROLE OF FAILURE IN ENGINEERING DESIGN: CASE STUDIES

The pages of engineering history are full of examples of design flaws that escaped detection in the design phase only to reveal themselves once the device was in actual use. Although many devices are plagued by minor design flaws from time to time, a few failure cases have become notorious because they affected many people, caused great property damage, or led to sweeping changes in engineering practice. In this section, we review several design failures from the annals of engineering lore. Each event involved the loss of human life or major destruction of property, and each was caused by an engineering design failure. The mistakes were made by engineers who did the best they could, but had little prior experience or had major lapses in engineering judgment. After each incident, similar disasters were averted, because engineers were able to study the *causes* of the problems and establish new or revised engineering standards and guidelines. Studying these classic failures and the mistakes of the engineers who caused them will help you to avoid making similar mistakes in your own work.

There are no freak accidents . . . only unexpected ones.

The examples of failure that follow all had dire consequences. Each occurred once the product was in use, long after the initial design, test, and evaluation phases. Remember that it's always better for problems to show up *before* the product has gone to market. Design problems can be corrected easily during testing, burn-in, and system evaluation. If a design flaw shows up in a product or system that has already been delivered for use, the consequences are far more serious. As you read the examples of this section, you might conclude that the causes of these failures in the field should have been obvious, and that their occurrences were the result of some engineer's carelessness. Indeed, it's relatively easy to play "Monday-morning quarterback" and analyze the cause of a failure *after* it has occurred. But as any experienced engineer will tell you, spotting a hidden flaw during the test phase is not always easy when a device or system is complex and has many parts or subsystems that interact in complicated ways. Even simple devices can be prone to hidden design flaws that elude the test and evaluation stages. One of the marks of a good engineer is the ability to ferret out flaws and errors *before* the product finds its way to the end user. You can help to strengthen your abilities with the important intuitive skill of flaw detection by becoming familiar with the classic failure incidents discussed in this section. If you are interested in learning more details about any of the case studies, you might consult one of the references listed at the end of the chapter.

6.3.1 Case 1: Tacoma Narrows Bridge

The Tacoma Narrows Bridge, built across Puget Sound in Tacoma, Washington in 1940, was the longest suspension bridge of its day. The design engineers copied the structure of smaller, existing suspension bridges and simply built a longer one. As had been done with countless shorter spans, stiffening trusses deep in the structure of the bridge's framework were omitted to make it more graceful and visually appealing. No calculations were done to prove the structural integrity of a longer bridge lacking internal stiffening trusses. Because the tried-and-true design methods used on shorter spans had been well tested, the engineers assumed that these design methods would work on longer spans. However, they were incorrect. On November 7, 1940, during a particularly windy day, the bridge started to undulate and twist, entering into the magnificent torsional motion shown in Figure 6.3. After several hours, the bridge crumbled as if it were made from dry clay; not a single piece of the bridge remained between the two main center spans.

What went wrong? The engineers responsible for building the bridge had relied on calculations made for smaller bridges, even though the assumptions behind those calculations did not apply to the longer span of the Tacoma Narrows Bridge. Had the engineers heeded some basic scientific intuition, they would have realized that three-dimensional structures cannot be directly scaled upward without limits.

6.3.2 Case 2: Hartford Civic Center

The Hartford Civic Center was the first of its kind. At the time of its construction in the mid-1970s, no similar building had ever been built. Its roof was made using

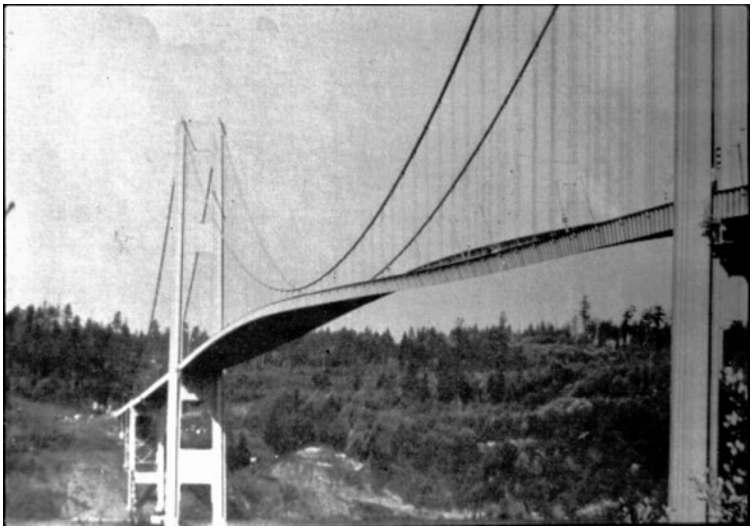


Figure 6.3
The Tacoma Narrows Bridge in torsional vibration.

a frame structure of interconnected trusses and joints, rather than from a more conventional I-beam construction method. Hundreds of rods were interconnected in a visually appealing, two-layer pattern consisting of an array of horizontal steel bars and diagonal interconnects. Instead of performing detailed hand calculations, the design engineers relied on the latest computer models to compute the loading on each individual member of the roof structure. Recall that computers in those days were much more primitive than those we enjoy today. The PC had not yet been invented, and all work was performed on mainframe computers that were very slow by today's standards. Hence, the engineers used a simplified computational model that ignored susceptibility of the structure to torsional buckling modes. It was this mode of failure that initiated the collapse of the Civic Center roof, but the deficiency in the design was left undetected by the computer simulations.

On January 18, 1978, just a few hours after the center had been filled to capacity with thousands of people watching a basketball game, the roof collapsed under a heavy snow load, demolishing the building. Miraculously, no one was hurt in the collapse.

Why did the collapse occur? Some attribute the failure to the engineers who designed the civic center and chose not to rely on their basic judgment and intuition gleaned from years of construction practice. An investigation after the collapse revealed that field engineers noticed anomalies in the structure during its assembly and erection, but their concerns were not heeded by the project managers who chose to rely on the computer models. These computer models had been written by programmers, not structural engineers, during the days when computer modeling was in its infancy. The programmers based their code algorithms on structural formulas from textbooks. In addition to omitting buckling modes from the computer model, the programmers failed to include basic derating factors at the structural joints to account for the slight changes in layout (e.g., variations in angles, lengths, connections, and fabrication methods) that occur when a complex structure is actually built. The design engineers trusted the output of computer models that had never been fully tested. Under a normal roof load, many of the truss joints were stressed beyond their safe limits. The addition of a heavy snow load proved too much for the structure to bear.

Figure 6.4
The Space Shuttle *Challenger* explodes during launch (*Photo courtesy of RJS Associates.*)

6.3.3 Case 3: Space Shuttle Challenger

The NASA Space Shuttle *Challenger* blew up during launch on a cold day in January 1986 at Cape Kennedy (Canaveral) in Florida. Thousands witnessed the explosion as it happened [see Figure 6.4]. Hundreds of millions watched news tapes of the event for weeks afterwards. After months of investigation, NASA traced the problem to a set of O-rings used to seal sections of the multisegmented booster rockets. The seals were never designed to be used in cold weather, and on that particular day, it was about 28°F (−2°C), a very cold day for Florida. The overly cold O-rings were either too stiff to properly seal the sections of the booster rocket or became brittle and cracked due to the unusually cold temperatures. Flames spewed from an open seal during acceleration and ignited an adjacent fuel tank. The entire spacecraft blew up, killing all seven astronauts on board, including a high school teacher. At the time, it was the worst space disaster in U.S. history.

In using O-rings to seal adjacent cylindrical surfaces, such as those depicted in Figure 6.5, the engineers had relied on a standard design technique for rockets. However, O-rings had never been used on a rocket as large as the *Challenger's* booster rockets. This factor, combined with the unusually cold temperature, brought the seal to its limit, and it failed.

There was, however, another dimension to the failure. *Why* had the booster been built in multiple sections, requiring O-rings in the first place? The answer is

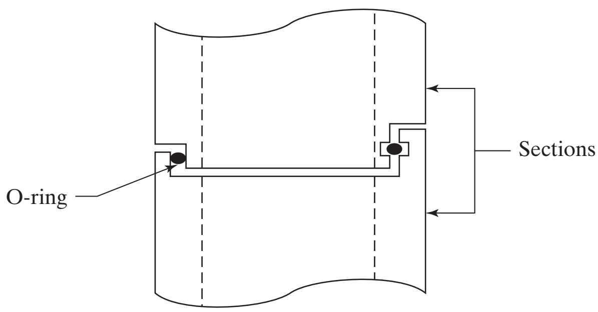


Figure 6.5
Schematic depiction of O-ring seals.

complex, but the cause was largely attributable to one factor: The decision to build a multisection booster was, in part, *political.* Had engineering common sense been the sole factor, the boosters would have been built in one piece without O-rings. Joints are notoriously weak spots, and a solid body is almost always stronger than a comparable one assembled from sections. The manufacturing technology existed to build large, one-piece rockets of the correct size. But a senator from Utah lobbied heavily to have the contract for constructing the booster rockets awarded to a company in his state. It was not physically possible to transport a large, one-piece booster rocket all the way from Utah to Florida over existing rail lines. Trucks were too small, and no ships were available that could sail to land-locked Utah, which lies in the middle of the United States. NASA's decision to award the contract to the Utah company resulted in a multisection O-ring-sealed booster rocket whose smaller pieces could easily be shipped by rail or truck.

Some say the catastrophe resulted from a lack of ethics on the part of the design engineers who suspected the O-ring design of having potential problems. Some say it was the fault of NASA for succumbing to political pressure from Congress, its ultimate funding source. Others cite the launch managers who over rode warnings from engineers about the cold weather because they had no comprehension of the technical issues. Still others say it was just an unusual convergence of circumstances, since neither the Utah senator nor the design engineers knowingly advocated for a substandard product. The sectioned booster had worked flawlessly on many previous shuttle flights that had not been launched in subfreezing temperatures. Still, others say that by putting more weight on a political element of the project, rather than on pure engineering concerns, the engineers compromised on less-than-desirable design concept that had never before been attempted on something so large.

6.3.4 Case 4: Kansas City Hyatt

If you've ever been inside a Hyatt hotel, you know that their internal architectures are unique. The typical Hyatt hotel has cantilevered floors that form an inner trapezoidal atrium, and the walkways and halls are open, inviting structures. In the case of the Kansas City Hyatt, first opened in 1981, the design included a two-layer open-air walkway that spanned the entire lobby in midair, from one balcony to another. During a party that took place not long after the hotel opened, the walkway was filled with people dancing in time to the music. The weight and rhythm of the load of people, perhaps in resonance with the walkway, caused it to collapse suddenly. Over one hundred people died, and the event will be remembered forever in the history of hotel management. Although the hotel eventually reopened, to this day the walkway has never been rebuilt.

The collapse of the Hyatt walkway is a classic example of failure due to lack of construction experience. In this case, however, the error originated during the *design* phase, not the construction phase. In order to explain how the walkway collapsed, consider the sketch of the skeletal frame of the walkway, as specified by the design engineer, shown here in Figure 6.6.

Each box beam was to be supported by a separate nut threaded onto a suspended steel rod. The rated load for each nut-to-beam joint was intended to be above the maximum weight encountered during the time of the accident. What's wrong with this picture? The problem is that the specified structure was not realistic to build. The design called for the walkway's two decks to be hung from the ceiling by a single rod at each support point. The rods were made from smooth steel with no threads. Threading reduces the diameter of a rod, so it's impossible to get a nut to

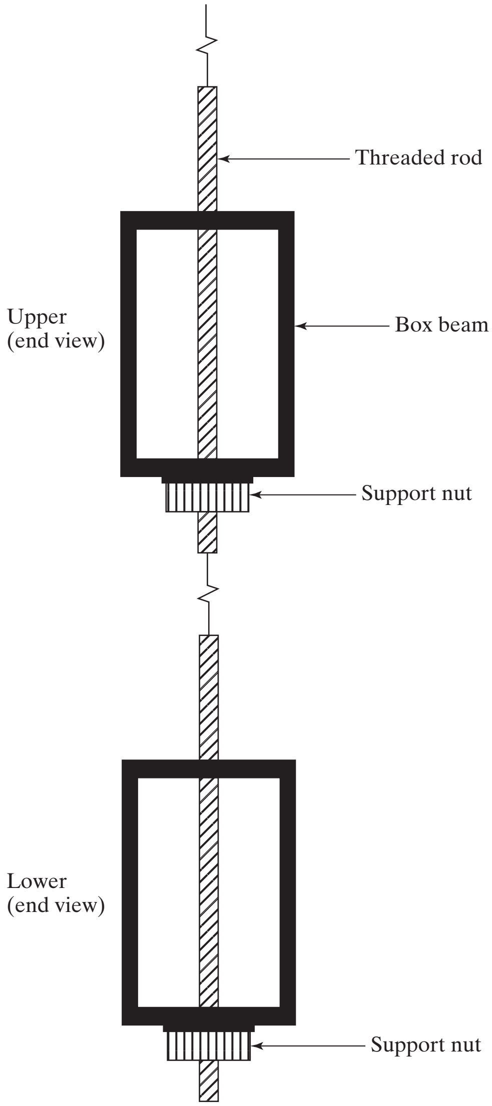


Figure 6.6
Kansas City Hyatt walkway support structure as designed.

the middle of a rod unless the rod is threaded for at least half its length. To construct the walkway as specified, each rod would have to be threaded for 20 feet, and numerous rods were needed for the long span of the walkway. Even with an electric threading machine, it would have taken days to thread all the needed rods. The contractor who actually built the walkway proposed a modification to the construction so that only the very ends of the rods would have to be threaded. The modification is illustrated in Figure 6.7.

The problem with this modification is that the nut (A), which was located at the lower end of the upper rod, now had to support the weight of *both* walkways. As an analogy, consider two mountain climbers hanging onto a rope. If both grabbed the rope simultaneously, but independently, the rope could hold their weight. If the lower climber instead grabbed the ankles of the upper climber, however, the upper climber's hands would have to hold the weight of *two* climbers. Under the full, or maybe excessive, load conditions of that day, the weight on nut (A) of the Hyatt walkway was just too much, and the joint gave way. Once the joint on one rod

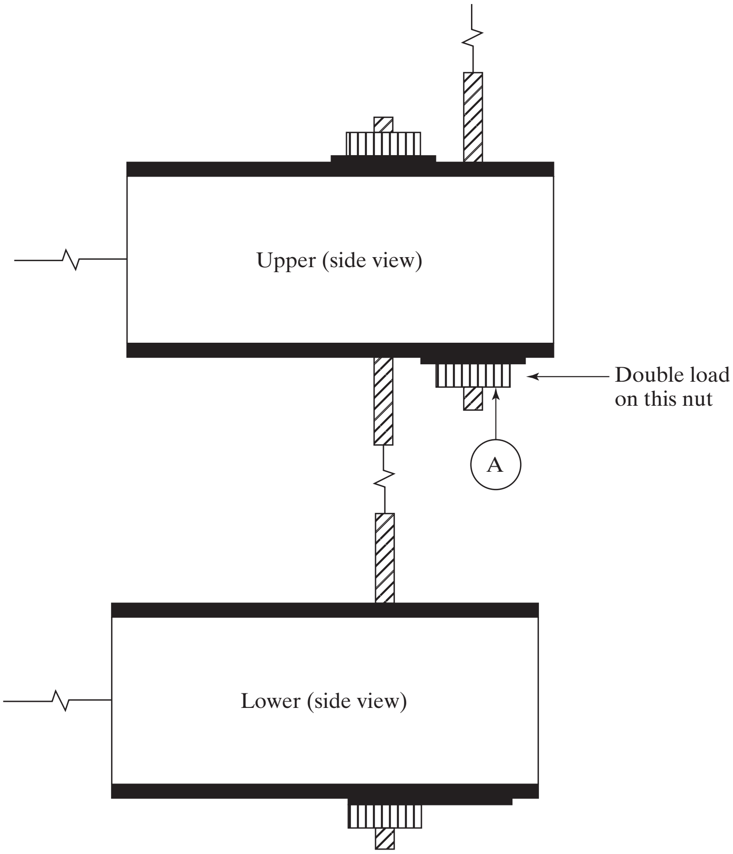


Figure 6.7
Kansas City Hyatt walkway support structure as actually built.

failed, the complete collapse of the rest of the joints and the entire walkway quickly followed.

Some attributed the fatal flaw to the senior design engineer who specified single rods requiring 20 feet of threading. Others blamed it on the junior engineer, who signed off on the modifications presented by the construction crew at the construction site, and the senior engineer, who should have communicated to the junior engineer the critical nature of the rod structure as specified. Perhaps both engineers lacked seasoning—the process of getting their hands dirty on real construction problems to understand how things are made in the real world.

Regardless of who was at fault, the design also left little room for *safety margins.* It is common practice in structural design to leave *at least* a factor-of-two safety margin between the calculated maximum load and the expected maximum load on a structure. The safety margin allows for inaccuracies in load calculations due to approximation, random variations in material strengths, and small errors in fabrication. Had the walkway included this common safety margin, the doubly stressed joint on the walkway might not have collapsed, even given its modified construction. The design engineers specified a walkway structure that was possible, but not practical, to build. The construction supervisor was unaware of the structural implications, but was eager to complete the job. Hence he ordered a seemingly innocent, but ultimately fatal, change in the construction method. If either of the design engineers had had more experience working on a construction site, this shortcoming might have been discovered. Errors such as the Kansas City Hyatt's walkway collapse can be prevented by including workers from all phases of construction in the

Figure 6.8
Three Mile Island power plant.

design process, ensuring adequate communication between all levels of employees, and adding far more than minimal safety margins where public safety is at risk.

6.3.5 Case 5: Three Mile Island

Three Mile Island was a large nuclear power plant in Pennsylvania (see Figure 6.8). It was the site of the worst nuclear accident in the United States, and it was nearly comparable to the total meltdown at Chernobyl, Ukraine. Fortunately, the incident at Three Mile Island resulted in only a near miss of a meltdown. However, it also led to the shutdown and trashing of a billion-dollar electric power plant, resulting in significant loss of electrical generation capacity to the power grid in the eastern United States.

On the day of the accident, a pressure buildup occurred inside the reactor vessel. In such situations, it was normal procedure to open a relief valve to reduce the pressure to safe levels. The valve in question was held closed by a spring and was opened by applying voltage to an electromagnetic actuator. However, the designer of the electrical control system had made one critical mistake. As suggested by the schematic diagram in Figure 6.9, indicator lights in the control room lit up when power was applied to or removed from the valve actuator coil. Unfortunately, the control panel gave no indication about the *actual* position of the valve. After the pressure-relief operation, the valve at Three Mile Island became stuck in the open position. Although the actuation voltage had been turned off and lights in the control

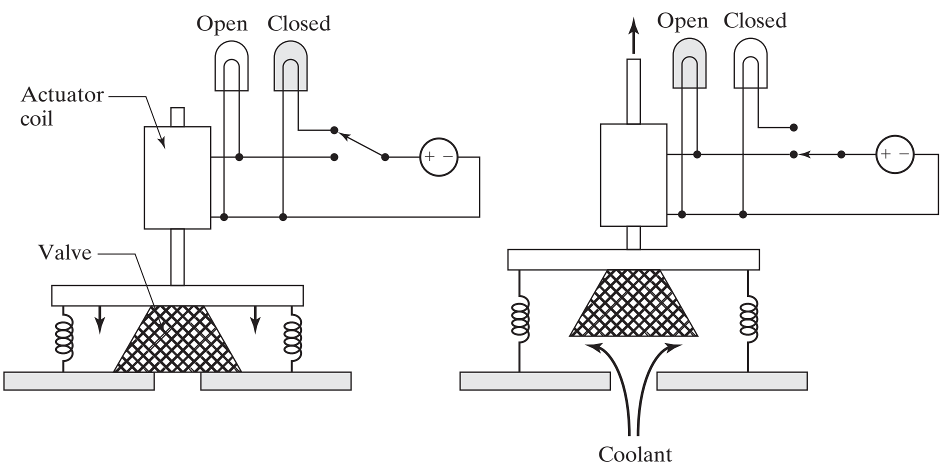


Figure 6.9
Valve indicator system as actually designed.

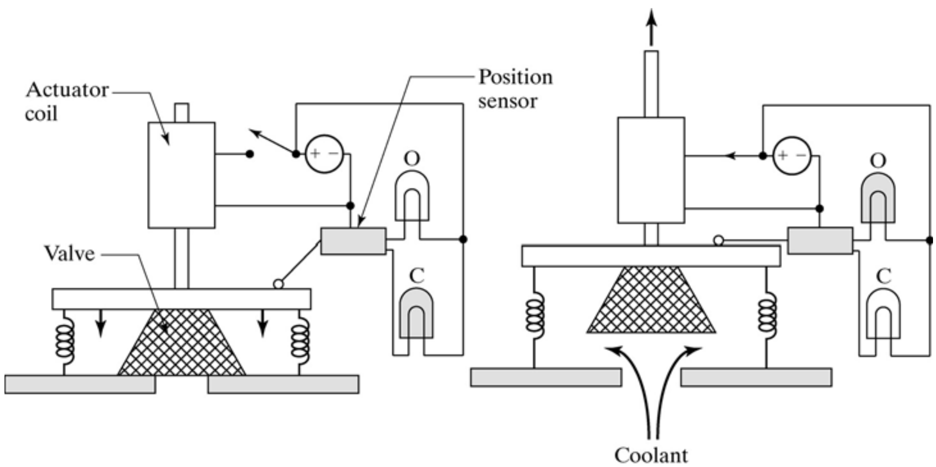
room indicated that the valve was closed, it was actually stuck open. The mechanical spring responsible for closing the valve did not have enough force to overcome the sticking force. The operators, believing that the valve was closed, tried to diagnose the problem; meanwhile, coolant leaked from the vessel for almost two hours. Had the operators known that the valve was open, they could have closed it manually or taken other corrective measures. In the panic that followed, however, the operators continually believed their control-panel indicator lights and thought that the valve was closed. Eventually, the problem was contained, but not before a rupture nearly occurred in the vessel. Such an event would have resulted in a complete core meltdown and spewed radioactive gas into the atmosphere. Even so, damage to the reactor core was so severe that the plant was permanently shut down. It has never reopened.

The valve actuation system at Three Mile Island was designed with a poor human–machine interface. The ultimate test of such a system, of course, occurs during an emergency, when the need for absolutely accurate information is critical. The operators assumed that the information they were receiving was accurate, while in reality it was not. The power plant's control panel provided the key information by inference, rather than by direct confirmation. A better design would have included an independent sensor that unambiguously verified the true position of the valve, as suggested by the diagram of Figure 6.10.

6.3.6 Case 6: USS Vincennes

The *Vincennes* was a U.S. missile cruiser stationed in the Persian Gulf during the Iran–Iraq war. On July 3, 1988, while patrolling the Persian Gulf, the *Vincennes* received two IFF (Identification: Friend or Foe) signals on its Aegis air-defense system. Aegis was the Navy's complex, billion-dollar, state-of-the-art information-processing system that displayed more information than any one operator could possibly hope to digest. Information saturation was common among operators of the Aegis system. The *Vincennes* had received two IFF signals, one for a civilian plane and the other for a military plane. Under the pressure of anticipat-

Figure 6.10
Valve indicator system as it should have been designed and built.



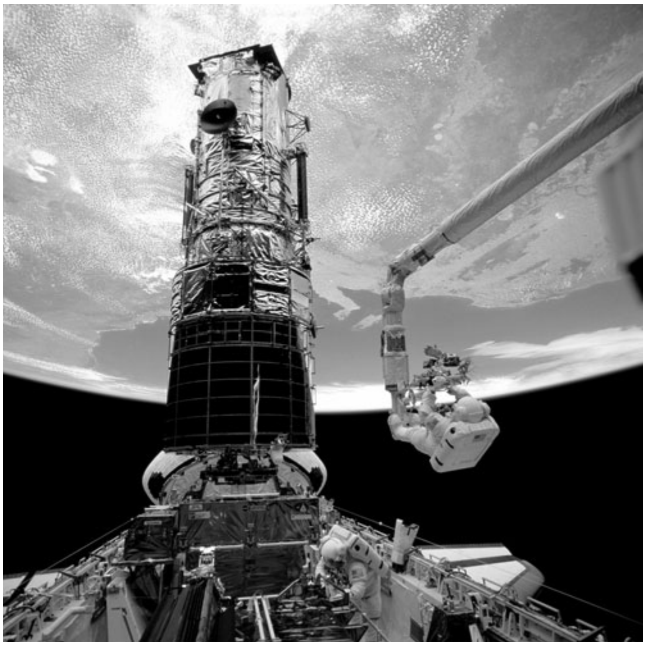
ing a possible attack, the overstimulated operator misread the cluttered radar display and concluded that only one airplane was approaching the *Vincennes*. Repeated attempts to reach the nonexistent warplane by radio failed. The captain concluded that his ship was under attack and made the split-second decision to have the civilian airplane shot down. Two hundred ninety civilians died needlessly.

What caused this catastrophic outcome? Was it bad military judgment? Was it an operating error? Were the engineers who designed the system at fault? The Navy officially attributed the accident to "operator error" by an enlisted sailor, but in some circles, the blame was placed on the engineers who had designed the system. Under the stress of possible attack, and deluged with information, the operator simply could not cope with an ill-conceived human–machine interface. Critical information, which is needed most during crises, should have been uncluttered and easy to interpret. The complex display of the Aegis system was an example of something that was designed just because it was technically possible. It resulted in a human–machine interface that became a weak link in the system.

6.3.7 Case 7: Hubble Telescope

The Hubble orbiting telescope was put into space at a cost of over a billion dollars. Unaffected by the distortion experienced by ground-based telescopes due to atmospheric turbulence, the Hubble has provided spectacular photos of space and has made possible numerous astronomical discoveries. Yet, the Hubble telescope did not escape design flaws. Of the many problems that plagued the Hubble during its first few years, the most famous was its improperly fabricated mirrors. They were distorted and had to be corrected by the installation of an adaptive optical mirror that compensated for aberrations. The repairs were conducted by a NASA Space Shuttle crew. Although this particular flaw is the one most often associated with the Hubble, it was attributed to sloppy mirror fabrication rather than to a design error.

Another little-known design error more closely illustrates the lessons of this chapter. The Hubble's solar panels were deployed in the environment of space, where they were subjected to alternate heating and cooling as the telescope moved in and out of the Earth's shadow. The resulting expansion and contraction cycles caused the solar panels to flap like the wings of a bird. Attempts to compensate for the unexpected motion by the spacecraft's computer-controlled stabilizing program led to a positive feedback effect, which only made the problem worse. Had the design engineers anticipated the environment in which the telescope was to be operated, they could have compensated for the heating and cooling cycles and avoided the problem. This example illustrates that it is difficult to anticipate all the conditions under which a device or system may be operated. Nevertheless, extremes in operating environment often are responsible for engineering failures. Engineers must compensate for this problem by testing and *retesting* devices under different temperatures, load conditions, operating environments, and weather conditions. Whenever possible (though obviously it was not possible in the case of the Hubble), a system should be tested in as many different environmental conditions as possible, particularly if those conditions may be encountered in the field.



6.3.8 Case 8: de Haviland Comet

The de Haviland Comet was the first commercial passenger jet aircraft. A British design, the Comet enjoyed many months of trouble-free flying in the 1950s until several went down in unexplained crashes. Investigations suggested that the fuselages of these planes had ripped apart in midflight. For years, the engineers assigned the task of determining the cause of the crashes were baffled. What, short of an explosion, could have caused the fuselage of an aircraft to blow apart in flight? No evidence of sabotage was found at any of the wreckage sites. After some time, the cause of the crashes was discovered. No one had foreseen the effects of the numerous pressurization and depressurization cycles that were an inevitable consequence of takeoffs and landings. Before jet aircraft, lower altitude airplanes were not routinely operated under pressure. Higher altitude jet travel brought with it the need to pressurize the cabin. In the case of the Comet, the locations of the window rivets developed fatigue cracks; after many pressurization and depressurization cycles, the fatigue cracks grew into large, full-blown cracks in the fuselage. This mode of failure is depicted in Figure 6.11.

Had the design engineers thought about the environment under which the finished product would be used, the problem could have been avoided. Content instead with laboratory stress tests that did not mimic the actual pressurization and depressurization cycles, the engineers were lulled into a false sense of security about the soundness of their design. This example of failure again underscores an important engineering lesson: Always test a design under the most realistic conditions possible. Always assume that environmental conditions will affect performance and reliability.

6.3.9 Case 9: The Collapsing Roof Panels

On July 10, 2006, a man and woman were driving through one of Boston's famed "Big Dig" tunnels. Specifically, they were traveling on the final eastbound section of

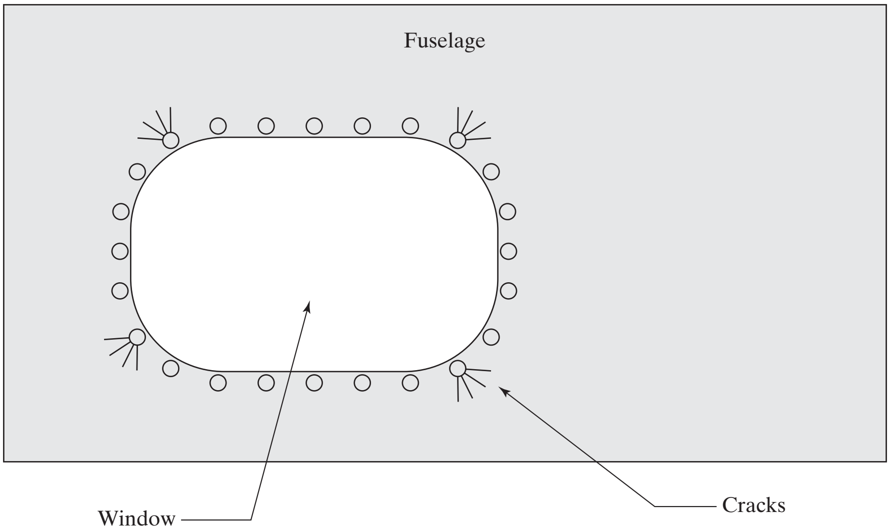


Figure 6.11
Stress cracks around the window rivets of the de Haviland Comet.

US Interstate 90 in a connector tunnel leading to the Ted Williams Tunnel in South Boston. Without warning, four concrete panel tiles, each weighing around three tons, fell from their ceiling mounts, crushing the car beneath. A total of about 26 tons of concrete and associated suspension hardware fell onto the vehicle and on to the roadway. The man survived, but the woman was killed. (See Figure 6.12)

For even the most novice of engineers, immediate questions come to the mind: How were these panels attached? Why were they made from concrete, and why so heavy? How could they have fallen so suddenly without prior signs of pending failure? The answers to these questions are complex, but some very basic errors on the part of the designers, engineers, and installers unmask the breaches in ethical behavior, the pressures of economics, and the lure of monetary gain connected with this incident.

Background

Boston, Massachusetts had a major traffic problem in the form of an elevated six-lane highway known as the Central Artery. The roadway, built in the 1950s, cut through the heart of the city. When it opened in 1959, the Central Artery comfortably carried about 75,000 vehicles a day. By the 1980s, it was carrying more than 200,000 cars, making it one of the most congested highways in the United States. The

Figure 6.12
Collapsed ceiling panels inside the "Big Dig." (*Photo courtesy of the National Transportation Safety Board*)

Central Artery/Tunnel Project was conceived as a grand project to ameliorate what were possibly the worst traffic problems in the country. When the project began in the 1980s, the projected cost through 2005 was an inconceivable $3.2 billion. As of 2008, the accumulated costs for construction and ongoing repairs have topped $21 billion.

(*Photo courtesy of the National Transportation Safety Board*)

The Players in the Story

Massachusetts Turnpike Authority. Oversees a 130-mile long toll highway extending across the state from east to west, including sections of the Big Dig.

Bechtel/Parsons Brinckerhoff. Responsible for the "conceptual design" of the roadway and for top-level management of its design and construction. Details of construction, such as the method for installing the ceiling and how much its panels should weigh, were left to subcontractors.

Gannett Fleming. International consulting firm specializing in engineering design and construction management. Designed the hanging ceiling system used in the I-90 tunnel.

Modern Continental. A large construction firm. Responsible for actual construction of the I-90 tunnel and its hanging ceiling.

Power Fasteners. Company specializing in anchoring and fastening products for concrete, masonry, and steel. Supplied the epoxy glue used to hold the ill-fated ceiling bolts.

National Transportation Safety Board. Independent federal agency responsible for investigating accidents involving aviation, highway, marine, pipelines, and railroads in the United States. Investigated the cause of the ceiling collapse.

Martha Coakley. Attorney General for the Commonwealth of Massachusetts. Oversaw the investigation leading to the indictment of some of the above-mentioned players.

Facts Determined During the Ensuing Investigation

Sources for the information used in this example were obtained principally from *The Boston Globe* (*www.boston.com*) and the website of the Massachusetts Turnpike Authority (*www.masspike.com*). While no one can know the intent of any of the players in the story, these sources have underscored the lingering doubts that still surround the incident. As an engineer-in-training, you should read the descriptions and

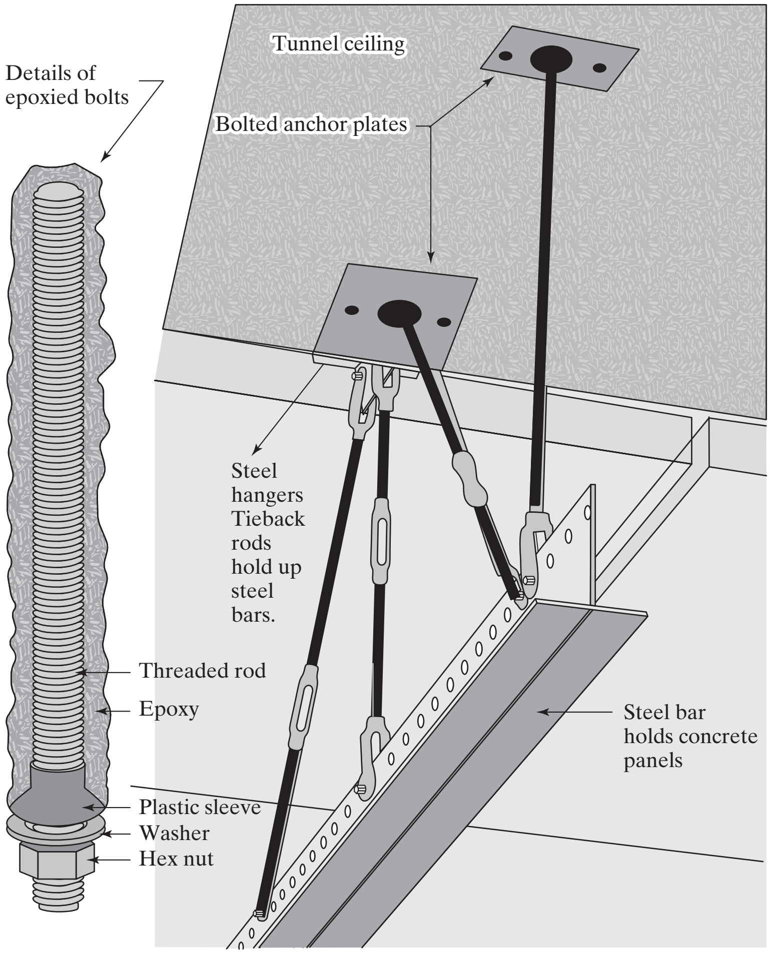


Figure 6.13
Details of support system for concrete ceiling panels. The upper brackets were secured by bolts inserted into holes drilled in the concrete ceiling. Epoxy glue filled the space between the bolts and the hole cavities.

form your own independent opinion. In any event, the following facts were clearly established in the aftermath of the incident:

The concrete panels were designed to hang from the top of the tunnel. The panels were specified to be held by metal bracket supports attached to the ceiling by hanging rods. This configuration is illustrated in Figure 6.13. The holding brackets were to be anchored to the concrete ceiling via bolts inserted into drilled holes and held in place by epoxy glue.

Epoxy is a polymer whose stiffness changes with time and temperature. If a load is applied suddenly, the epoxy holds well for short periods. If the load is continuously applied thereafter (i.e., a "static load"), molecules in the polymer may begin to slide past one another, causing some epoxies to gradually deform in a process called "creep." The particular epoxy used in the tunnel had poor creep resistance. The fact was overlooked by the engineers responsible for installation. This lapse in rigor resulted from a general lack of understanding in the "construction community" about epoxy creep under static load.

Modern Continental used Power Fasteners' Fast Set™ epoxy for installing the adhesive anchors into the ceiling. This epoxy formulation had been shown, via previous testing, to succumb to creep failure under sustained tensile loading. Modern

Continental's contract was modified several times prior to the installation to allow for changes in the installation of "adhesive anchors for ceiling struts" in the I-90 tunnel. After the incident, a spokesperson for the company said, "We are confident that our work fully complied with the plans and specifications provided by the Central Artery Tunnel Project", adding that Big Dig officials inspected and approved the tunnel ceiling.

Power Fasteners neglected to inform Modern Continental about the lack of creep resistance of the specific epoxy being purchased for the job. Interestingly, bolts in other similarly anchored systems in earlier built sections of the Big Dig had shown signs of pulling out due to epoxy creep and were repaired.

Seven years before the accident, in 1999, a safety officer working for Modern Continental warned his superiors that the bolts could not possibly hold the heavy ceiling panels. The memo stated, in part, that he could not "comprehend how this structure can withstand the test of time."

The Massachusetts Turnpike Authority did not establish ongoing and timely inspection of tunnel components once the Big Dig was opened to traffic. Modern Continental similarly did not institute its own inspection program during and after construction to ensure that the installed ceiling anchors were working properly.

The overseers of the project, Gannett Fleming and Bechtel/Parsons Brinckerhoff, failed to identify epoxy creep as a critical long-term failure mode. Their design specifications and approval process for the epoxy anchors did not specify creep-resistant epoxy or, better yet, a different (and more costly) method of supporting the concrete ceiling panels.

Outcome of the Case

The National Transportation Safety Board determined, not surprisingly, that the probable cause of the ceiling was the inappropriate use of an epoxy anchor adhesive that was not creep resistant. Over time, the epoxy deformed and fractured until several ceiling support anchors pulled free and allowed a portion of the ceiling to collapse.

As a result of its investigation, the NTSB issued new recommendations concerning the future use of tensile-loaded epoxies. One of those recommendations was to prohibit the use of adhesive anchors in sustained tensile-load overhead highway applications where failure of the adhesive would result in a risk to the public or, at the very least, to require creep testing on all anchor adhesives proposed for overhead applications.

The Massachusetts Attorney General pursued criminal negligence suits against only three of the companies involved: Bechtel/Parsons Brinckheroff, Modern Contintental, and Power Fasteners.

Bechtel/Parsons Brinckerhoff agreed to pay $450 million to the Massachusetts Turnpike Authority to cover the costs of ceiling repair and other known major leaks and design flaws. In return, the Attorney General's office agreed not to further pursue criminal charges against the company. The settlement had no direct compensatory effect on the victim's family. A spokesperson for B/PB deemed the settlement to be "in the best interests of all concerned."

The family of the deceased victim settled with Power Fasteners for $6 million. Power Fasteners denied responsibility, but a company spokesperson said that the settlement would " . . . allow the healing process to begin. We also hope that this will lead others who, unlike Powers, truly were responsible for the accident, to do the same."

Modern Continental, the most highly paid of the Big Dig contractors, sought the shelter of US Bankruptcy Court in June 2008, claiming up to $1 billion in debts.

As of the printing of this book, the criminal negligence case is still pending against the firm, but no settlement is in the works.

To date, no officials of Bechtel/Parsons Brincknerhoff, Gannett Fleming Modern Continental, or Power Fasteners have resigned as a result of the Big Dig ceiling collapse.

EPILOGUE (with apologies to the classic story)

One day, the Little Red Hen was examining the aftermath of some fallen ceiling panels.

"This situation is a disaster," she said. "Who was responsible?"

"Not I," said the Duck.
"Not I," said the Cat.
"Not I," said the Dog.

"Then I'll convene a commission to placate the public by placing blame on at least someone," said the Little Red Hen. And she did.

6.4 PREPARING FOR FAILURE IN YOUR OWN DESIGN

First-time designs often betray previously hidden flaws after an initial period of successful use. Design flaws eventually show up because the operating environment changes, a previously untried sequence of events occurs, or weak points in the design encounter repeated stress. Sometimes, failure occurs just because of plain old statistics. As the saying goes, "If something is bound to fail, it *will* fail sooner or later." After a failure occurs, it's the engineer's job to determine the cause, fix the problem, and begin tests again. At the same time, it's up to the design engineer to identify as many of the bugs and weaknesses as possible during the early phases of the design process. Thorough testing and retesting under all sorts of operating conditions is essential. An unsuccessful first prototype presents an excellent opportunity to discover and weed out bugs before the final version of the device is put to market.

In the commercial sector, the rush to market a product ahead of competitors puts pressure on the engineer to complete the test and evaluation phases as quickly as possible. For this reason, many consumer products develop problems soon after they are released. If you purchase a product during its first year of issue, expect to find bugs and weaknesses that were not discovered on the factory floor.

Despite this admonition, you should be eager to apply your engineering design skills to new technology and innovation. If all engineers were content to stay with tried-and-true designs, technical progress would cease. Understanding when to stay within the bounds of a traditional design and when to move on to new creative frontiers requires experience, knowledge, and intuition. When you encounter failure in your own design projects, do not be discouraged. Recognize failure as an inevitable part of the design process. Use it to learn, discover, and expand your capabilities as an engineer.

KEY TERMS

Bugs
Failure
Flaw
Safety margin
Ethics
Redundancy
Standards
Society

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PROBLEMS

6.1 Identify a product or system in your own experience that has failed. Write a short summary of the cause of the failure and how you might improve upon the design.

6.2 Look up and write a synopsis of the following classic engineering failure incidents:

(a) Exxon Bayway refinery, Linden, New Jersey (1990)
(b) General Electric rotary compressor refrigerators (1990)
(c) Green Bank radio telescope (1989)
(d) Union Carbide chemical leak, Bhopal, India (1984)
(e) Korean Airlines Flight 007 (1983)
(f) Interstate 95 Bridge, Mianus River, Connecticut (1983)
(g) Alexander L. Kielland oil platform, North Sea (1980)
(h) American Airlines DC-10 (1979)
(i) Skylab (1979)
(j) The New York City power blackout (1976)
(k) The windows in the John Hancock Tower, Boston, Massachusetts (1976)
(l) Big Ben, London (1976)
(m) Bay Area Rapid Transit (BART) (1973)
(n) Point Pleasant Bridge, Ohio River, Ohio–West Virginia (1967)
(o) The Apollo 1 capsule fire (1967)
(p) The Great Northeast power blackout (1965)
(q) Quebec City Bridge (1907)
(r) The Johnstown flood (1889)
(s) Liberty Bell, Philadelphia (1835)

6.3 Consider the case of the Tacoma Narrows bridge. Given what we now know about structural design, and given the availability of detailed computer modeling, do you think the same sort of mistake could be made today? After answering this question, look up the London Millennium Footbridge on the Internet.

6.4 Consider the incident involving the Space Shuttle Challenger disaster.

(a) Who could or should have acted to prevent the accident, or was it unforeseeable?
(b) Was any company or party guilty of negligence?

(c) Which factors other than technical (economic, social, etc.) contributed to the failure. How might these have been circumvented to ensure best engineering practices?

6.5 Consider the case of the Kansas City Hyatt walkway. Who do you think was more at fault, the junior engineer, the senior engineer, the architect, or the construction boss?

6.6 In light of the ongoing debate about the safety of nuclear power, consider the case of the Three Mile Island nuclear power plant, as well as the meltdown of the plant in Chernobyl, Ukraine. Are these incidents omens of more pending nuclear accidents, or do they serve as means to ensure the safety of other present and future power plants?

6.7 Discuss the case of the *USS Vincennes* in the context of cognition and ergonomics. Who was more at fault, the designers or the sailors manning the system?

6.8 In light of the errors made in designing the Hubble Space Telescope, what can you conclude about the extent to which engineering design decisions should be evaluated and tested prior to implementation? Do you think that more iterations around the design loop could have prevented the flaw?

6.9 Consider the case of the de Haviland Comet. Should flights have been grounded immediately pending identification of the cause of the very first crash?

6.10 Consider the story of the Big Dig ceiling collapse outlined in Example 6.3.9. Answer the following questions:

(a) Who could or should have acted to prevent the accident, or was it unforeseeable?
(b) Was any company or party guilty of negligence?
(c) Who could have acted to prevent the accident?
(d) Was the accident unforeseeable?
(e) Which individuals, if any, were guilty of negligence?
(f) Should any individual involved have been convicted of involuntary manslaughter?
(g) Were the monetary settlements appropriate?

CHAPTER 7

Learning to Speak, Write, and Make Presentations

Objectives

In this chapter, you will learn about

- Writing effective e-mail messages and memos.
- Preparing for meetings, presentations, and conferences.
- Writing technical proposals, reports, and journal papers.
- Preparing an instruction manual.
- Identifying the characteristics of good oral and written communication.
- Studying examples of good and bad writing styles.

Imagine that you have just purchased a new, top-of-the-line computer with the fastest available processor, many megabytes of memory, a huge disk drive, and a large sophisticated sound card. When you get the computer home from the store, you notice that the model you bought has been shipped without a monitor. In fact, the computer is missing entirely a socket where a monitor can be connected. In all other respects, the computer is state-of-the-art and in perfect condition. What would your reaction be? You probably would take the computer back to the store claiming, of course, that any computer, no matter how fast or powerful, is useless without a means to extract the information it produces. Now imagine a similar scenario in which the computer has a monitor but comes with a very poor modem capable of a maximum data transfer rate of only 300 baud (about 30 printed characters per second). Such a slow modem would indeed limit the efficiency with which your computer could talk to other computers over the Internet. Reading electronic mail (e-mail) would be hopelessly slow, and accessing Web pages would be next to impossible. You probably would take this second computer back to the store also, claiming it to be a powerful machine that is incapable of communicating with others.

People are a little bit like computers in this respect. The smartest person in the world, the fastest thinker, the most prolific scientist or engineer, is severely handicapped without an ability to communicate with others. The famous physicist Dr. Steven Hawking, author of *A Brief History of Time*[1] and other works on cosmology, has been acknowledged as one of the most brilliant minds of modern physics. A debilitating disease known as ALS took away his ability to speak and move his limbs and facial muscles, cutting off all normal means of communication. His thoughts and ideas have come to the world one agonizing word at a time by way of synthesized computer speech. How much more the world would understand about the nature of the universe were Stephen Hawking able to communicate using normal human speech and body language.

[1]Stephen W. Hawking, *A Brief History of Time.* Toronto: Bantam Books, 1988.

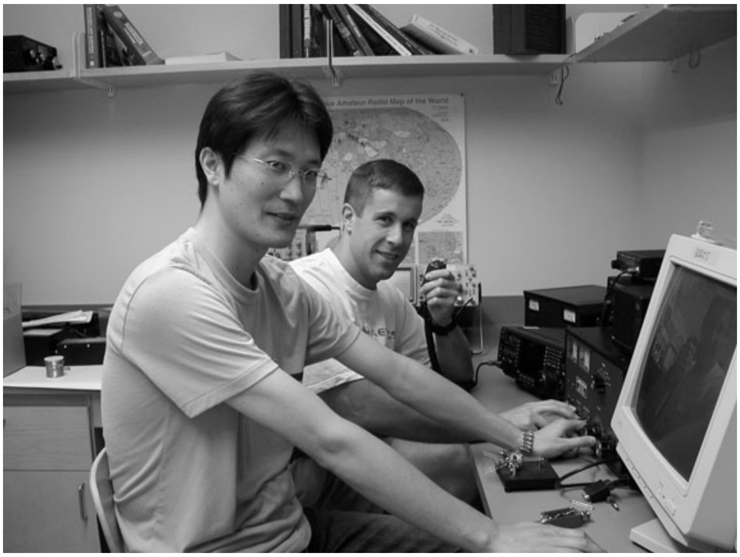

Figure 7.1
Good communication skills are important to all aspects of engineering.

7.1 THE IMPORTANCE OF GOOD COMMUNICATION SKILLS

Asked what the most important single skill is for new engineers in the workplace, most every employer will state emphatically: *communication skills!* (Figure 7.1) Teamwork may fail if the members of the team cannot communicate well with each other. The best software programmer in the world will do a poor job if the ideas behind the software are not well understood by the user. The most proficient mechanical designer will fail if the structure being designed is set up incorrectly or is used in an improper manner. Communication skills are so important that the Accreditation Board for Engineering and Technology, the national organization responsible for accrediting programs in schools of engineering in the United States and Canada, has listed oral and written communication as mandatory elements for all engineering programs regardless of discipline. Listening also is a very important skill for students of all types. Engineering departments have risen to the challenge by teaching these skills in many different ways, from writing workshops and courses taught by English departments to required oral presentations by students in key core courses.

In this chapter, we cover some of the most basic of oral and written communication skills. Although not all inclusive, the scenarios presented in this chapter cover many of the communication situations in which you might find yourself during your engineering career. Topics include preparing for meetings, conferences and presentations, drafting short memos, writing letters and electronic mail, and writing long technical reports and journal papers.

7.2 PREPARING FOR MEETINGS, PRESENTATIONS, AND CONFERENCES

Whenever you get together to socialize, you are participating in an informal meeting. You also participate in an informal meeting when you meet with your boss or coworkers to discuss the status of your latest project. Are these two events similar? Should you approach both with the same level of preparation? In the first case, you'd feel silly if you prepared beforehand for a social gathering with your friends. The purpose of such a gathering would be to relax and dispense with formalities. In the case of a meeting with your boss, you *should* spend time preparing beforehand because the meeting will reflect upon your work, your competency, and your role and status within the company. The same could be said for a meeting with your professor to discuss your work as a student. Preparing for an informal meeting takes only a small amount of forethought and planning, because no long speech or formal presentation is required. On the contrary, you may come across as being phony if your conversation seems contrived or orchestrated. Natural speech and hand gestures are always preferable at an informal meeting. You should, however, take the time to think about the content of the meeting beforehand. What will be the topics of conversation? What are your own opinions or thoughts about those topics? Are you being called upon to provide information? If so, take the time to prepare a list that highlights your important points or gives a summary of recent data. Perhaps a one-page outline of your progress to date would be beneficial. Or maybe a list of future planned tasks would be appropriate. Whatever the setting, a brief, to-the-point, one-page document is always helpful at an informal meeting that isn't a social gathering. The following list gives a few examples of informal meetings of various types along with suggestions for a document that might be passed out to all those present at the meeting.

- Project status review: Prepare a one-page bullet list of accomplishments that you've achieved since the last meeting.
- Report on recent tests: Prepare a one- or two-page table showing test results.
- Discussion on market potential of customers: compile a list of the 10 most important customers from the past five years.
- Product design review: Write a one-page summary of the key features of your design concept for the product under development.
- Changes in company procedure: Draw an outline of your proposed organizational chart.

7.3 PREPARING FOR A FORMAL PRESENTATION

Engineers are called upon frequently to make formal presentations to design teams, management personnel, customers, and other large groups of people. Sometimes, engineers must present formal papers at technical conferences. In contrast to an informal presentation, a formal presentation requires careful preparation. You should organize your talk much like a written document. It should contain an introduction, body, summary, and recommendations or conclusion. The following points will help you to prepare an interesting talk that meets its objectives.

1. Know your audience and plan upon an appropriate level of detail.
2. Assume that the customer is hearing about your topic for the first time.
3. Check out audio-visual equipment before the audience arrives. If you are using a laptop computer to present a slide show, determine *ahead of time* that it interfaces properly with the room's computer projection equipment.
4. Dress in suitable attire.
5. Cite the purpose of the talk within the first few minutes.
6. Tell your audience why it's you who is speaking.
7. Show an outline of your talk at the beginning. Give an initial overview of what the presentation will address. A single anecdote can help put the audience at ease and establish rapport.
8. Keep your talk simple. It's easy to get lost in technical details without addressing the main points of your presentation. Leave discussion of details for audience

questions. In that way, you'll be able to spotlight only those technical issues of true interest to the audience.

9. Keep your talk short. If you plan to use between 50 percent and 60 percent of the allotted time, you probably will end on time.
10. Ask your own questions, and then answer them. Prepare visual aids to use as your own cues. Use bullets (•) as thought initiators and breakpoints. Use your visual aids, calling attention to them as your talk progresses. Try to format all slides the same way. Maintain eye contact. Never read! If you've brought along notes, refer to them as infrequently as possible.
11. Do not show the audience equations. The audience has little time to decipher them. This rule can be broken occasionally.
12. End your talk with "thank you, any questions?" or a concluding slide. In this way, the audience will know when your talk is over.
13. Restate postpresentation questions so that the entire audience can hear them. Restating a question also will help to clarify its content and will give you an extra moment to formulate your response.

The following example illustrates the elements of a good oral presentation. The context is an engineer who is presenting the results of recent mechanical loading tests to a group of professors and students.

EXAMPLE 7.1

Mechanical Loading and Testing

Dan began with a short introduction that explained the purpose of his talk. "Thank you all for coming to my presentation. In this talk I will summarize test results on samples of materials that are candidates for the chassis frame of our new vehicle. As you all know, we've decided to go with composites—matrices of glass, carbon fiber, and epoxy resin— for the principal structural members of the vehicle. This choice will result in some extra costs, because these materials are more expensive than aluminum, plastic, or steel, but ultimately we'll have a better performing and more competitive vehicle. I've done some initial tests on sample compositions and wish to share them with you." Dan displayed the first of his overhead transparencies:

Loading Tests on L-type Carbon Composites
Daniel Little
Electric Car Project
Team Xebec

His next slide summarized the content of his presentation, providing an overview to the audience:

Summary of Presentation

- Description of Composite Materials
- Selection of Test Samples
- Stress-Strain Properties (Nondestructive Test)
- Maximum Load to Failure (Destructive Test)
- Fatigue Tests (Destructive Test)

"Let me begin by providing a brief review of composites. These materials were adopted by the aircraft industry as possible lightweight alternatives to more expensive metals, such as titanium and magnesium. Now they're used in everything from bicycles to sailboat masts. Composites are made from a matrix of carbon or glass threads woven into the desired shape and impregnated with high tensile-strength epoxy resin." Dan passed out several samples of composite materials. They were black in color and felt like plastic. He put up a slide that included Table 7-1 plus two questions that he planned to answer during his talk:

Structural Frame for the Peak-Performance Design Competition

- Should we use composites?
- What composition of fiber and epoxy is best?

Table 7-1 Description of Various Composite Materials

Product	Percent Carbon	Approximate Cost Per Pound
L-8	8	$96
L-10	10	$102
L-12	12	$113
L-16	16	$120
L-20	20	$136
L-24	24	$141

"Composition, to remind you, is a measure of the percent weight of carbon fiber to epoxy. The diameter of the fibers is also a factor. Basically, the more fiber there is in the mixture, the more expensive the material will be. The trick is to find the optimal composition while considering strength *and* cost. I have here some data on carbon composition, because carbon fiber is the type we're most likely to choose." Dan displayed an overhead that described the various composites he had tested.

"Above about a 24-percent fill rate, this particular composite has too little epoxy resin to hold together well," explained Dan, "and below 8 percent, too little carbon fiber to retain tensile strength."

Dan next described the first of the tests performed on the samples. "The first test consisted of determining the stress–strain relationship for each of the materials in the sample list for a number of different fiber diameters. As a review, let me remind you that *stress* is a fancy word for applied force, and *strain* is another term for the amount by which the material stretches (or compresses) in response to the applied force. In a *linear* material, the strain, or stretch, is directly proportional to the applied stress. Double the stress, and you've doubled the strain. If too much strain occurs due to too much applied stress, the material will go into its nonlinear region in which added stress produces a large irreversible increase in strain.

"Now let me explain the tests I've performed. The first involves measuring the stress–strain, or force–displacement, properties of the material using the following setup." Dan put up the overhead shown in Figure 7.2.

"The sample to be tested is first machined into a round bar of 4-mm diameter. It's then installed in a tensile test machine that can apply a stretching force to the bar. The applied force is measured by a load cell that produces a voltage in proportion to the applied force. A strain gauge is used to measure the strain. It's actually a thin-film resistor that's glued right onto the side of the test sample. Its resistance changes in proportion to how much the sample has been stretched from its rest length. Here's a typical plot of data taken on one sample, in this case L-8." Daniel put up the slide shown in Figure 7.3.

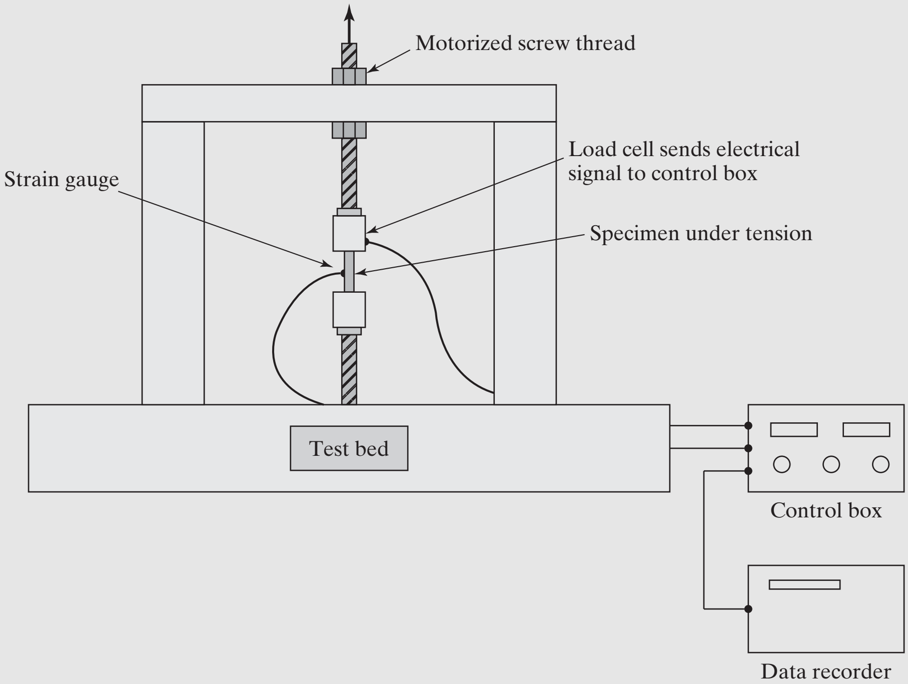

Figure 7.2
Instron™ test bed and computerized data recorder. The tensile test specimen is inside.

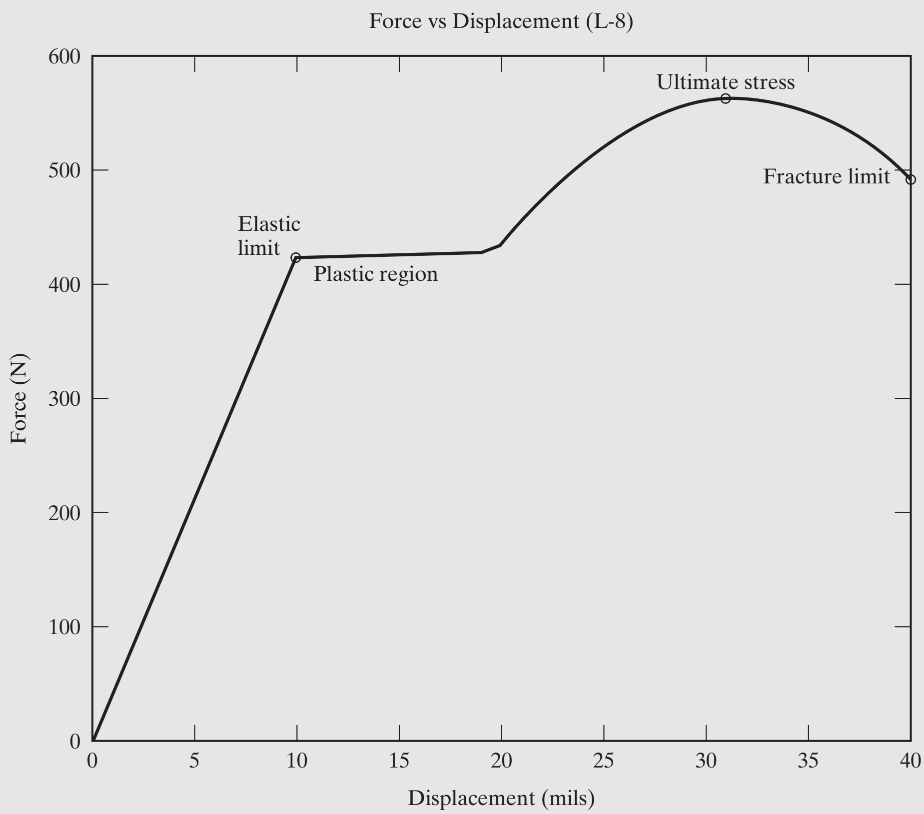

Figure 7.3
Force–displacement curve for Dan's bar sample showing linear region and elastic limit.

"The slope of the linear portion of this curve will be equal to the reciprocal of the material's elastic constant. The breakpoint in the curve defines the elastic limit. For our application, we'd like an elastic constant for the overall bar we tested of about 6 kN/mm and an elastic limit of at least 400 N to ensure an adequate safety margin of about five times the largest force we realistically expect on the components.

"Let me show you the results of measurements obtained from one of my test matrices."[2] Dan put Table 7-2 up on the screen. He'd copied it from a page in his engineer's logbook, which served as a written record of the data.

Table 7-2 Measured Elastic Constant (kN/mm) Under Tensile Force for 4-mm Diameter Carbon Composite Test Samples

	Carbon Fiber Diameter (mils)				
Sample	**3**	**4**	**5**	**6**	**Percent Carbon**
L-8	8.4	7.1	6.5	6.0	8
L-10	9.0	7.6	6.6	6.2	10
L-12	9.5	8.2	6.9	6.5	12
L-16	9.7	8.8	7.2	6.8	16
L-20	9.9	9.2	7.5	7.1	20
L-24	10.1	9.7	7.8	7.4	24

"The entries in this first test matrix table indicate the measured elastic constant of each sample in kilonewtons per millimeter of displacement. This next table gives the elastic limit of each sample in kilonewtons." Dan then presented a slide showing Table 7-3.

Table 7-3 Measured Elastic Limit (kN) Under Tensile Force for 4-mm Diameter Carbon Composite Test Samples

	Carbon Fiber Diameter (mils)				
Sample	**3**	**4**	**5**	**6**	**Percent Carbon**
L-8	0.28	0.33	0.41	0.52	8
L-10	0.29	0.34	0.42	0.53	10
L-12	0.30	0.36	0.43	0.56	12
L-16	0.32	0.38	0.46	0.58	16
L-20	0.30	0.36	0.44	0.56	20
L-24	0.29	0.34	0.42	0.53	24

"In the following figure, I've plotted the most important parameter, the elastic constant, versus percent carbon using fiber diameter as the third parametric variable." Daniel put up the plot shown in Figure 7.4.

"In my next overhead, I've plotted the elastic limit versus percent carbon, again using fiber diameter as the parametric variable." Dan put up the second plot of Figure 7.5.

"Because we need an elastic limit of at least 0.4 kN, we're limited to fiber diameters of 5 mils or more. Similarly, the largest elastic constants occur for 6-mil fiber, but

[2]A *test matrix* consists of a table of methodically performed tests in which one variable changes on the vertical axis and one along the horizontal axis.

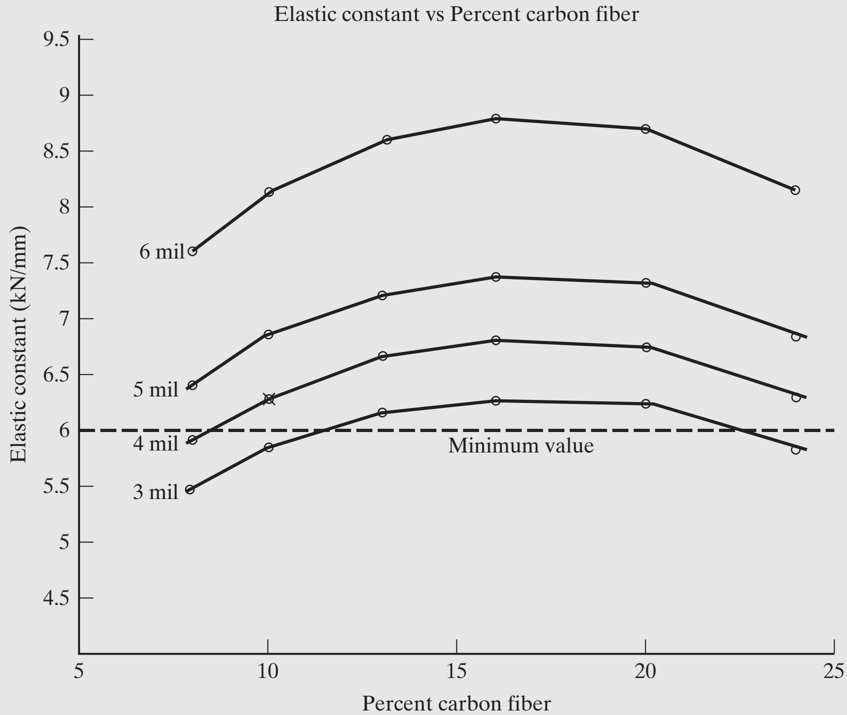

Figure 7.4
Force–displacement ratio versus percent carbon for Dan's bar sample.

the 5-mil fiber has adequate properties. Based on my tests, I'm recommending that we go with 16 percent carbon composite with 5-mil fiber for the prototype version of our vehicle. Thank you for your attention. Are there any questions?"

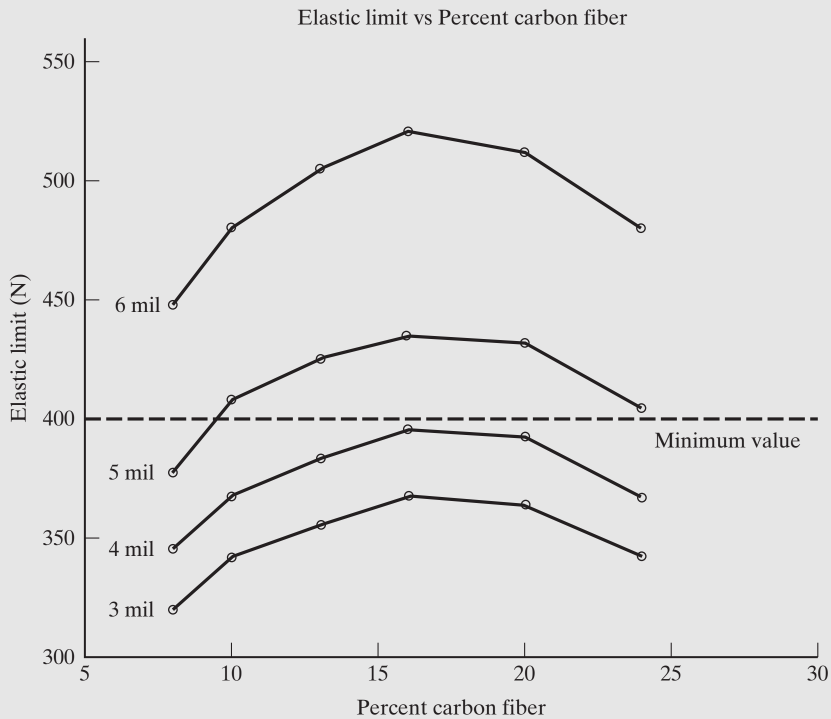

Figure 7.5
Elastic limit of Dan's bar sample versus percent carbon.

7.4 WRITING ELECTRONIC MAIL, LETTERS, AND MEMORANDA

As an engineer, you'll often need to compose short memoranda, faxes, e-mail messages, and notes to fellow engineers, supervisors, employees, or customers. Whether sent on paper or electronically, a memo must convey its message clearly and concisely. It must leave no room for ambiguity or misinterpretation, and it must be written in proper grammatical style. When you engage in a face-to-face conversation, you can modify your communication approach on the spot, depending on the person's reaction. But you will not have the benefit of witnessing the reaction of a person who has received a memo. A written memo must be carefully crafted to elicit the desired reaction on the first reading.

7.4.1 Writing Electronic Mail Messages

Electronic mail, or e-mail, has become the communication tool of choice for countless individuals worldwide. Engineers certainly are included in this group of e-mail participants. E-mail has become an indispensable part of an engineer's work environment as well as an integral part of the design process. E-mail has many uses, but its most common use is as a replacement for hard-copy memoranda. Before electronic mail, communication between employees was conveyed by distributing paper to each recipient. The method was slow and labor intensive.

Electronic mail has made distribution an instantaneous and incidental event. The act of composing an e-mail message, rightfully so, now takes up the largest fraction a sender's time. In the age of electronic mail, the sender has more time to *think* about what is being written, because almost no time is needed to copy and distribute the document. One of the most common mistakes in e-mail writing, however, is to assume that messages sent electronically do not have to be prepared with the same care as do other written documents. An e-mail message that is sloppy and poorly written will not be taken as seriously as one that is carefully written in a professional manner. The wise writer sets a proper tone by preparing e-mail messages with the same care as paper memos. The recipient of an e-mail message will read it in private, just like a written memo, and may treat it with the same formality as a memo received on paper. In addition, an e-mail memo can be forwarded to large numbers of additional recipients instantly, spawning multiple exposures. Some people print out received e-mail messages, thereby further blurring the distinction between paper and electronic memos.

The formula for writing a competent and effective electronic mail message is easy to learn. A good message should include the following three items:

- A *header* that indicates the recipient, sender, subject, and date
- A *first sentence* that states the purpose of the message
- A *body* that delivers the key points of the message

7.4.2 Header

In our information-abundant world, document organization has become a critical component in business, commerce, and all engineering disciplines. A header that announces the *recipient, sender, subject,* and *date* of the e-mail helps both the sender and receiver to categorize the message and properly file it for future reference. Identifying the subject of the message in the header will also set its tone and prepare the reader for the message to follow. Has the memo been sent to a general distribution list? Is it intended for one person's eyes only? Will the message to follow be formal, informal, alarming, or humorous? A properly designed header will set the tone for the message and prepare the reader to receive it. The header of a memo should look something like this:

To: Karin Peterson
From: Frederick Unlu
Subject: Test Data for Motor Evaluation
Date: April 12, 2009

An alternative form suitable for a message sent to a group of people might look like this:

To: Distribution
From: Tina Oulette, Team Leader
RE: Next Team Meeting
April 12, 2009

Note that many electronic mail systems include automatic prompts for header entries, and most all include a date stamp on the message regardless of whether the sender inserts one on his or her own. Nevertheless, it's a good idea to specifically include a header similar to one of the foregoing examples, because the Internet system often adds network routing information between the automated header and the body of the text.

7.4.3 First Sentence

A good message will clearly state its purpose in the first, or possibly the second, sentence. A sentence that begins with, "I am writing this message to inform you . . . " will help the reader unambiguously understand why you have written the message. Stating the purpose of the message right at the beginning will help formulate its tone and state its objectives. Will your message provide information, request a response, ask for permission, or give instructions? The structure of the first sentence will determine the way in which the body is received. It will also ensure that the reader does not misinterpret your reason for writing.

EXAMPLE 7.2

The Trip Request

As an example of the power of the first sentence, consider the following memo that was sent by an employee of an engineering company. The engineer was writing to his boss to ask for permission to attend a conference of the American Society of Mechanical Engineers.

To: Roscoe Varquin
From: Harry Coates
Subject: Upcoming ASME Conference

Date: January 14, 2009

Roscoe,

As you may know, the American Society of Mechanical Engineers is holding a conference on lightweight composites in Dayton, Ohio, at the end of June. I think that someone from our company should attend this meeting. Over the past several years, composites have shown promise as a viable alternative to steel or aluminum. They combine the strength of the former with the light weight of the latter. It's time that we learned more about these important materials.

The conference will be held at the Dayton Buena Vista. I've spoken with our travel agent and found that flights will cost about $400 for a round trip. Hotel will be $82 per day, and the conference registration fee is $180. Please let me know what you think.

Critique. Harry began his message by explaining the upcoming conference and proceeded to present his data about how much it would cost him to make the trip. Despite what seemed like a clear explanation, Harry never got to go to the conference. Although Roscoe was convinced of its value to the company, Harry had presented his data but never stated explicitly in his first sentence that it was *he* (Harry) who wanted to attend the conference. The message brought the matter to Roscoe's attention, and it was Roscoe himself who wound up going to the conference! The confusion resulted because Harry failed to clearly state the purpose of his memo. His e-mail message would have been *much* more effective had it begun with the simple sentence, "I would like permission to attend the upcoming ASME conference in June." Harry learned, much after the fact, that it's important to state the purpose of a memo in its first sentence. Had he talked to Roscoe in person, he might have detected the confusion by witnessing his boss's reaction on the spot, but his chosen method of communication omitted the link of personal contact.

7.4.4 Body

When composing the body of an e-mail message, follow basic rules of style and grammar. Each idea or concept should have its own paragraph, and paragraphs should never consist of a single sentence only. Each paragraph should follow logically from its predecessor so that the flow of ideas makes sense to the reader. When you compose a message, think about the sequence of ideas so that your message has structure and flows logically. Use the full-screen edit feature of your software, rather than the one-line-at-a-time mode available on some e-mail systems. In this way, you will be able to go back and revise or restructure the body of the message before sending it.

EXAMPLE 7.3

Visit to the Customer's Workplace

One quality of a good e-mail message is its ability to convey correctly all the subtleties of a given subject. Without personal contact to enhance communication, an e-mail message must be precise and readily comprehended on the first reading. Consider the following not-so-well written message that describes the visit of a software engineer to the client's workplace. Try to identify the deficiencies in the memo. Its subject concerns a program called the Universal Information System. The task involved rewriting an original UNIX version of the program to run under Microsoft Windows 98. The software program is used by the client to keep track of customer charge card records. The software engineer in charge was writing a memo to her boss summarizing the results of a recent exploratory visit to the client.

To: Roscoe Varquin
From: L. Berkin
Subject: Universal Information System

February 26, 2009

On the 25th of February, my group met with the customer. We were allowed to use a user's ID in order to bring up his account record on the UIS. The customer crossed out the user's name on the sheet containing his information, but it turned out that the UIS listed his account with both his name and social security number. My group made a record of how the system was set up in order for us to have the same heading in our program.

I learned some of the commands that are used on the UIS Galaxy system. The command TR14 finds the user's in-question account and displays it on the monitor. The TR33 command displays all transactions which the user made since the specified date. Last, but not least, the TR35 command displays all payments made since the given date. It turned out that this command was a recent one designed and implemented by one of our fellow employees who recently left the company. In our program, we will assume that this command will be used by the customer, even though there is doubt that no one would keep it up to date except for the fellow employee whose stay there is not guaranteed.

Meeting with the customer at her office made it clearer what they expect of the product. They want the product easy to use. They want the account summary sheet to highlight all the transactions not yet paid for. In all, I learned several commands and got some exposure to the UIS system. This was a profitable meeting.

Critique Despite its poor grammar and flow of ideas, the body of the message does contain the following key points:

- An opportunity to see a demonstration of the UIS system took place.
- The customer erroneously allowed us to see the identity of a sample account holder.
- A program within the UIS system is called "Galaxy."
- The UIS system includes several commands:
  - TR14: Customer account,
  - TR33: Transactions display, and
  - TR35: Payment history.
- The TR35 command was designed by a previous employee of the company.
- The meeting was useful.
- The customer wants unpaid transactions highlighted.

Regardless of its content, however, the body is deficient, because the order in which the information is presented is entirely random. The message lacks logical progression, contains no preamble, and includes no added comments to aid in interpretation. Each fact is presented with no accompanying explanation of how it fits into the overall context of the memo. Additionally, the information contained in the first paragraph is irrelevant to the writer's boss who would not care that the customer made a mistake while attempting to access the system. The writer seems to have had a list of facts in her head and proceeded to regurgitate them on paper in whatever order they came to mind. The message also omits critical information. The author of the memo does not mention the identity of the customer or who the person was that gave the tour and demonstration. There is no mention of what the letters "UIS" stand for, and the term "Galaxy" is used without explanation. It's highly likely that this memo underwent very little onscreen editing or rewriting and probably was poorly received.

Now consider the following version of the message, which was written and revised using proper grammar, construction, and form prior to being sent.

To: Roscoe Varquin
From: L. Berkin
Subject: Summary of customer meeting at Boulton Industries
February 26, 2009

Roscoe,

This memo summarizes what we learned during our visit to Boulton Industries on February 25, 2009. Our project team met with Boulton's representative, Ms. Connie Donaldson, at their Weston office. The meeting provided us with an overview of the customer's existing Universal Information System (UIS) and introduced us to the procedures commonly used in Ms. Donaldson's office. We worked with her on the UIS system using actual account records.

The UIS system contains an application program called Galaxy that allows the customer to view account records. The record of an account holder is accessed by entering an ID number into the Galaxy system at the menu prompt. The account data can then be viewed in a variety of formats useful to the customer.

Several user programs, called Transaction (TR) screens, reside within Galaxy and help the user to display account information. These TR screens are used routinely by Boulton employees for processing monthly bills and servicing customer call-in inquiries. During our meeting, we recorded the display headings of each important TR screen so that we can create the same headings on our PC-based Windows98 version of the UIS system.

As part of our tour, Ms. Donaldson demonstrated some of the commonly used TR screens. One command, for example, is called TR14. It retrieves a specified account record and displays it as a standard mailing form on the monitor. A second command, called TR33, displays all transactions that have occurred since a date specified by the user. A third command, called TR35, displays the history of all payments made since the user-specified date. This last command was written previously for Boulton by one of our employees. When writing our new version of the program, we should assume that this command again will be used by Boulton to process records, and we should plan to integrate the feature into the Windows version of the program.

I feel that we learned enough from our meeting to enable us to proceed with the Boulton UIS project. If necessary, we can return to Ms. Donaldson's office at a later date to obtain more information.

Sincerely yours,
Laura Berkin

Software Division

7.4.5 Writing Formal Memos and Letters

The informality of an e-mail message in not appropriate for all communication. At times, the added formality of a written, hard-copy letter is preferable. Formality suggests importance. Applying for a job or sending a follow-up thank-you letter, for example, are situations that call for a formal written letter. Likewise, if your information has archival quality, or if your message may have legal implications, then you should send your memo in paper format. Besides carrying more social weight than an e-mail message, a paper letter can bear a binding signature.

The rules for composing and sending a written letter are almost identical to those for sending electronic mail. One key difference is that a formal letter normally does not contain a To and From header, but instead it begins with the recipient's address and a formal salutation. A letter should be well presented on good paper or letterhead and be printed in an attractive format. The following example illustrates some of the finer points of writing an effective formal letter. The first version shows the letter as originally written, and the second shows the results of a much needed revision.

EXAMPLE 7.4

Summary of Test Results

The following letter was written by an engineer who wished to summarize the results of mechanical loading tests for a client. The letter is based on the following points, listed here in the order in which the author wrote them down in his logbook:

- Initial loading tests are completed.
- Test samples were composites of carbon and epoxy.
- Control samples were steel.
- Same shape was chosen for each; steel was machined, composites were molded.
- Samples were composites and steel.
- Initial difficulties with fitting samples into test machine.
- Made a holding jig to allow testing.
- We should go with composites at slightly increased diameter.
- Numerical data from test results:

Diameter	Composite	Steel
0.25 in	245 lbf	321 lbf
0.375 in	1644 lbf	1790 lbf
0.50 in	3021 lbf	3229 lbf

The letter as written by the engineer reads as follows:

Apex Systems
Structural Testing Laboratory
730 Commonwealth Ave.,
West Roxbury, MA 02132

Helen Brickland
Access Engineering
44 Cummington St.
Boston, MA 02215

January 18, 2009

Dear Ms. Brickland:

We've completed the initial loading tests on the samples made from composites and steel. The samples had the same shape, and the steel was machined and the composites molded. We had some initial difficulties fitting the samples into the test machine but finally made a holding jig to allow testing. I think that we should go with composites at slightly increased diameter.

Here are the pieces of data:

- 25 in. diameter: composite 245 lbf, steel 321 lbf
- 375 in. diameter: composite 1644 lbf, steel 1790 lbf
- 50 in. diameter: composite 3021 lbf, steel 3229 lbf

Sincerely yours,

Ed Garber
Mechanical Engineer

Critique. This letter is correctly formed and includes all needed information, but the writer would have done a better job of stating his objectives if the first sentence had cited the real purpose of the letter, which was to make a recommendation to Ms. Brickland that composites be used instead of steel. A better opening might have been the following:

Dear Ms. Brickland:

For the past month, Apex Systems has been performing loadings tests on samples of composites and steel for Access Engineering. Based on our test results, I'd like to recommend that we choose composites for this project.

The original letter has other problems beyond those of its first sentence. Its body, for example, is completely disorganized. Although the author has followed almost verbatim the ordering of ideas as recorded in his logbook, those ideas were not particularly well ordered to begin with. The letter reads disjointedly, as if it's been poorly edited. The sentences are choppy and do not flow from one to another. The numerical data should have been presented in more concise tabular form. Finally, the author failed to describe the purpose of the tests, didn't go into detail about how they were performed, and didn't describe the test samples other than to say that they were a mix of composites and steel. He should have provided the dimensions of the samples, the composition mix of the composites, and how many of each type of sample were tested.

A revised version of the letter that corrects for these deficiencies might look something like the following:

Apex Systems
Structural Testing Laboratory
730 Commonwealth Ave.,
West Roxbury, MA 02132

Helen Brickland
Access Engineering

44 Cummington St.
Boston, MA 02215
January 18, 2009

Dear Ms. Brickland:

The mechanical group working on the Delta vehicle project with Access Engineering has just completed tests on samples of the composite and steel materials that we are evaluating for the main structural members of the frame. Based on our test results, our group recommends that we choose composites of slightly enlarged diameter for the structural materials. The details of the tests are described below.

Samples of machined steel and molded composites were fabricated in the shape of standard tensile test specimen bars having a variety of diameters in the range 0.25 in. to 0.50 in. (ASME specification 246). These samples were stressed to the breaking point in our lab's Instron test machine. Although we had some initial difficulties in fitting the samples of diameter other than 0.5 in. into the test machine, we were able to make a holding jig to accommodate testing of all samples. The numerical data from our tests results are summarized in the following table:

Breaking Force Under Tension			
Diameter (in):	0.250	0.375	0.500
Composite (lbf):	245	1644	3021
Steel (lbf):	321	1790	3229

Given the much lighter weight of the composite material, however, its strength-to-weight ratio is much higher than that of steel. I recommend that your company go with composites for this project.

Sincerely yours,

Ed Garber
Mechanical Engineer

This second version is much improved over the original. The author has articulated the purpose of the letter in the second sentence, rather than in the first, but it works well here because the letter still reads and flows nicely. The first sentence serves as a preamble to the real purpose of the letter which is revealed in the sentence that begins, "Based on our test results ... "

The data are also well presented in the table contained within the letter. Instead of putting the units next to each entry, Ed has written them just once next to the category titles on the left-hand side. This format makes for a much neater display of data. Ed also has elaborated on the details of the tests. When Ms. Brickland reads the letter, the context in which the tests were taken will immediately be clear. This point is an important one. Ed might falsely conclude that Ms. Brickland will understand its context, because his primary work assignment over the past month has been the taking of data and the testing of the materials. But Helen, as a manager, is likely to be juggling dozens of projects and details, and she will welcome a letter that first refreshes her memory about its context and background. In addition, she may find herself reading the letter at some future time when the background details of the test procedures have faded from memory. Or she might forward the letter to someone else who is unfamiliar with the details that Ed has correctly provided.

Professional Success: Preparing a Presentation for a Nontechnical Audience

At times an engineer must make a presentation to a nontechnical audience. You also may encounter this challenge while you are a student. Perhaps you'll be invited to speak at your old high school. Maybe you'll be asked to explain the activities of a research laboratory to visiting parents and prospective students. Or maybe you'll receive a class assignment to prepare a talk on a technical subject for a general audience. In these and similar situations, the following few basic principles can guide you:

- Assume the audience knows nothing about your topic.
- Explain background material without using jargon words. (You'd be surprised at how many seemingly common words are really part of the engineer's private lexicon.)
- Start at the beginning to provide the big picture.
- Pretend that you're speaking to a group of fourth graders.
- Avoid showing equations to a nontechnical audience. (You'll probably pique their math anxiety.)

7.5 WRITING TECHNICAL REPORTS, PROPOSALS, AND JOURNAL ARTICLES

Technical reports, proposals, and journal articles are the engineer's equivalent of term papers. As an engineer, you are likely to face the task of writing one of these documents at some point in your career. Unlike short e-mail messages, memos, and letters, which are usually only a few paragraphs long, longer technical documents require considerable thought and preparation and usually cannot be finished in one sitting. The sections that follow highlight some of the key elements of these longer documents.

7.5.1 Technical Report

A technical report is used to convey important findings or test results to a controlled audience. Technical reports seldom undergo peer review, and distribution of the report is done at the discretion of the author or employer.

The typical technical report is between two and twenty pages long. In content and form, it's not unlike a lab report you might prepare in some of your college courses. Although the format may vary somewhat, most technical reports contain the following elements: Introduction (or Background), Experimental Setup (if applicable), Theory, Data, Analysis, and Conclusion.

The introduction serves as a preamble to the document and states its reason for having been written. Unlike the first sentence of a simple memo, the introduction of a technical report can occupy a paragraph, a page, or sometimes many pages. A person pressed for time will merely skim the introduction, so it, along with the conclusion, should provide a self-contained overview of the entire report.

If the document describes the results of an experiment, a section should be included that describes the physical setup. This section should provide enough detail such that a reasonably competent person could completely reconstruct the experimental apparatus and obtain similar results. It should describe instruments, apparatus, mechanical techniques, dimensions, and other key parameters.

The data section includes the results of any experiments or tests that were performed. It should explain why each set of data is presented, how it was obtained, and what bearing it has on the main purpose of the document. A report or journal paper is likely to be used later as a reference source, so it's important to present data completely and accurately. The presentation should be easily digested by someone not intimately familiar with the details of the project.

The analysis section is where the data are evaluated, interpreted, and used to support any claims made in the report. Mathematical calculations belong in this section, as do plots and charts derived from the data. In some cases, particularly in reports that deal with design work, the analysis and data sections appear in reverse order. First the analysis of the device is presented, followed by data on tests that show whether the device meets the predictions of the analysis.

Finally, the conclusion is used to summarize the claims, results, and observations included in the report. Some individuals may not have time to read the whole report, but need to be familiar with its content. The conclusion section should be written to serve the needs of a person who only has time to browse or skim the report. The conclusion should be a stand-alone section that summarizes all the key points of the report.

7.5.2 Journal Paper

Journal papers provide a way in which engineers disseminate information of interest to other engineers. They also provide a public forum in which engineers and scientists can announce "first to invent" status of a new technology or discovery. Most journal papers, particularly those sponsored by professional organizations, must undergo peer review before publication. This procedure helps insure their quality and accuracy. Although the standard format—introduction, theory, experiment, data, analysis, and conclusion—is appropriate for journal papers, many publications specify their own format in which a journal paper must be submitted.

7.5.3 Proposal

A proposal differs from a report or journal paper in that its primary objective is usually to secure *money*. A proposal attempts to convince a client or funding source that your organization can best handle a research or design job, or perhaps that your product will be best for a particular application. In addition to the various sections of a technical report, a proposal often includes additional sections on objective, budget, company background, and personnel.

7.6 PREPARING AN INSTRUCTION MANUAL

One of the most common documents written by engineers is the instruction manual. An instruction manual introduces the user to your product and provides information regarding its setup, operation, and use. A well-written instruction manual also includes sections on safety information, troubleshooting, repair, and theory of operation, if applicable. While not all engineered devices require an instruction manual (the operation of a snow shovel, for example, should be self-explanatory), those that involve detailed operating procedures should be accompanied by instructions. Indeed, user perception of many products is derived directly from the quality of the instruction manual.

The sections of a typical instruction manual are outlined below. If the manual is long, a table of contents with page numbers should be included. Obviously, the need for each of the sections suggested below will depend on the specific product described by the manual.

7.6.1 Introduction

The introduction should provide an overview of the product. It should explain the purpose of the product, its usefulness to the user, its special features, and proper use of the manual itself. Various titles for the introductory section include "Getting Started," "Welcome to Product X," "Before Using Your Device," and so forth.

7.6.2 Setup

The setup section should outline the procedures that the user must follow before the product is ready for use. This section should appear at the front of the manual, where it will be easy to find. It should guide the user through the setup procedure step by step, and it should use illustrations liberally.

7.6.3 Operation

The operation section of the instruction manual is its most important part. A first-time user will use this section to learn how to operate the product and will refer to it thereafter to clarify points of operation. Because of its likely use as a reference source, the operation section should be carefully laid out and organized so that the user can extract information without having to read the entire manual from the beginning.

7.6.4 Safety

Safety is a very important aspect of engineering design, and any such information relevant to the well-being of the user must be included in the instruction manual. If the product has dangerous moving parts or high voltages, includes safety panels or guards that must not be removed, or has the potential to emit flying objects or capture loose clothing, then appropriate warnings should be included. In our overly litigious society, where personal injury lawyers advertise freely on the radio and TV, safety warnings have become pervasive. Some safety warnings may seem overly cautious or even ridiculous (e.g., don't put your fingers in the moving blades or you might get hurt), but safety warnings have become a necessary part of engineering.

7.6.5 Troubleshooting

Expect your product to break down, regardless of how well it is made. If it should happen not to malfunction over its lifetime, consider yourself lucky. Products do fail, and the troubleshooting section should guide the user through a simple set of tests that can help identify the source of any malfunction and get the system running again. The section should outline simple repairs that the user can try before taking the more drastic step of returning the product. If appropriate, include a section that explains how to get in touch with the manufacturer (you) in case difficulties cannot be resolved by the user.

Never assume that the user will understand something that is not clearly specified. The following troubleshooting entries may seem silly, but many instruction manuals contain similar versions:

Symptom: No lights or displays of any kind are lit; unit appears to be dead.
Possible Cause: Unit is unplugged or has a blown fuse.
Remedy: Plug cord into proper outlet. Replace fuse.

Symptom: No sound is coming from the speaker.
Possible Cause: Volume control is turned all the way down.
Remedy: Turn volume knob clockwise.

Symptom: Drive shaft does not turn.
Possible Cause: Clutch is not engaged.
Remedy: Engage clutch by moving lever to the "on" position.

Symptom: No flame emits from burner.
Possible Cause: Pilot light is extinguished.
Remedy: Relight pilot. (See Section 2.1: Lighting the Pilot Light.)

Symptom: Pilot light cannot be lit.
Possible Cause: No gas supply.
Remedy: Open main gas valve; replace propane tank.

7.6.6 Appendices

Information likely to be of interest only to a special readership should be included in appendices. Examples include circuit schematics, exploded assembly diagrams, theory of operation, and lists of part numbers.

7.6.7 Repetition

One of the subtle features of a good instruction manual is its ability to engage the reader regardless of where he or she begins reading it. This attribute can be achieved by repeating informative details at several junction points throughout the document.

As you write the manual, imagine the viewpoint of a reader who has begun to read it somewhere in the middle of the document. Restate key information at topical transitions and major section headings, rather than referring to previous sections. Do not assume that the reader remembers details covered previously if they are relevant to the present section.

EXAMPLE 7.5

The ATM Simulator

The following example contains (slightly edited) excerpts from an instruction manual written by senior project students in the Department of Electrical and Computer Engineering at Boston University.[3] It includes many of the elements mentioned above and illustrates the overall features of a good instruction manual. The manual explains the operation of a simulator for a bank automatic teller machine designed to teach banking procedures to elementary school and special needs students.

Automated Teller Machine Simulator
Instruction Manual
Terrier Technologies of Boston

WELCOME TO THE TTB ATM SIMULATOR

The Terrier Technologies of Boston Automated Teller Machine simulator has been designed to help you teach students the important aspects of banking skills. The unit has been designed for simplicity and ease of use. It should provide you with many years of trouble-free operation.

HOW TO USE THIS MANUAL

The TTB ATM users' manual is divided into several sections and an appendix. The first two sections provide a general overview of setup and system start-up, respectively. The third section explores the inside of the ATM simulator and discusses its various modules. The remaining two sections deal with care and troubleshooting of the equipment. The appendix contains wiring diagrams and computer software codes.

OVERVIEW OF OPERATION

The TTB ATM simulator is a self-contained product. Each of its modules simulates the operation of a real bank ATM machine. Account information is stored in the computer connected to the ATM panel. A banking session begins by prompting the user to insert a card into the card slot. Once the card has been properly inserted, the user is asked for a password to be entered via the keypad. After entering the correct password, the user is asked to choose from the following list of transactions:

1. Deposit
2. Withdrawal
3. Fast Cash
4. Account Balances

Once the type of transaction has been chosen, the simulator asks the user to choose between a savings account and a checking account. The user can withdraw

[3]"G. DeBernardi, R. DeMayo, M. Givens, M. Magne, E. McMorrow, and S. Tansi, *Automated Teller Machine Simulator Instruction Manual.* Terriers Technologies of Boston, 1992.

facsimile money from the cash dispenser or place an envelope in the deposit slot. Immediately following the transaction, a receipt of the session is printed out and the user's account is updated inside the computer.

The system operator has additional choices not shown on the main user menu. These additional choices include: Modify Parameters, Troubleshooting, and Print Account Information. The Modify Parameters command enables the system operator to update user accounts. The Troubleshooting command tests the individual modules of the ATM simulator. Print Account Information makes a printout of all user names and account balances. The ATM simulator is also equipped with two flip-up panels. The top panel exposes the main keyboard used by the system operator to initiate and update accounts. The bottom panel provides access for paper replacement for the receipt printer and provides access to the cash dispenser.

INITIAL START-UP (SYSTEM OPERATOR)

The power switch is located on the rear of the unit. Plug in the power cord and move the power switch to the ON position. You should hear a whirring sound as the internal disk drive is activated. To begin the session for entering or updating user accounts, first access the keyboard by raising its hinged cover. The screen display will give instructions on how to proceed.

SETTING UP OR CHANGING AN ACCOUNT

To set up a new account or change a previous account, access Modify Parameters from the Main Menu. Once this selection has been made, the following set of selections will appear on the screen:

1. ID Number
2. Password Savings
3. Checking
4. Account Balances

Choose your selection by pressing the appropriate number on the numeric keypad. Using the arrow keys, move the cursor to the entry for the user account to be edited. The following set of commands can be used to enter and edit field data:

Enter: Access the field that needs to be added or edited.
Ins: Add information to a user field.
Del: Delete information from a user field.
Esc: Return to the Main Menu.

All fields must be filled if the system is to access each user account properly. Once all account information has been entered, a full printout can be made by choosing Print Account Information from the Main Menu.

BEGINNING A BANKING SESSION

When all user accounts have been entered, the unit is ready for simulated banking sessions. From the Main Menu, select Begin Session to begin a simulation. The screens will guide the user through the entire process in a manner very similar to a real automated teller machine.

INSIDE THE ATM SIMULATOR

An 8088 computer is used to control all aspects of operation for the simulator. The system operator controls the account balances and all other program functions via the keyboard. The display consists of a 13-inch monochrome monitor. The screen guides the user through the entire process and provides help whenever necessary. Display screens are similar to those found on real ATM bank machines. Additional screens take the system operator through the account information sequences.

KEYPAD

The TTB ATM keypad is identical to that found on real Diebold ATM machines. It consists of fifteen keys (11 blue and 4 white). The 0 through 9 blue digits and decimal-point keys are used for selecting dollar amounts, and the four white keys, labeled A, B, C, and D, are used for making transaction decisions. Pressing the CANCEL key will terminate the session at any given time.

CARD SLOT

After the system operator has set up user accounts, the simulator will wait for the insertion of a bank card. The card must be placed into the machine in the proper direction shown on the diagram on the ATM front panel. The card will be pulled into the slot by the TTB ATM and will remain in place unless the card is inserted in the wrong direction, the transaction is terminated by the user, or the system is shut down or loses power.

MONEY DISPENSER

The user may ask the ATM for a withdrawal in increments of ten dollars. If the user asks for cash in other increments, the simulator will inform the user that the transaction is not allowed and will suggest trying again. Once an amount has been specified for withdrawal, the cash dispenser will drop facsimile ten-dollar bills into the money bin. The system operator can reload the machine with money when needed.

RELOADING

When bills need to be reloaded, the operator should access the cash dispenser from the back of the TTB ATM by pushing down on the springs and placing a neatly packed stack of facsimile bills into the unit. Be sure that the bills can roll out freely by manually turning the dispensing wheels until the bills can move easily.

DEPOSIT SLOT

As in most ATM machines, money or checks can be deposited by placing a deposit envelope into the deposit slot. After the simulator has informed the user that it is ready to receive a deposit, it awaits the insertion of an envelope. The deposit slot module will pull the envelope inside the unit. Deposit envelopes may be collected later by the system operator from the deposit bin. An indicator light located on the back panel of the TTB ATM will inform the system operator if a deposit envelope has been received. Once the envelope has been securely received by the ATM, the user's account will be updated automatically.

PRINTER

After a transaction has been completed, the simulator will produce a copy of the transaction and balance information. The printer is mounted on the side of the unit for easy access. The paper is the same type used in adding machines. Its roll should be placed on the bar so that it can be fed into the printer. When the paper roll runs out, it can be easily replaced by sliding a new roll on to the bar. The printer is connected to the computer via a standard Centronics printer interface cable.

EQUIPMENT MAINTENANCE

The main unit may be cleaned with a damp (not wet), lint-free cloth. Aerosol sprays or other cleaning solvents are not recommended for cleaning. If the screen gets dirty, use a clean cloth or paper towel to wipe the screen.

The unit contains no user serviceable internal parts. Repairs should be performed only by a qualified TTB technician. Moving or tampering with any of the components of the TTB ATM may adversely affect the operation of the overall system.

SAFETY PRECAUTIONS

Even though the TTB ATM unit is designed to be as safe as possible, a few circumstances can lead to hazard conditions. For your own safety, and that of your equipment, always take the following precautions. Disconnect the power plug if

- the power cord or plug becomes damaged, or
- any piece of clothing gets caught in the bank card, printer, envelope, or money dispensing slots, or
- any liquid is spilled on the unit, or
- the ATM simulator is dropped.

TROUBLESHOOTING

Problem: No lights or displays of any kind are lit; unit appears to be dead.
Possible Cause: Unit unplugged or has a blown fuse.

Problem: Keys are stuck.
Possible Cause: Keys may begin to stick due to temperature or excessive use. Try to loosen stuck keys by gently pulling them up. WARNING: Do not pull too hard or the keys may break off.

Problem: No response from keypad.
Possible Cause: The TTB ATM may not be in transaction simulation mode.

Problem: Envelope is not being pulled into the deposit slot.
Possible Cause: The wheel of the drive motor may be stuck. Pull up on the traction wheel or remove the envelope and push it manually through the slot.

Problem: Bills are not being dispensed from the machine.
Possible Cause: The money dispenser may be empty.

SERVICE AND SUPPORT

Service for the ATM simulator is available through our local field service network. Please contact:
Terrier Technologies of Boston
ECE Department, Boston University
8 Saint Mary's St.
Boston, MA 02215
617-353-9052

7.7 PRODUCING GOOD TECHNICAL DOCUMENTS: A STRATEGY

With the possible exceptions of the short memo and e-mail message, writing good documents takes preparation, time, and effort. Whether your writing task consists of an instruction manual, technical report, journal paper, annual summary, or an entire book, it will stand a better chance of accomplishing its objectives if it is well written. As with any other skill, learning to write well requires practice, patience, and attention to detail. In this section, we review several time-tested techniques for improving your writing abilities. Although different writers develop individual styles, most follow the same basic rules outlined below.

7.7.1 Plan the Writing Task

Before sitting down to write, gather all pertinent information. Assemble the results of design calculations, tests, experiments, user specifications, and all other available material. If it's pertinent to the writing task, make sure your engineering logbook is by your side. Gather reference citations, figures, and graphics, if applicable. Have everything at your disposal before you begin the writing task.

7.7.2 Find a Place to Work

One of the most important lessons to learn about writing long documents is that you must devote an uninterrupted block of time to the job. It's simply not possible to write well if you are distracted by telephones, e-mail, television, or people coming to talk to you. Writing a complex document takes a long time, sometimes hours or days. When you face a writing task, persistent concentration over an extended period of time will help get you into a creative writing mode. Your mind must sort ideas, arrange their flow, and commit them to well-written and enticing prose. Choosing precise words is an art form similar to painting, sculpting, or composing music. Your writing will flow more smoothly if you find a secluded spot where you'll have absolutely no interruptions. The telephone, your e-mail terminal, or other people stopping by will almost certainly break your concentration during writing and interrupt the creative process. In an ideal world, writers would be able to post "Writing in Progress: Do Not Disturb" signs over office doorways or cubicle portholes. In the real world, such sequestered spots are not always available. Go wherever you can find privacy. A library, cafeteria (during off hours), lab bench, or even the corner donut shop provide mental seclusion, despite their public nature, because they provide uninterrupted time for writing.

7.7.3 Define the Reader

Decide who will be reading your document. Some readers will know more about your subject than you do. Others will know nothing at all. It's important to know the technical level of your reader so that you can set the *tone* of the document. Suppose, for example, that you are reporting on loading tests for a group of nonengineers. In such a case, you probably wouldn't include material on spring constants, test methods, or Young's modulus of elasticity. If the report were for engineering students or professors, you might want to include these items.

Regardless of the technical level of your readers, you should decide how much detail the reader will need about the topic. Also be aware of what the reader will do with the document. Will it be redistributed? Will someone else read it? Answering these questions will help you set the tone of the document.

7.7.4 Make Notes

Professional writers always seem to get their documents to read just right. You, too, can produce well-organized, easy-to-read documents by mastering one valuable method used by the professionals. Before you begin writing the actual document, make random, stream-of consciousness notes—one line reminders—of *anything* that might need to go into the document. At this stage, give no particular attention to order or emphasis. Include the obvious essentials, as well as the possibly needless trivia. Many writers find it more effective to perform this step with traditional paper and pencil rather than on a computer, because the act of keyboard typing is known to occupy a sizable fraction of brain activity, leaving less mental power for creative and organizational activities. Regardless of which method you choose for recording your ideas, the key at this stage is not to worry about the order in which you write things down on your list. Commit all your ideas to paper now. You'll scrutinize them at a later step in the writing process.

7.7.5 Create Topic Headings

Your next step should be to form the overall structure of the document. To accomplish this task, you should write down the topic headings that will need to go into the finished work. Again, you should write these items down in random order, paying no attention at this stage to how they will be structured. Each of these topic headings eventually will become a paragraph or sequence of paragraphs in the finished document. When you're done with your list, examine each topic heading to see if additional headings come to mind. Delete irrelevant headings and group remaining headings into the main topic areas of the document. When your list of topic headings is complete, arrange them in a suitable order. Decide which order of presentation is the most interesting, logical, and easiest to understand. It's at this point that the main structural framework of the document begins to take shape.

7.7.6 Take a Break

Before you begin to write the actual document, take a break. Clear your mind before beginning the writing process.

7.7.7 Write the First Draft

If you've done a good job of preparing your list of one-line notes, you'll be ready to begin the writing process. Find an interruption-free spot to work, and start to write. Don't worry about writing in perfect form at this stage. Expect to revise your document many times before it's completed. The important thing during the first draft stage is to get your words down on paper. Use a word processor or write by hand and type later, whichever method suits you. As previously mentioned, using a keyboard detracts from the creative energy of writing for some people, so don't feel that you must compose the first draft on a word processor. A word processor is an indispensable tool for writing, of course, but its main advantage comes in the revision process. On the other hand, if you *can* learn to compose the first draft directly on a word processor, you'll save a lot of time otherwise spent in transcribing handwritten pages.

At this point in the writing process, don't be too concerned about spelling or exact phrasing. These aspects of the document will be corrected and modified later, in the revision phase.

If the work is short, write the first draft in one work session. If the document is long, divide the work into medium-length work sessions. At the end of each work session, rapidly scan the draft and make only *obvious* changes. Do not do major revisions at this time. When the draft is finished, again take a break to clear your mind. If time permits, set aside the document for another day so that you can approach it with a fresh perspective.

7.7.8 Read the Draft

After your break, when you are no longer intently focused on the document, reread it as if you are seeing it for the first time. Check your writing style for clarity. Are there vague, confusing, or ambiguous passages? Are the sentences in the correct order? Is there a logical flow within each paragraph and between successive paragraphs? Check for correct tone. Is the writing style suitable for both the subject matter and the reader?

Try not to read the draft solely from your computer screen. A document always looks different when it's been printed out on paper, because the reader is able to absorb more text at once and get a better feeling for how the entire document is structured.

7.7.9 Revise the Draft

A document seldom is ready for distribution after the writing of its first draft. After you write the first draft, take the time to review your work. Revise words, reword sentences, rearrange paragraphs, and reorganize sections to further refine and clarify meaning. As you revise, mercilessly slash unnecessary words and sentences. Weigh each word and phrase, and keep only those words and phrases that carry important meaning. Technical writing should be direct and to the point. Keep each paragraph relevant. Replace complicated phrases with simple words, and limit superlatives. As you reread your document, give it at least one pass in which you ignore content and look at words, sentences, and paragraphs in their grammatical context only. Remove "fat," unnecessary words and details that have low information content. You should also recheck factual statements, formulas, numbers, and calculations for accuracy. Be careful to proofread material cited from other documents. Almost all word processors include a spelling checker. Get into the habit of using one before sending out a document of any kind.

7.7.10 Revise, Revise, and Revise Again

After you've made your first revision, revise, revise, and revise again. Most good writers devote three or more, and sometimes dozens, of rewrites to get a document to read just right. Each chapter of the book you are reading now was revised at least six times before being sent to the editor for publication. Even though some typographical errors may remain, the content and its presentation have undergone substantial changes from start to finish.

7.7.11 Review the Final Draft

When you feel that your document is finished, put it aside and come back to it, preferably on another day when you will not be prejudiced by the intensity of the writing process. As you read your document, evaluate it as an outside reader would. Keep an open mind and ask yourself the question, "How would *I* react to what I have written? Will it produce the intended reaction or response from the reader?" If the answer is "yes," your document is ready for the outside world.

7.7.12 Common Writing Errors

Errors in usage and grammar are common in work prepared by student writers. Learning to write well takes practice, discipline, and the careful advice of a good teacher. Despite this observation, it is possible to learn some elements of good writing. In particular, understanding and avoiding common writing errors will help you immensely as you try to develop good writing habits. The writing errors listed in the following sections are typical of those found in written assignments submitted by engineering students. Review them so that you can avoid making similar mistakes in your own work. Additional examples of correct and incorrect usages can be found in references such as Strunk and White (1979).[4]

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[4]W. Strunk and E.B. White, *The Elements of Style.* New York: MacMillan, 1979.

Parallelism. Sentences that include multiple items or ideas should follow parallel construction.

Correct: "Our module will provide data communication, consume minimal power, and satisfy the customer's needs." (All three phrases begin with a verb.)

Incorrect: "Our module will provide data communication, minimal power will be consumed by it, and it will satisfy the customer's needs." (The three clauses don't have the same construction.)

Commas. Use a comma to separate the second part of a sentence only when the second half could stand on its own as a complete sentence.

***Correct* (do use a comma):** "We will supply five commands to the robot, and we will power the robot with batteries." (The second half of the sentence, "We will power the robot with batteries," is a complete sentence.)

***Incorrect* (don't use a comma):** "We will supply five commands to the robot, and power it with batteries." (The second half of the sentence, "and power it with batteries," cannot stand on its own as a separate sentence. The comma after the word "robot" should be omitted.)

Past, Present, and Future Tense. Maintain consistent tense (past, present, or future) as your writing progresses, or at least within a given paragraph.

Correct: "The routes will be difficult to change once they have been programmed into memory. This drawback also will apply to future versions of the robot." (future, future)

Incorrect: "The routes will be difficult to change once they have been programmed into memory. This drawback also applies to future versions of the robot." (future, present)

Use of the Word "This." For clarity the word "this" is best used as an adjective, not a noun or pronoun. It should be accompanied by an object of reference.

Correct: "This problem will be solved by designing a new system."

Incorrect: "This will be solved by designing a new system." (i.e., this ... what?)

Use of the Words "Input" and "Output." "Input" and "output" are best used as nouns. Their use as verbs is often awkward and unprofessional.

Correct: "The input to the mixing circuit consisted of three microphone voltage signals. The output was fed to the amplifier in the form of a voltage summation."

Incorrect: "The microphone signals were inputted to the mixer. Their combined sum was outputted to the amplifier."

Punctuation Around Parentheses. When words are set aside by parentheses, place a period *before* the trailing parenthesis if the parenthetical thought is an independent sentence.

Correct: "Our design project was completed on time. (We had been given a week to complete it.)

Incorrect: "Our design project was completed on time. (We had been given a week to complete it).

Infinitives ("To" Verbs). Never split an infinitive. If you use the word "to" followed by a verb, do not put words in between.

Correct: "The purpose of this section is also to help you with your homework."

Incorrect: "The purpose of this section is to also help you with your homework."

KEY TERMS

E-mail	Memorandum	Presentation
Report	Instruction manual	

PROBLEMS

7.1 Write a report that outlines the design process for a hybrid gasoline electric vehicle design competition.

7.2 The following document outlines the approach to be taken in the design of a system for paging contest participants over a three-minute time interval as part of an engineering design competition. It is an example of very poor writing. Rewrite the proposal, taking into account the writing principles and suggestions outlined in this chapter.

The three-minute pager receiver will be based on a simple bandpass filter that is tuned to a distinct RF band for each receiver. Additionally, each receiver will tune into a general public announcement band which will broadcast voice messages or tones. The cost will be held very small by constructing our own receiver circuits.

Power consumption is minimized by sleep mode. In sleep mode, the receiver's PA band amplifier will be disconnected from its power source via a relay or power monitor switch. Detection of a wakeup signal on the wakeup band will close the circuit between the PA band's amplifier and the speaker.

In addition, preliminary cost research shows that a three-minute countdown circuit and LCD screen can be constructed for under nine dollars in quantities of 100. A speaker and blinking LED can also be provided at minimal cost.

The countdown itself would also be initiated by reception of the wakeup signal. The end of the internal countdown would power down the PA band amplifier, or a second detection on the wakeup band would toggle the power off.

The unit itself could be wearable and styled after a pager or smartcard. We have scheduled a meeting for Tuesday, January 21, at 11 am.

7.3 The following memo was written by an engineer responsible for designing a parts counting device. The writing style is very poor. Rewrite the memo using the guidelines discussed in this chapter.

During our first conversation with the customer, we came to an initial design for the project and have scheduled a meeting with the clients on Tuesday. For the design, first thing come across is a detector to physically count the parts falling through the sorting mechanism and we generally prefer to use a photosensor. For the counting mechanism, two methods are proposed and yet remain undecided. One of them is to program a PLA whose reprogramming process could be too complicated for the end user. However, it's advantage is that the design would be simple and cheap. Another approach is to use a microprocessor to do the counting. However, since our team don't have any experience on this subject before, we are still seeking advice and reference. Finally, when the designated no. of parts are counted, the counter will activate a visual and audio signal which prompts the user that parts are ready for packaging. Then the user can put a plastic bag underneath the container and push a button which opens up the bottom of the container.

The above would conclude our initial idea and we will come up with more details and specifications after the meeting.

7.4 Write a memo to your fictitious boss asking permission to attend a technical conference.

7.5 Write a short instruction manual that explains how to operate your VCR.

7.6 Write a memo to all students in your laboratory addressing the importance of safety procedures and protocol.

7.7 Write a memo that summarizes the following information relating to data communication protocol:
Data Protocol:

*DCE = Data Communication Equipment (female connector)

Computer, processor, host: receives data, decodes, establishes communications

*DTE = Data Terminal Equipment (male connector)

Terminal, printer, data board - Sends data and displays output

Parallel Data: 8 or 16 bits of data sent simultaneously with a DR (Data Ready) strobe from the DTE to the DCE and a CTS (Clear to Send) signal from the DCE

Serial Data: 1 start bit; 8 data bits; 2 stop bits, 14,400 baud (bits audio); no parity

Synchronous data - a clock line must be established between DCE and DTE

Asynchronous data - relies on nearly precise timing and start/stop bits

RS-232 standard (receive-send asynchronous data)

Positive and negative voltages (MARK = 1 = NEG; ZERO = 0 = POS)

Held in MARK state when not in use

DB-25 Connector: pin 1 - shield

pin 2: transmit data to DCE

pin 3: receive data at DTE

pin 5: clear to send (CTS) from DCE to DTE

pin 7: signal ground

Note: The DTE sends data on pin 2

7.8 Write a proposal to your student governing body asking for money to start an on-campus amateur radio club.

7.9 The following memo was handed in by the employee of a small company specializing in adaptive aides for physically challenged individuals. The memo is not written particularly well. Rewrite the memo using the principles and guidelines outlined in this chapter.

To: Xebec Management

From: H. Chew

This project is to work with a 47-year-old individual who has no speech capability and limited physical abilities. The subject groans and grunts to indicate discomfort, displeasure, requesting, and refusing. During dinner, our customer would like us to provide the subject with a means to indicate "I want more," "I want something else," and "I want a link," etc.

To solve this problem, we had called the customer for more information, and she would give us a video tape that is talking about the older person. We also had a team meeting to discuss the project. At the end of the meeting, we considered that we would design a box which consists of an interface panel and a data control unit. The interface panel would consist of four 2.5″ buttons. Each button represents a prerecorded phrase. The sets of outputs from the buttons will correspond to the mode selected. The data control unit consists of the power supply, speech memory, speech synthesizer, and audio amplifier.

7.10 The following entries were collected by a design team working on a major software project. These notes are to be used by the team to write a summary report to the project manager indicating the features that the finished product must have. The software is to be a voice synthesizer system that will enable individuals with impaired speech capability and limited motor skills to communicate by way of a simple computer mouse. Using the rough notes provided by the design team, write the finished report to the project manager.

- Topics covered include the alarm, requests, and greetings portions of the user interface.
- The requests frame should be configured to allow the user to express common requests.
- The greetings frame must have the most common greetings and be designed for easy access.
- All frames should give the user the option to reconfigure them in any order desired.
- The alarm frame will consist of five buttons for use in an emergency only.
- Alarm messages include help, pain, fire, police, and ambulance.
- Requests include drink, food, bathroom, book, pen, television, radio, and music.
- Greetings include hello, goodbye, good morning, good evening, and good night.

7.11 Compose the text of an e-mail message that announces a meeting of your design team for a design competition called "Peak Performance."

7.12 Compose the text of an e-mail message in which you request a meeting with your boss to discuss a possible raise in salary.

7.13 Compose the text of an e-mail message in which you request a meeting with your professor to discuss a possible change in your course grade.

7.14 Compose the text of an e-mail message in which you ask a semiconductor manufacturer to send you a free sample of a microprocessor chip.

7.15 Compose the text of an e-mail message in which you inform a client about your travel plans for an upcoming technical review meeting.

7.16 Compose the text of an e-mail message in which you provide arrival information for a government contractor who is coming to your laboratory to review your work.

7.17 Compose the text of an e-mail message in which you ask for volunteers for a committee to review company safety standards.

7.18 Compose the text of an e-mail message in which you solicit volunteers to participate in the annual company blood drive for a local hospital.

7.19 Compose the text of an e-mail message in which you ask your boss for permission to attend the annual conference of the Control and Automation Group of the Institute of Electrical and Electronics Engineers (IEEE).

7.20 Compose the text of an e-mail message in which you reassure a nervous customer that your prototype for a manufacturing system will be shipped on time.

7.21 Prepare a set of overhead slides in which you outline your design approach for a car design competition called "Peak Performance."

7.22 Prepare a set of overhead slides in which you describe the results of combustion tests on a new aircraft engine.

7.23 Prepare a set of overhead slides in which you outline plans for a proposed new light-rail transportation system in a metropolitan area.

7.24 Prepare a set of overhead slides in which you describe the benefits of a proposed new graphical user interface for a record-keeping system for a real estate company.

7.25 Prepare a set of overhead slides in which you describe the important features of a professional quality mountain bicycle.

7.26 Prepare a set of overhead slides in which you report the results of tests on a high-speed data link for transferring cell phone routing information from site to site.

7.27 Write a letter to the human resources director of Alpha Corporation in which you reply to a classified advertisement seeking software engineers.

7.28 Write a letter to the human resources director of Beta Corporation in which you reply to a classified advertisement seeking entry-level mechanical design engineers.

7.29 Write a letter to the human resources director of Gamma Corporation in which you reply to a classified advertisement seeking biomedical engineers for synthetic drug development.

7.30 Write a letter to the human resources director of Delta Corporation in which you reply to a classified advertisement seeking mechanical engineers to work on developing jet engines.

7.31 Write a letter to the human resources director of XYZ Corporation in which you reply to a classified advertisement seeking industrial engineers to design manufacturing systems.

7.32 Write a letter to the human resources director of Omega State Highway Department in which you reply to a classified advertisement seeking civil engineers for highway construction.

7.33 Write a letter to the graduate admissions director of State University in which you request information about possible financial aid for Master's degree study.

7.34 Write a letter to the CEO of your company in which you highlight the details of an unethical practice that you have uncovered within the company.

7.35 Write a letter to the sales manager of your company in which you detail the virtues of the new pencil that your engineering division has designed.

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