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Intro to ME: Design and Analysis

Prepared For

Namas Chandra

Florida State University
Mechanical Engineering

Course: Introduction to Mechanical Engineering
Course Number: EML 3004C
Term: Fall

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Upper Saddle River, NJ 07458

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All the content in ESource was written by educators specifically for freshman/first-year students. Authors tried to strike a balanced level of presentation, an approach that was neither formulaic nor trivial, and one that did not focus too heavily on advanced topics that most introductory students do not encounter until later classes. Because many professors do not have extensive time to cover these topics in the classroom, authors prepared each text with the idea that many students would use it for self-instruction and independent study. Students should be able to use this content to learn the software tool or subject on their own.

While authors had the freedom to write texts in a style appropriate to their particular subject, all followed certain guidelines created to promote a consistency that makes students comfortable. Namely, every chapter opens with a clear set of **Objectives**, includes **Practice Boxes** throughout the chapter, and ends with a number of **Problems**, and a list of **Key Terms**. **Applications Boxes** are spread throughout the book with the intent of giving students a real-world perspective of engineering. **Success Boxes** provide the student with advice about college study skills, and help students avoid the common pitfalls of first-year students. In addition, this series contains an entire book titled ***Engineering Success*** by Peter Schiavone of the University of Alberta intended to expose students quickly to what it takes to be an engineering student.

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About the Authors

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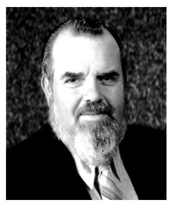
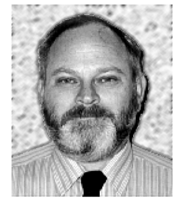


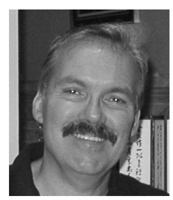
Martin D. Bradshaw was born in Pittsburg, KS in 1936, grew up in Kansas and the surrounding states of Arkansas and Missouri, graduating from Newton High School, Newton, KS in 1954. He received the B.S.E.E. and M.S.E.E. degrees from the University of Wichita in 1958 and 1961, respectively. A Ford Foundation fellowship at Carnegie Institute of Technology followed from 1961 to 1963 and he received the Ph.D. degree in electrical engineering in 1964. He spent his entire academic career with the Department of Electrical and Computer Engineering at the University of New Mexico (1961-1963 and 1991-1996). He served as the Assistant Dean for Special Programs with the UNM College of Engineering from 1974 to 1976 and as the Associate Chairman for the EECE Department from 1993 to 1996. During the period 1987-1991 he was a consultant with his own company, EE Problem Solvers. During 1978 he spent a sabbatical year with the State Electricity Commission of Victoria, Melbourne, Australia. From 1979 to 1981 he served an IPA assignment as a Project Officer at the U.S. Air Force Weapons Laboratory, Kirkland AFB, Albuquerque, NM. He has won numerous local, regional, and national teaching awards, including the George Westinghouse Award from the ASEE in 1973. He was awarded the IEEE Centennial Medal in 2000.

Acknowledgments: Dr. Bradshaw would like to acknowledge his late mother, who gave him a great love of reading and learning, and his father, who taught him to persist until the job is finished. The encouragement of his wife, Jo, and his six children is a never-ending inspiration.



Stephen J. Chapman received a B.S. degree in Electrical Engineering from Louisiana State University (1975), the M.S.E. degree in Electrical Engineering from the University of Central Florida (1979), and pursued further graduate studies at Rice University. Mr. Chapman is currently Manager of Technical Systems for British Aerospace Australia, in Melbourne, Australia. In this position, he provides technical direction and design authority for the work of younger engineers within the company. He also continues to teach at local universities on a part-time basis.

Mr. Chapman is a Senior Member of the Institute of Electrical and Electronics Engineers (and several of its component societies). He is also a member of the Association for Computing Machinery and the Institution of Engineers (Australia).



Steven C. Chapra presently holds the Louis Berger Chair for Computing and Engineering in the Civil and Environmental Engineering Department at Tufts University. Dr. Chapra received engineering degrees from Manhattan College and the University of Michigan. Before joining the faculty at Tufts, he taught at Texas A&M University, the University of Colorado, and Imperial College, London. His research interests focus on surface water-quality modeling and advanced computer applications in environmental engineering. He has published over 50 refereed journal articles, 20 software packages and 6 books. He has received a number of awards including the 1987 ASEE Merriam/Wiley Distinguished Author Award, the 1993 Rudolph Hering Medal, and teaching awards from Texas A&M, the University of Colorado, and the Association of Environmental Engineering and Science Professors.

Acknowledgments: To the Berger Family for their many contributions to engineering education. I would also like to thank David Clough for his friendship and insights, John Walkenbach for his wonderful books, and my colleague Lee Minardi and my students Kenny William,

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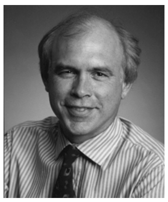

Mark Dix began working with AutoCAD in 1985 as a programmer for CAD Support Associates, Inc. He helped design a system for creating estimates and bills of material directly from AutoCAD drawing databases for use in the automated conveyor industry. This system became the basis for systems still widely in use today. In 1986 he began collaborating with Paul Riley to create AutoCAD training materials, combining Riley's background in industrial design and training with Dix's background in writing, curriculum development, and programming. Mr. Dix received the M.S. degree in education from the University of Massachusetts. He is currently the Director of Dearborn Academy High School in Arlington, Massachusetts.

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Charles B. Fleddermann is a professor in the Department of Electrical and Computer Engineering at the University of New Mexico in Albuquerque, New Mexico. All of his degrees are in electrical engineering: his Bachelor's degree from the University of Notre Dame, and the Master's and Ph.D. from the University of Illinois at Urbana-Champaign. Prof. Fleddermann developed an engineering ethics course for his department in response to the ABET requirement to incorporate ethics topics into the undergraduate engineering curriculum. *Engineering Ethics* was written as a vehicle for presenting ethical theory, analysis, and problem solving to engineering undergraduates in a concise and readily accessible way.

Acknowledgments: I would like to thank Profs. Charles Harris and Michael Rabins of Texas A & M University whose NSF sponsored workshops on engineering ethics got me started thinking in this field. Special thanks to my wife Liz, who proofread the manuscript for this book, provided many useful suggestions, and who helped me learn how to teach "soft" topics to engineers.

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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 devised and developed the senior design project class taken by all electrical and computer engineering students at Boston University. In this class, the students work for a virtual engineering company developing products and systems for real-world engineering and social-service clients.

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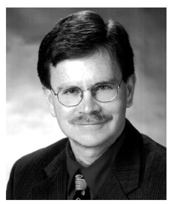

Steven Howell is the Chairman and a Professor of Mechanical Engineering at Lawrence Technological University. Prior to joining LTU in 2001, Dr. Howell led a knowledge-based engineering project for Visteon Automotive Systems and taught computer-aided design classes for Ford Motor Company engineers. Dr. Howell also has a total of 15 years experience as an engineering faculty member at Northern Arizona University, the University of the Pacific, and the University of Zimbabwe. While at Northern Arizona University, he helped develop and implement an award-winning interdisciplinary series of design courses simulating a corporate engineering-design environment.

Douglas W. Hull is a graduate student in the Department of Mechanical Engineering at Carnegie Mellon University in Pittsburgh, Pennsylvania. He is the author of *Mastering Mechanics I Using Matlab 5*, and contributed to *Mechanics of Materials* by Bedford and Liechti. His research in the Sensor Based Planning lab involves motion planning for hyper-redundant manipulators, also known as serpentine robots.

Scott D. James is a staff lecturer at Kettering University (formerly GMI Engineering & Management Institute) in Flint, Michigan. He is currently pursuing a Ph.D. in Systems Engineering with an emphasis on software engineering and computer-integrated manufacturing. He chose teaching as a profession after several years in the computer industry. “I thought that it was really important to know what it was like outside of academia. I wanted to provide students with classes that were up to date and provide the information that is really used and needed.”

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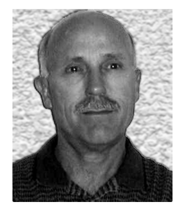

Joe King received the B.S. and M.S. degrees from the University of California at Davis. He is a Professor of Computer Engineering at the University of the Pacific, Stockton, CA, where he teaches courses in digital design, computer design, artificial intelligence, and computer networking. Since joining the UOP faculty, Professor King has spent yearlong sabbaticals teaching in Zimbabwe, Singapore, and Finland. A licensed engineer in the state of California, King’s industrial experience includes major design projects with Lawrence Livermore National Laboratory, as well as independent consulting projects. Prof. King has had a number of books published with titles including MATLAB, MathCAD, Exploring Engineering, and Engineering and Society.

David C. Kuncicky is a native Floridian. He earned his Baccalaureate in psychology, Master’s in computer science, and Ph.D. in computer science from Florida State University. He has served as a faculty member in the Department of Electrical Engineering at the FAMU–

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Ron Larsen is a Professor of Chemical Engineering at Montana State University, and received his Ph.D. from the Pennsylvania State University. He was initially attracted to engineering by the challenges the profession offers, but also appreciates that engineering is a serving profession. Some of the greatest challenges he has faced while teaching have involved non-traditional teaching methods, including evening courses for practicing engineers and teaching through an interpreter at the Mongolian National University. These experiences have provided tremendous opportunities to learn new ways to communicate technical material. Dr. Larsen views modern software as one of the new tools that will radically alter the way engineers work, and his book *Introduction to MathCAD* was written to help young engineers prepare to meet the challenges of an ever-changing workplace.

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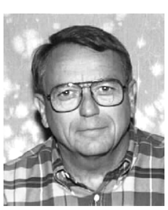

Sanford Leestma is a Professor of Mathematics and Computer Science at Calvin College, and received his Ph.D. from New Mexico State University. He has been the long-time co-author of successful textbooks on Fortran, Pascal, and data structures in Pascal. His current research interest are in the areas of algorithms and numerical computation.

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Acknowledgments: I'd like to thank my colleagues at USC–Aiken, especially Professors Mike May and Laurene Fausett, for their encouragement and feedback; and my parents, Felice and Morton Leifer, for being there and providing support (as always) as I completed this book.

Richard M. Lueptow is the Charles Deering McCormick Professor of Teaching Excellence and Associate Professor of Mechanical Engineering at Northwestern University. He is a native of Wisconsin and received his doctorate from the Massachusetts Institute of Technology in 1986. He teaches design, fluid mechanics, an spectral analysis techniques. Rich has an active research program on rotating filtration, Taylor Couette flow, granular flow, fire suppression, and acoustics. He has five patents and over 40 refereed journal and proceedings papers along with many other articles, abstracts, and presentations.

Acknowledgments: Thanks to my talented and hardworking co-authors as well as the many colleagues and students who took the tutorial for a "test drive." Special thanks to Mike Minbiole for his major contributions to Graphics Concepts with SolidWorks. Thanks also to Northwestern University for the time to work on a book. Most of all, thanks to my loving wife, Maiya, and my children, Hannah and Kyle, for supporting me in this endeavor. (Photo courtesy of Evanston Photographic Studios, Inc.)

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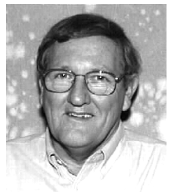

Larry Nyhoff is a Professor of Mathematics and Computer Science at Calvin College. After doing bachelor's work at Calvin, and Master's work at Michigan, he received a Ph.D. from Michigan State and also did graduate work in computer science at Western Michigan. Dr. Nyhoff has taught at Calvin for the past 34 years—mathematics at first and computer science for the past several years.

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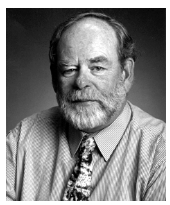

Paul Riley is an author, instructor, and designer specializing in graphics and design for multimedia. He is a founding partner of CAD Support Associates, a contract service and professional training organization for computer-aided design. His 15 years of business experience and 20 years of teaching experience are supported by degrees in education and computer science. Paul has taught AutoCAD at the University of Massachusetts at Lowell and is presently teaching AutoCAD at Mt. Ida College in Newton, Massachusetts. He has developed a program,

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Robert Rizza is an Assistant Professor of Mechanical Engineering at North Dakota State University, where he teaches courses in mechanics and computer-aided design. A native of Chicago, he received the Ph.D. degree from the Illinois Institute of Technology. He is also the author of *Getting Started with Pro/ENGINEER*. Dr. Rizza has worked on a diverse range of engineering projects including projects from the railroad, bioengineering, and aerospace industries. His current research interests include the fracture of composite materials, repair of cracked aircraft components, and loosening of prostheses.

Peter Schiavone is a professor and student advisor in the Department of Mechanical Engineering at the University of Alberta, Canada. He received his Ph.D. from the University of Strathclyde, U.K. in 1988. He has authored several books in the area of student academic success as well as numerous papers in international scientific research journals. Dr. Schiavone has worked in private industry in several different areas of engineering including aerospace and systems engineering. He founded the first Mathematics Resource Center at the University of Alberta, a unit designed specifically to teach new students the necessary *survival skills* in mathematics and the physical sciences required for success in first-year engineering. This led to the Students' Union Gold Key Award for outstanding contributions to the university. Dr. Schiavone lectures regularly to freshman engineering students and to new engineering professors on engineering success, in particular about maximizing students' academic performance.

Acknowledgements: Thanks to Richard Felder for being such an inspiration; to my wife Linda for sharing my dreams and believing in me; and to Francesca and Antonio for putting up with Dad when working on the text.

David I. Schneider holds an A.B. degree from Oberlin College and a Ph.D. degree in Mathematics from MIT. He has taught for 34 years, primarily at the University of Maryland. Dr. Schneider has authored 28 books, with one-half of them computer programming books. He has developed three customized software packages that are supplied as supplements to over 55 mathematics textbooks. His involvement with computers dates back to 1962, when he programmed a special purpose computer at MIT's Lincoln Laboratory to correct errors in a communications system.

David I. Schwartz is an Assistant Professor in the Computer Science Department at Cornell University and earned his B.S., M.S., and Ph.D. degrees in Civil Engineering from State University of New York at Buffalo. Throughout his graduate studies, Schwartz combined principles of computer science to applications of civil engineering. He became interested in helping students learn how to apply software tools for solving a variety of engineering problems. He teaches his students to learn incrementally and practice frequently to gain the maturity to tackle other subjects. In his spare time, Schwartz plays drums in a variety of bands.

Acknowledgments: I dedicate my books to my family, friends, and students who all helped in so many ways. Many thanks go to the schools of Civil Engineering and Engineering & Applied Science at State University of New York at Buffalo where I originally developed and tested my UNIX and Maple books. I greatly appreciate the opportunity to explore my goals and all the help from everyone at the Computer Science Department at Cornell.

John T. Sears received the Ph.D. degree from Princeton University. Currently, he is a Professor and the head of the Department of Chemical Engineering at Montana State University. After leaving Princeton he worked in research at Brookhaven National Laboratory and Esso Research and Engineering, until he took a position at West Virginia University. He came to MSU in 1982, where he has served as the Director of the College of Engineering Minority Program and Interim Director for BioFilm Engineering. Prof. Sears has written a book on air pollution and economic development, and over 45 articles in engineering and engineering education.

Michael T. Snyder is President of Internet startup Appointments123.com. He is a native of Chicago, and he received his Bachelor of Science degree in Mechanical Engineering from the University of Notre Dame. Mike also graduated with honors from Northwestern University's Kellogg Graduate School of Management in 1999 with his Masters of Management degree. Before Appointments123.com, Mike was a mechanical engineer in new product development for Motorola Cellular and Acco Office Products. He has received four patents for his mechanical design work. "Pro/ENGINEER was an invaluable design tool for me, and I am glad to help students learn the basics of Pro/ENGINEER."

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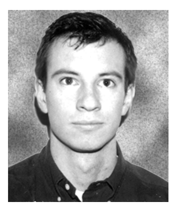

Jim Steger is currently Chief Technical Officer and cofounder of an Internet applications company. He graduated with a Bachelor of Science degree in Mechanical Engineering from Northwestern University. His prior work included mechanical engineering assignments at Motorola and Acco Brands. At Motorola, Jim worked on part design for two-way radios and was one of the lead mechanical engineers on a cellular phone product line. At Acco Brands, Jim was the sole engineer on numerous office product designs. His Worx stapler has won design awards in the United States and in Europe. Jim has been a Pro/ENGINEER user for over six years.

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Royce Wilkinson received his undergraduate degree in chemistry from Rose-Hulman Institute of Technology in 1991 and the Ph.D. degree in chemistry from Montana State University in 1998 with research in natural product isolation from fungi. He currently resides in Bozeman, MT and is involved in HIV drug research. His research interests center on biological molecules and their interactions in the search for pharmaceutical advances.

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Reviewers

ESource benefited from a wealth of reviewers who on the series from its initial idea stage to its completion. Reviewers read manuscripts and contributed insightful comments that helped the authors write great books. We would like to thank everyone who helped us with this project.

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Denise Jackson *University of Tennessee, Knoxville*
Kathleen Kitto *Western Washington University*
Terry Kohutek *Texas A&M University*
Larry Richards *University of Virginia*
Avi Singhal *Arizona State University*
Joseph Wujek *University of California, Berkeley*
Mandochehr Zoghi *University of Dayton*

Books

Stephen Allan *Utah State University*
Naeem Abdurrahman *University of Texas, Austin*
Anil Bajaj *Purdue University*
Grant Baker *University of Alaska–Anchorage*
Betty Burr *University of Houston*
William Beckwith *Clemson University*
Haym Benaroya *Rutgers University*
Tom Bledsaw *ITT Technical Institute*
Tom Bryson *University of Missouri, Rolla*
Ramzi Bualuan *University of Notre Dame*
Dan Budny *Purdue University*
Dale Calkins *University of Washington*
Arthur Clausing *University of Illinois*
James Devine *University of South Florida*
Patrick Fitzhorn *Colorado State University*
Dale Elifrits *University of Missouri, Rolla*
Frank Gerlitz *Washtenaw College*
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John Graham *University of North Carolina–Charlotte*
Malcom Heimer *Florida International University*
A.S. Hodel *Auburn University*
Vern Johnson *University of Arizona*
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Ron Eaglin *University of Central Florida*
Susan Freeman *Northeastern University*
Frank Gerlitz *Washtenaw Community College*
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1

What Is Engineering?

Sections

- 1.1 Engineering Has Many Fields
- 1.2 Professional Engineering Organizations
- 1.3 The Engineer: Central to Project Management
- 1.4 Engineering: A Set of Skills
- Key Terms

Objectives

- Engineering as a career.
- Engineering professional organizations.
- The relationship between the engineer and other professionals.
- The foundations of engineering design: knowledge, experience, and intuition.

If you're reading this book, you're 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 use computers. Maybe you simply followed the advice of your high school guidance counselor. Whatever your reason for studying engineering, you are entering a career full of discovery, creativity, and excitement. Imagine yourself several years from now, after you've finished your college studies. What will your life be like as an engineer? How will the classes you've taken in school relate to your work and career? This book will help provide you with a vision of the future while teaching you the important principles of engineering design.

As an aspiring engineer, you have much to learn. You must master the foundations of all engineering disciplines: basic math, physics, and chemistry. You must study the specialized subjects of your chosen discipline, for example, circuits, mechanics, materials, or computer programming. You also must learn how to stay on top of technological advances by embracing a program of lifelong learning. The world embraces new technological advances almost on a daily basis, and 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. However, you also must learn about the primary mission of the engineer: the practice of design. The ability to build real things is what sets an engineer apart from professionals in the basic sciences. While physicists, chemists, and biologists draw general conclusions by observing specific phenomena, an engineer moves from the general to the specific. Engineers harness the laws of nature and use them to produce devices or systems that perform tasks and solve problems. This process defines the essence of design. You must become proficient at it if you want to become an engineer. This book will teach you the principles of design and help you to apply them to your class assignments, design projects, and future job activities.

1.1 ENGINEERING HAS MANY FIELDS

A perusal of the Web sites of *engineering* colleges around the world will reveal a wide variety of engineering programs. Although the names may vary slightly, most engineers are trained in one of the following traditional engineering degree programs (listed alphabetically): aeronautical, agricultural, biomedical, chemical, civil, computer, electrical, industrial, mechanical, naval, petroleum, and systems. From reading this list, one might get the impression that engineers are highly specialized professionals who have little interaction with people from other fields. In reality, the opposite is true. The best engineers are multidisciplinary individuals who are familiar with many different fields and specialties. The mechanical engineer knows something about electrical circuits, and the electrical engineer understands basic mechanics. The computer engineer is familiar with the algorithms used in industrial processes, and the industrial engineer knows how to program computers. Many of the great engineering accomplishments of the past century, including our global communication network; the Internet; life-extending biomedical technology; inexpensive, reliable air transportation; our ground transportation infrastructure; and the sequencing of the human genome were made possible by interactive teams of engineers from many disciplines.

Although engineers have multidisciplinary skills, most are trained in a specific degree program and spend much time using their specialized training. For this reason, we precede our study of design by reviewing the characteristic features of the various types of engineers and their fields of expertise.

1.1.1 Aeronautical Engineer

Aeronautical (or aerospace) engineers use their knowledge of aerodynamics, fluid mechanics, structures, control systems, heat transfer, and hydraulics to design and build everything from rockets, airplanes, and space vehicles to high-speed bullet trains 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 possible human flight and space exploration. Aeronautical engineers find employment in many industries, but 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, the NASA Space Shuttle, deep space exploration, space stations, and the jumbo jet. The International Space Station, shown in Figure 1.1, for example, will be completed by teams of aeronautical and other engineers.

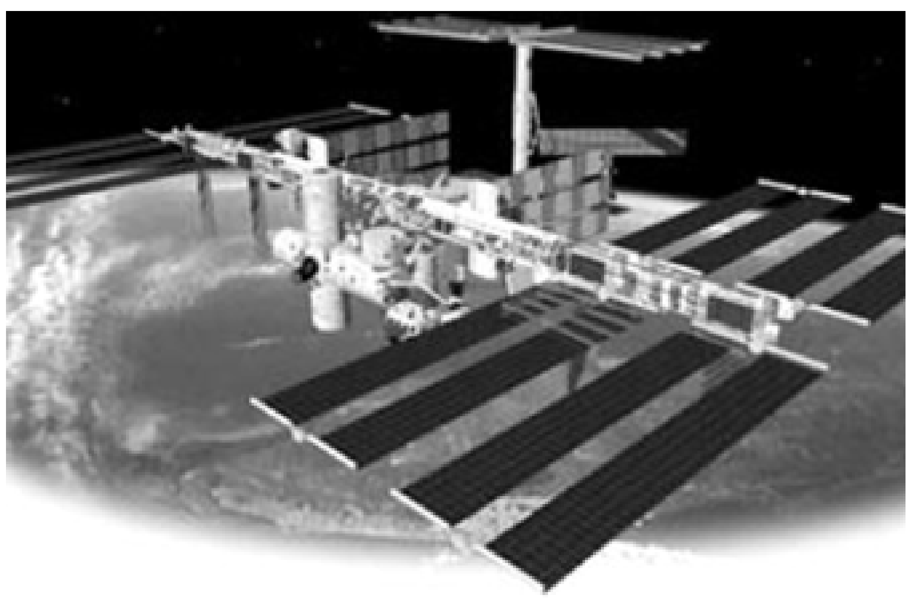

Figure 1.1 Artist's view of NASA's International Space Station. This station is being built by teams of aerospace and aeronautical engineers working together with other types of engineers and scientists. (*Photo courtesy of NASA.*)

1.1.2 Agricultural Engineer

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 ever-growing population is one of the most formidable challenges of the 21st century. Agricultural engineers will play an important role in this endeavor by applying technology and engineering know-how to improve crop yields, increase food output, and develop cost-effective and environmentally sound farming methods. Agricultural engineers work with ecologists and biologists, chemists, and natural scientists to understand the impact of human agriculture on the earth's ecosystem.

1.1.3 Biomedical Engineer

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 knowledge of biology, physiology, and chemistry to produce medical instrumentation, prosthetics, assistive appliances, implants, and neuromuscular diagnostics. Biomedical engineers have participated in designing many devices that have helped improve medical care over the past several decades. Many biomedical engineers enter medical school upon graduation, but others go on to graduate school or seek employment in any of a number of health- or medical-related industries. The rapidly emerging world of biotechnology, which bridges the gap between engineering and molecular genetics, is also the province of the biomedical engineer (Figure 1.2). This discipline examines the fundamental functions of cells and organisms from an engineering point of view. The science of cloning, for example, has been made possible in part by the world of molecular engineers. 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. The biomedical engineer also is involved in the area of microfluidics, in which tiny bio-processing systems are built on small chips of silicon or other materials. This technology, part of the field of micro-electromechanical systems, or MEMS, is sometimes referred to as "lab on a chip." Another exciting area of biomedical engineering is the field of *bioinformatics* which combines computer science with the study of genomics, including the human genome.

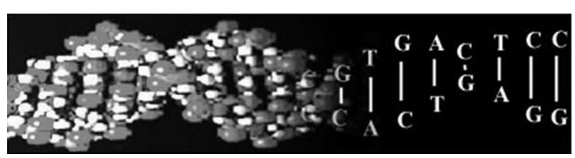

Figure 1.2 Genetics is one of the new frontiers of biomedical engineering. (*Graphic courtesy of the Center for Advanced Biotechnology, Boston University.*)

1.1.4 Chemical Engineer

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, a chemical engineer is needed to 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 petroleum, petrochemicals, plastics, cosmetics, electronics, food, and pharmaceuticals. Their skills are needed wherever a manufacturing process involves organic or inorganic chemical reactions on a production scale. Typically, chemical engineers are employed by large companies that produce products for worldwide distribution.

1.1.5 Civil Engineer

The civil engineer is concerned with the design and construction of our nation's infrastructure. Civil engineers design transportation systems, roads, bridges, buildings, airports, and other large structures, such as water treatment plants, aquifers, and waste management facilities. One classic example of civil engineering on a grand scale is the Hoover Dam shown in Figure 1.3. Designing such a large structure requires knowledge of fluid and soil mechanics, strength of materials, concrete engineering, and construction practices. Civil engineers also may be involved in designing smaller structures such as houses, landscapes, and recreational parks. Over the next few 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 the unique handicap of having 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 is seldom possible to build a trial test structure on the scale of most civil engineering products. There are no full-scale prototypes in civil engineering. A civil engineer must be sure that a design will meet its specifications well before its final construction.

Figure 1.3 The Hoover Dam at the Nevada–Arizona border was designed by civil engineers.

The civil engineer works closely with construction personnel and may spend much time at job sites reviewing the progress of construction tasks. Civil engineers often are employed in the public sector, but also may find work in large or small construction companies and private development firms. One renowned example of a large, public-sector civil engineering effort is the famed "Big Dig" in Boston, Massachusetts (Figure 1.4). This multibillion-dollar, 10-year effort, the most expensive and extensive single transportation infrastructure project in U.S. history, is formally known as Central Artery/Tunnel Project.

Figure 1.4 Boston's Central Artery/Tunnel Project: The "Big Dig." Civil engineers will be responsible for revitalizing the nation's infrastructure in the 21st century. (*Photo courtesy of the Central Artery/Tunnel Project.*)

1.1.6 Computer Engineer

Computer engineering encompasses the broad categories of hardware, software, and digital communication (Figure 1.5). A computer engineer applies the basic principles of engineering and computer science to the design of computers, networks, software systems, and peripheral devices. The computer engineer also is responsible for designing and building the interconnections between computers and their components, including distributed computers, local area networks (LANs), wireless networks, and Internet servers. For example, a computer engineer might combine microprocessors, memory chips, disk drives, DVD drives, display devices, LAN cards, and drivers to produce computer systems. Graphical user interfaces, embedded computer systems, fault-tolerant computers, software systems, wireless interfaces, operating systems, and assembly language programming are also the responsibility of the computer engineer. Computer scientists, who traditionally are more mathematically oriented than are computer engineers, also become involved in writing 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 of which both hardware and software share equally important roles include CPU design, desktop and laptop PC design, cellphone 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, 1982), the explosion of personal computing that began with the first desktop PC (IBM, 1984), and the advances in data communication networks that began with the U.S. Department of Defense Arpanet and grew into the Internet and the World Wide Web.

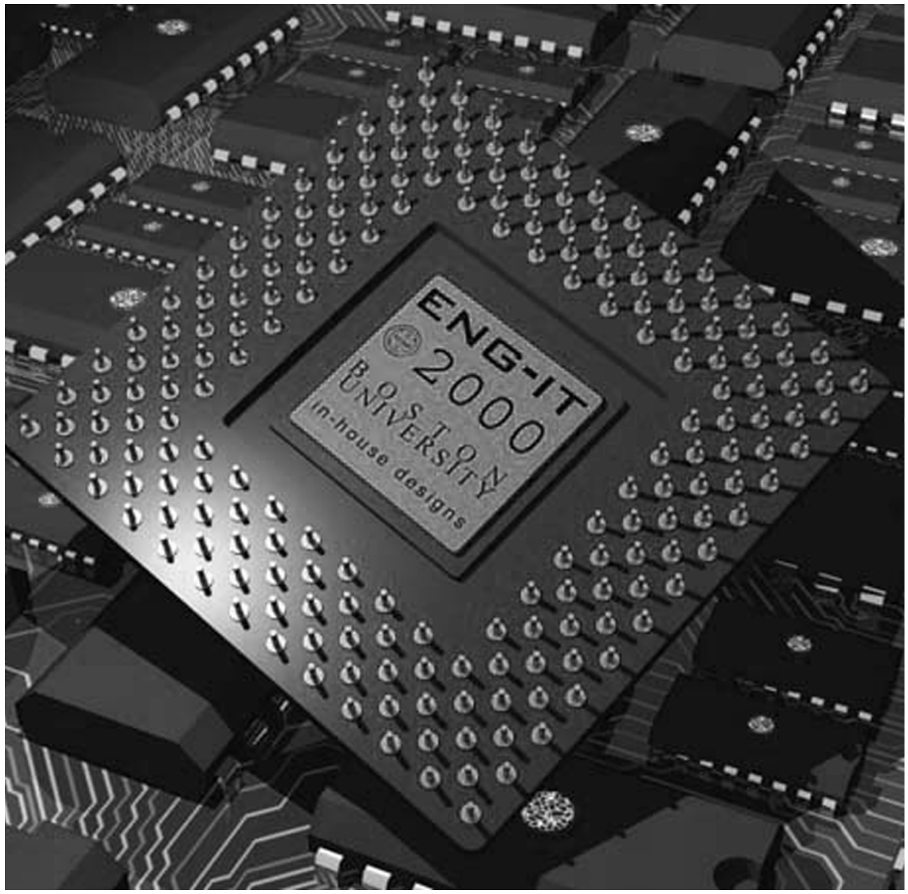

Figure 1.5 Computer engineers design the hardware and software for today's computer systems. (*Image courtesy of C. Moreira and L. Katz.*)

1.1.7 Electrical Engineer

Electrical engineering is a far-reaching discipline whose subjects are linked by a single common thread: the use and control of electricity. Because information can be expressed in electronic form, computers also fall into this broad category. Whether on a large or small scale, electrical engineers are responsible for many technology areas including microelectronics, data communication, radio, television, lasers (Figure 1.6), fiber optics, video, audio, computer networks, speech processing, imaging systems, electric power systems, and alternative energy sources, such as solar and wind power. 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, as well as knowledge of circuits and electronics, semiconductor devices, analog and digital signal processing, digital systems, electromagnetics, and control systems. The electrical engineer also is fluent in many areas of computer engineering. Some of the more recent accomplishments that have involved

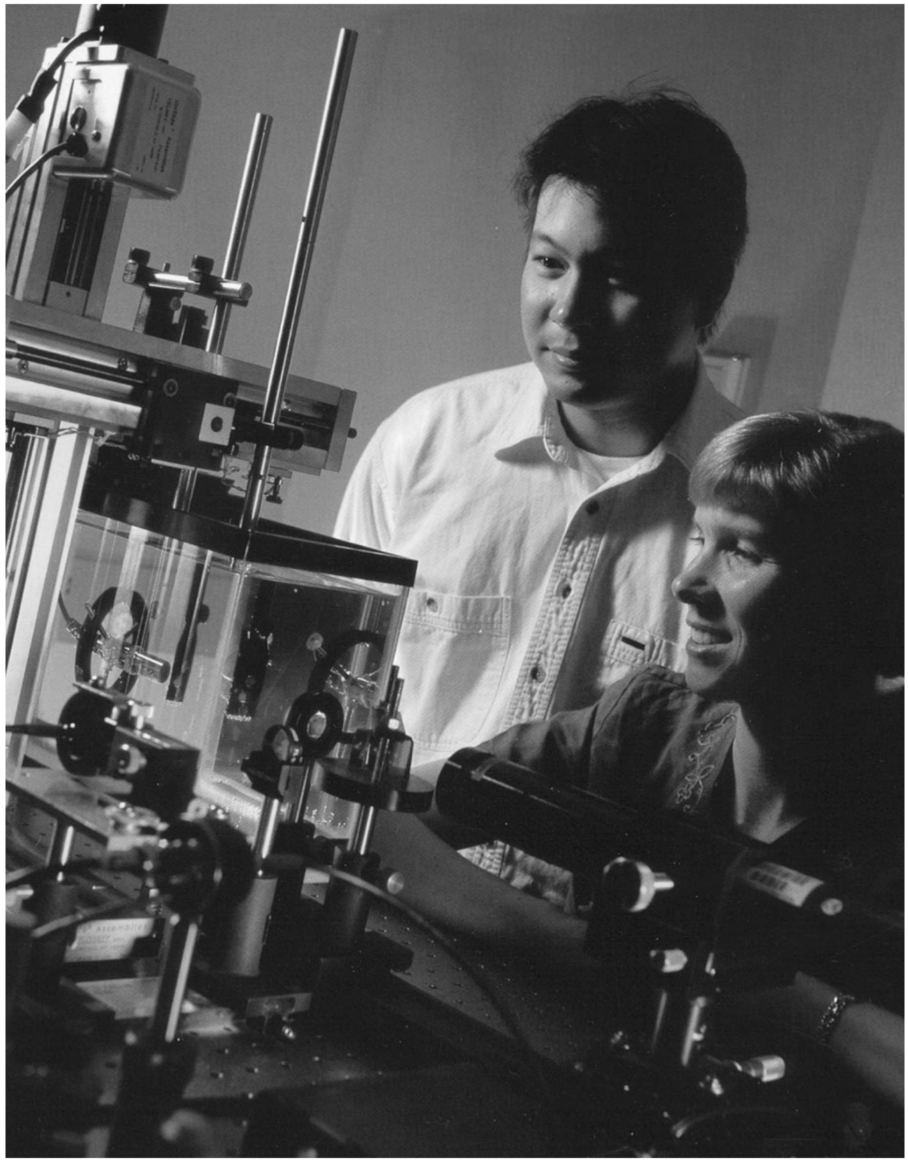

Figure 1.6 The laser, first invented around 1960, has become an indispensable tool for the electrical engineer. (*Photo courtesy of Boston University Photo Services.*)

electrical engineers include the microelectronic revolution (e.g., microprocessors and large-scale integration on a chip); wireless communications (e.g., cellular telephones, pagers, and data links); photonics (e.g., lightwave technology, lasers, and fiber-optic communication); and micro-electromechanical systems (e.g., laboratory on a chip).

1.1.8 Industrial Engineer

The 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 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. The industrial engineer is 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 minimizing cost. Skills required for this discipline include knowledge of product development, materials processing, 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, is becoming increasingly important to the field of industrial engineering.

One of the more recent areas to emerge as the province of the industrial engineer is the use of robotics in manufacturing. Building, moving, and controlling robots requires knowledge of aspects of mechanical, electrical, and computer engineering. Most programs in industrial engineering include courses in these other areas. Another emerging 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 as part of the design process.

1.1.9 Mechanical Engineer

The mechanical engineer is responsible for designing and building physical structures of all sorts. Devices that involve mechanical motion, such as automobiles, bicycles, engines, disk drives, keyboards, fluid valves, jet engine turbines, power plants, and flight structures, are all designed by mechanical engineers. Mechanical engineers are fluent in the topics of statics, dynamics, strength of 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 acoustics, precision machining, environmental engineering, water resources, combustion, power sources, robotics, transportation, and manufacturing systems. Compared with all engineering disciplines, the mechanical engineer interfaces most easily with other types of engineers because mechanical engineering requires such a broad educational background.

One of the newest areas of study involving mechanical engineers is the emerging field of micro-electromechanical systems, or MEMS, in which tiny microscopic machines are fabricated on wafers of silicon and other materials. Figure 1.7, for example, shows a tiny micromotor built on a silicon chip. MEMS has the potential to do for mechanics what the integrated circuit did for electronics, namely permit large-scale integration on single silicon chips of entire systems made from basic devices. Mechanical engineers work closely with electrical engineers in this exciting new discipline.

1.1.10 Mechatronics Engineer

The mechatronics 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 products and manufacturing systems. Engineers who work in this emerging 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. Mechatronics engineers are responsible for the innovation, design, and development of machines and systems that can automate production

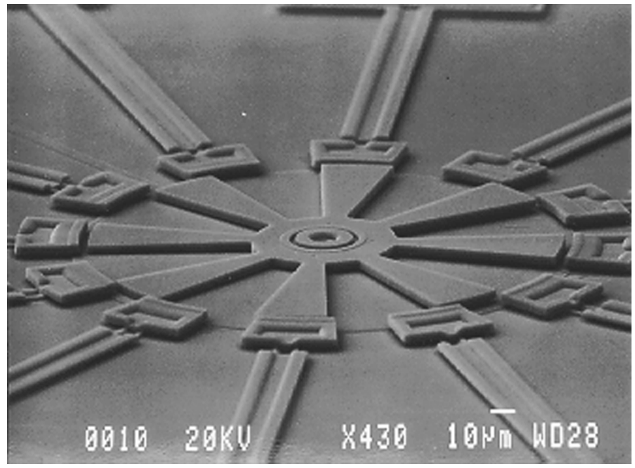

Figure 1.7 Tiny MEMS silicon micromotor measuring 100 micrometers in diameter. (*Photo courtesy of Cronos, Inc.*)

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.

1.1.11 Naval Engineer

The naval engineer (or naval architect) designs ships, submarines, barges, and other seagoing vessels and also is involved in the design of oil platforms, shipping docks, seaports, and coastal navigation facilities. Naval engineers are fluent in many of the subjects studied by mechanical engineers, including fluid mechanics, materials, structures, statics, dynamics, water propulsion, and heat transfer. In addition, naval engineers learn about 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.

1.1.12 Petroleum Engineer

Over 70 percent of the world's current energy needs are satisfied by petroleum products, and this situation is unlikely to change for at least the next half century. The principle challenge of the petroleum engineer is to help 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 base of knowledge 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 of study 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. Did you know that 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. Lastly, because many petroleum companies operate on a worldwide scale, the petroleum engineer has the opportunity to work in many foreign countries.

1.1.13 Systems Engineer

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. Communications systems, transportation networks, manufacturing systems, power distribution networks, and avionics are but some of the areas in which systems engineers play a central role. 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 at home working with most other types of engineers.

1.2 PROFESSIONAL ENGINEERING ORGANIZATIONS

Most branches of engineering are represented by professional societies that bind together members with similar backgrounds, training, and professional expertise. These societies operate on a worldwide scale and publish one or more journals for which engineers write papers and articles of interest to members of the field. Each organization offers its members technical and informational services, including 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 and the technical publications they produce. Each society has an official Web site from which you can obtain additional information. The text provided here has been taken from each organization's Web site.

1.2.1 Aeronautical and Aerospace Engineering

From the American Institute of Aeronautics and Astronautics (www.aiaa.org):

> "For more than 65 years, the American Institute of Aeronautics and Astronautics (AIAA) and its predecessors, has been the principal society of the aerospace engineer and scientist. Officially formed in 1963 through a merger of the American Rocket Society (ARS) and the Institute of Aerospace Sciences (IAS), the purpose was, and still is, 'to advance the arts, sciences, and technology of aeronautics and astronautics, and to promote the professionalism of those engaged in these pursuits.' Both ARS and IAS brought to the relationship a long and eventful history—stretching back to 1930 and 1932, respectively—and each left its mark on the Institute. The merger combined the imaginative, opportunistic, and risk-taking desire of those rocket, missile, and space professionals with the more established, well-recognized achievers from the aviation community."

> "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. Also, many prominent corporations and governments worldwide rely on AIAA as a stimulator of professional accomplishment in all areas related to aerospace. Consider this: Since 1963, AIAA members have achieved virtually every milestone in modern American flight."

Key Publications: *Aerospace America, AIAA Bulletin, Aerospace Database, Student Journal*

1.2.2 Biomedical Engineering

From the Biomedical Engineering Society (http://mecca.org/BME/BMES/society/index.htm):

> "The Biomedical Engineering Society (BMES) is an interdisciplinary society established on February 1, 1968 in response to a manifest need to provide a society that gave equal status to representatives of both biomedical and engineering interests. As stated in the Articles of Incorporation, the purpose of the Society is: 'To promote the increase of biomedical engineering knowledge and its utilization.' Today, the society represents over 1,000 professionals and over 1,000 student members (undergraduate and graduate). There are 34 BMES student chapters and about two-thirds of the ABET-accredited bioengineering/ biomedical engineering undergraduate programs have BMES student chapters."

Key Publications: *Annals of Biomedical Engineering, BMES Bulletin*

1.2.3 Chemical Engineering

From the American Institute of Chemical Engineers (www.aiche.org)

> "Founded in 1908, the American Institute of Chemical Engineers (AIChE) is a nonprofit organization providing leadership to the chemical engineering *profession*. Representing 57,000 members in industry, academia, and government, AIChE provides forums to advance the theory and practice of the profession, upholds high professional standards and ethics, and supports excellence in education. Institute members range from undergraduate students, to entry-level engineers to chief executive officers of major corporations. As AIChE approaches the 21st Century, technological, political, social, and economic changes in our society require that we evaluate and refine our strategic plan. This will assure relevance to our members, the profession, and society at large."
>
> "Rapid changes in skill needs and career paths of chemical engineers create new opportunities for AIChE to assist its members. Institutional stakeholders are increasingly faced with the need for effective collaborations. At the same time, the explosive change in information and communication technology introduces challenges to deliver products and services more efficiently."
>
> "In response, our leadership has revised our vision and mission and has developed objectives and strategies that address these changes and that consider the organizational and financial resources and the business processes needed to assure AIChE's relevance in the 21st Century."

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

1.2.4 Civil Engineering

From the 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 every day. 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 Computer Engineering

From the Association for Computing Machinery (www.acm.org):

> "Founded in 1947 Association for Computing Machinery (ACM) is the world's first educational and scientific computing society. Today, our members — over 80,000 computing professionals and students worldwide — and the public turn to ACM for authoritative publications, pioneering conferences, and visionary leadership for the new millennium."
>
> "ACM publishes, distributes, and archives original research and first-hand perspectives from the world's leading thinkers in computing and information technologies. ACM offers over two dozen publications that help computing professionals negotiate the strategic challenges and operating problems of the day. The ACM Press Books program covers a broad spectrum of interests in computer science and engineering."
>
> "*Communications of the ACM* keeps information technology professionals up to date with articles spanning the full spectrum of information technologies in all fields of interest including object-oriented technology, multimedia, the Internet, and networking. *Communications* also carries case studies, practitioner-oriented articles, and regular columns, the ACM Forum, and technical correspondence."

Key Publications: *The ACM Digital Library* (a collection online publications); *Communications of the ACM*; *Crossroads* (a student magazine); and various ACM Transactions journals, including: *Computer-Human Interaction, Computer Systems, Database Systems, Design Automation for Electronic System, Graphics, Information System, Mathematical Software, Modeling and Computer Simulation, Networking, Programming Languages and Systems,* and *Software Engineering and Methodology*

1.2.6 Electrical Engineering

From The Institute of Electrical and Electronics Engineers (www.ieee.org):

> "The Institute of Electrical and Electronics Engineers (IEEE) helps advance global prosperity by promoting the engineering process of creating, developing, integrating, sharing, and applying knowledge about electrical and information technologies and sciences for the benefit of humanity and the profession. IEEE provides the latest information and the best technical resources to members worldwide. Today, IEEE connects more than 350,000 professionals and students to the solutions to tomorrow's technology needs."
>
> "The IEEE is one of the world's largest technical professional societies. Founded in 1884 by a handful of practitioners of the new electrical engineering discipline, today's Institute is comprised of more than 350,000 members who conduct and participate in its activities in approximately 150 countries. The men and women of the IEEE are the technical and scientific professionals making the revolutionary engineering advances which are reshaping our world today."
>
> "The technical objectives of the IEEE focus on advancing the theory and practice of electrical, electronics, and computer engineering and computer science. To realize these objectives, the IEEE sponsors technical conferences, symposia, and local meetings worldwide. It publishes nearly 25% of the world's technical papers in electrical, electronics, and computer engineering, and provides educational programs to keep its members' knowledge and expertise state-of-the-art."

Key Publications: *IEEE Spectrum*; *Proceedings of the IEEE*; plus over 40 specialized IEEE Transactions from its various societies, including (in alphabetical order): *Aerospace and Electronic Systems*; *Advanced Packaging*; *Antennas and Propagation*; *Applied Superconductivity*; *Automatic Control*; *Biomedical Engineering*; *Circuits and Devices*; *Communications*; *Computing in Science and Engineering Magazine (CiSE) Control Systems*; *Dielectrics and Electrical Insulation*; *Electromagnetic Compatibility*; *Electron Devices*; *Energy Conversion*; *Engineering Management*; *Geoscience and Remote Sensing*; *Image Processing*; *Industry Applications*; *Instrumentation and Measurement*; *Intelligent Systems*; *Lasers and Electro-Optics*; *Magnetics*; *Mechatronics*; *Medical Imaging*; *Microelectromechanical Systems*; *Microwave Theory and Techniques*; *Neural Networks*; *Parallel and Distributed Systems*; *Personal Communications*; *Photonics*; *Plasma Science*; *Power Electronics*; *Power Systems*; *Quantum Electronics*; *Reliability*; *Robotics and Automation*; *Semiconductor Manufacturing*; *Signal Processing*; *Software Engineering*; *Solid-State Circuits*; *Systems, Man, and Cybernetics*; *Ultrasonics, Ferroelectrics, and Frequency Control*; *Vehicular Technology*; *Very Large Scale Integration Systems*; and *Visualization and Computer Graphics*

1.2.7 Industrial and Manufacturing Engineering

From the Institute of Industrial Engineers (www.iienet.org):

> "Founded in 1948, the Institute of Industrial Engineers is the society dedicated to serving the professional needs of industrial engineers and all individuals involved with improving quality and productivity. Its 24,000 members throughout North America and more than 80 countries stay on the cutting edge of their profession through IIE's life-long-learning approach, as reflected in the organization's educational opportunities, publications, and networking opportunities. Members also gain valuable leadership experience and enjoy peer recognition through numerous volunteer opportunities."

Key Publications: *IIE Solutions, Industrial Management, IIE Transactions, The Engineering Economist, Student IE, Journal of the Society for Health Systems*

1.2.8 Mechanical Engineering

From the American Society of Mechanical Engineers (www.asme.org):

> "The 125,000-member ASME International is a worldwide engineering society. It conducts one of the world's largest technical publishing operations, holds some 30 technical conferences and 200 professional development courses each year, and sets many industrial and manufacturing standards. Founded in 1880 as the American Society of Mechanical Engineers, today ASME International is a nonprofit educational and technical organization serving a worldwide membership."
>
> "The work of the Society is performed by its member-elected Board of Governors and through its five Councils, 44 Boards, and hundreds of Committees in 13 regions throughout the world. There are a combined 400 sections and student sections serving ASME's worldwide membership."
>
> "Its vision is to be the premier organization for promoting the art, science and practice of mechanical engineering throughout the world. Its 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*; *ASME News*; *Applied Mechanics Reviews*; *plus journals in numerous specialty areas*; *including Applied Mechanics*; *Heat Transfer*; *Biomechanical Engineering*; *Computing and Information Science*; *Dynamic Systems*; *Measurement and Control*; *Electronic Packaging Energy Turbines and Power Engineering Materials Technology Fluids*; *Manufacturing Science*; *Mechanical Design*; *Offshore Mechanics*; *Arctic Engineering*; *Pressure Vessel Technology*; *Solar Energy*; *Tribology*; *Turbomachinery*; *Vibration and Acoustics*; and *Mechatronics*

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 one goes about choosing 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 in career advising. Be sure to attend one. Talk with the experts in career planning and job placement. Many college campuses host student chapters of professional organizations. These groups often organize tours of engineering companies. Attending such a tour can provide valuable perspective about the activities of a particular branch of engineering and provide you with 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. Also, 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 answers questions about jobs in engineering. Learn to make use of all available resources for help in choosing your college major.

1.3 THE ENGINEER: CENTRAL TO PROJECT MANAGEMENT

When we think of the word "design," we may imagine a lone engineer 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 sole entrepreneur who single-handedly changes the face of technology. 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 or important to my career goals?" The answer to these questions lies in the multidisciplinary nature of engineering. At times, an engineer does work alone, but most of the time, engineers must interface with individuals who come from different educational backgrounds. Engineering projects can be complex undertakings that require teamwork and the coordination of many people of different skills and personality traits. An engineer must learn the languages of physicists, mathematicians, chemists, managers, fabricators, technicians, lawyers, marketing staff, and secretaries. It's been said that a good engineer acts as the glue that ties a project together, because he or she has learned to communicate with specialists from each of these varied fields. Learning to communicate across all these occupations requires that the engineer have a broad education and the ability to apply a full range of skills and knowledge to the design process.

1.3.1 The Well-Rounded Engineer

To help illustrate the breadth of communication skills required of an engineer, imagine that you work for the fictitious company depicted in Figure 1.8. Each person shown in the outer circle brings to the company a different professional expertise and is represented by a famous person with an appropriate background. Notice that you, the design engineer, are in the center of the organizational circle. Other engineers on your design team may join you in the center, but each of you can easily communicate with any one specialist in the outer ring. As an engineer, 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 the individual most likely to act as central coordinator.

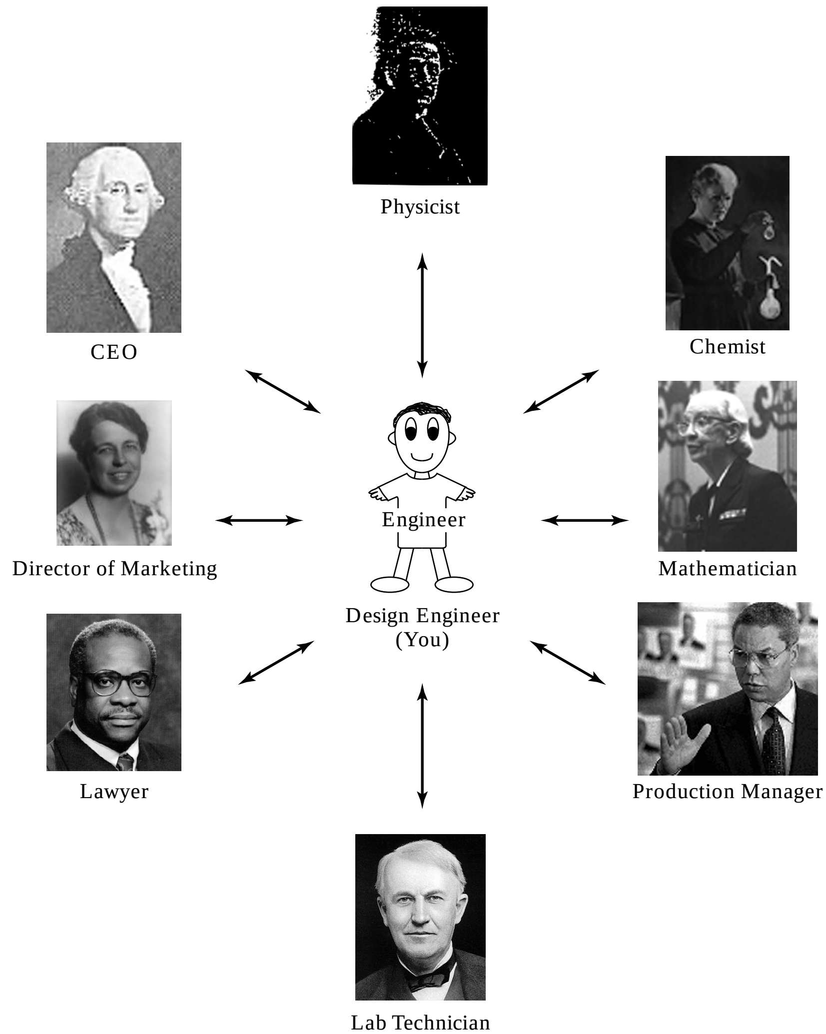

Figure 1.8 The professional circle with the design engineer at its center.

The Physicist (e.g., Albert Einstein, best known for his theory of relativity). The physicist of the company is responsible for understanding the basic physical principles that underlie the company's product line. He spends his time in the laboratory exploring new materials, analyzing their interactions with heat, light, and electromagnetic radiation. He may discover a previously unknown quantum interaction that will lead to a new semiconductor device or perhaps he will explore the potential for using superconductors in the company's product. Or, he 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 his basic discoveries relate to the practical interests of the company.

The Chemist (e.g., Marie Curie, who discovered radium). 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 manufacturing 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 (e.g., ***Grace Hopper, former Navy admiral, mathematician, and computer specialist responsible for the term "computer bug").*** The mathematician of the company, who might also be a computer scientist, worries about things such as modeling, statistics, databases, and forecasting. She may be involved in an intriguing new database algorithm or mathematical method for modeling an engineering system. Perhaps she 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 (e.g., Colin Powell, U.S. Secretary of State, former U.S. Army general, military planner, and co-architect of Operation Desert Storm). Like the army general in top command, the production manager is responsible for mobilizing materials, supplies, and personnel to manufacture company products. The production manager may worry about things such 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 has given you the ability to understand the job of the production manager and has provided you with the vocabulary needed to communicate with him.

The Lab Technician (e.g., Thomas Edison, famous tinkerer and experimenter, best known for inventing the incandescent light bulb). The lab technician is an indispensable member of the design team. An 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 and he have taken many of the same courses, although your courses probably have 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 (e.g., Clarence Thomas, lawyer and Supreme Court Justice). The lawyer worries about 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 substandard product? Is our new deal with Apex Corporation 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 (e.g., Eleanor Roosevelt, former First Lady of the United States). The director of marketing is a master of imagery and style. Her job is to sell the company's products to the public and convince 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 things such 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 can respond to her concerns about what the public needs from the product that you design.

The President/Chief Executive Officer (e.g., George Washington, first president of the United States). The CEO of the company probably has an MBA (Master's of Business Administration) or higher degree and a long history working in 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 courses on 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 design project on the economic health of the company.

1.4 ENGINEERING: A SET OF SKILLS

To be successful at design, an engineer must acquire technical, theoretical, and practical competency and must be a good organizer, and communicator. Three especially important skills that are at the foundation of engineering design 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, or 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 spans various 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 basic knowledge of many different subjects is necessary. Mechanical and computer engineers use electrical circuits. Electrical engineers build physical structures and use computers. Aeronautical engineers rely on software systems. Software engineers design airplane controls. 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 apart to see how they work also are important sources of engineering knowledge. As a young person, did you disassemble your toys, put together model kits, write your own computer games, create Web pages, or play with building sets, hammers, nails, radios, bicycles, or computers? Without knowing it, you began the path toward acquiring engineering knowledge. The professional engineer engages in similar 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. 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 the another, and a new engineer learns this information by working with other engineers. The history of what *hasn't* worked in the past is also a key part of this oral tradition.

An engineer also gains valuable experience by enduring design *failure*. When the first attempt at a design 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 gain true design experience.

1.4.3 Intuition

Intuition is a characteristic normally associated with fishermen, fortunetellers, and weather forecasters. Intuition is also an essential element of engineering. It refers to an engineer's basic instinct about what will or will not work as a problem solution. Although intuition can never replace careful planning, analysis, and testing, 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 and what will not work, grounded in extensive experience, 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 phrases such as, "That seems reasonable" or "That looks about right." or "Oh, about this much."

Intuition is a direct by-product of design experience and is acquired only through practice, practice, and more practice. In the information age, where much of engineering focuses on computers, engineers are tempted to solve everything by simulation and computer modeling. While the use of computers has dramatically accelerated the design cycle and has dramatically changed the practice of engineering, using them makes 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 heat overpower that circuit? Will friction rob that engine of too much power? How big should the vessel be for a production run of that new cosmetic? Developing intuition should be a key goal of your engineering education. How many times have you opened your computer to install new components? Do you alter hardware settings just to see what happens? Have you opened the hood of 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? 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 setting of your bicycle will help you to understand design tradeoffs, such as the conflict between strength and durability versus lightweight construction. 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

Your experience as an engineer can begin while you are a student. If your school has one, a cooperative education program is an excellent way to gain experience as an engineer. The typical program places you as an intern in an engineering company for 6 to 12 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 also can 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 she needs help in the lab. Many professors receive industry or government funding for their research, and many sponsor "Research for Undergraduates" programs, so you may even be paid an hourly wage or small stipend for your time. You'll be assigned tasks such as constructing experiments, wiring circuits, writing programs, obtaining data, preparing test samples, or assisting graduate students.

KEY TERMS

career	Intuition	Management
engineering	Knowledge	profession
Experience		

2

Mechanical Engineering as a Profession

SECTIONS

- 2.1 Introduction
- 2.2 The Role of a Mechanical Engineer
- 2.3 Becoming a Mechanical Engineer and the Lifelong Learning Process
- 2.4 Approaching and Solving an Engineering Problem
- 2.5 Summary
- Key Terms

OBJECTIVES

- Understand the role of mechanical engineering on society and the impact that this role has on everyday life.
- Recognize that mechanical engineers are problem solvers who approach problems in a logical way.
- Use a logical approach to solving problems.

2.1 INTRODUCTION

What exactly is a *mechanical engineer*? What does a mechanical engineer do? How does one go about becoming a mechanical engineer? These are some of the questions pertaining to mechanical engineers and their role in society that we will answer in this chapter.

For introduction, we may say that mechanical engineers work in many industries, often developing everyday products. Think for a moment about some of the products that you may have used. Did you get a drink of water, take a shower, drive a car, or ride a bike? The products used to perform all these activities involved a mechanical engineer in one way or another.

In developing these and other commercial products, mechanical engineers often work on a team, whose members may be from other disciplines. Thus, mechanical engineers interact with other professionals whose experience may lie in other engineering fields or in finance and marketing.

This is just a brief synopsis of the role of a mechanical engineer. In the sections that follow, we will examine this role further.

2.2 THE ROLE OF A MECHANICAL ENGINEER

Mechanical engineers are professionals devoted to employing the principles of motion, forces, and energy. Machines may be used to convert one motion to another, transform energy from one form to another, or apply forces. This implies that mechanical engineers are very much interested in the design, analysis, and fabrication of machinery.

To accomplish these tasks, a mechanical engineer must have a firm foundation in the underlying engineering sciences. These sciences include the study of the motion of fluids and gases, the deformation of solid materials, and the study of materials. To understand and apply principles from these sciences, mechanical engineers must have a firm grounding in science and mathematics.

To accomplish their goals, mechanical engineers work in a team environment, often with professionals from other disciplines. Because machines are used in numerous applications, mechanical engineers are employed in many different fields. Power generation, aerospace technology, and automotives are just a few industries that employ mechanical engineers. In general, mechanical engineers work in industry, developing various commercial products, and also work at universities, in government, and in consulting firms.

Mechanical engineers employed at a university teach the next generation of engineers. These individuals are motivated by their love of teaching and their desire to convey their experiences and knowledge to others. They also direct research activities and write books and technical papers.

Those working in government are employed at various research centers and help to focus the national attention towards new and promising areas of technology. NASA is a government agency that employs many mechanical engineers that develop technology for the aerospace sciences.

PROFESSIONAL SUCCESS

At NASA, the focus is divided into four areas called enterprises: the Office of AeroSpace Technology, Human Exploration, and Development of Space (HEDS), Destination: Earth and the

Office of Space Science. NASA centers work on various projects that fit in to these enterprises. For example, one of the goals of the Office of AeroSpace Technology is to develop an affordable high-speed transport that cuts the travel time to the far east and Europe by 50%, while meeting stringent aircraft noise and emission standards.

One of the endeavors in attaining these goals is to implement new advanced low-cost material and structural concepts. Mechanical engineers work side by side with material scientists developing and implementing new materials in structural applications. Because the aircraft will have to travel at very high speeds, the heating of certain portions of the exterior of the aircraft is a problem. Engineers use techniques developed from the study of thermal sciences and materials to dissipate or deal with this heat.

Mechanical engineers employed in consulting firms use their expertise to solve specific problems. Many mechanical engineers start consulting firms or join consulting firms after many years of experience.

Mechanical engineers work side by side with sales and marketing professionals. But, because of today's global marketplace and the needs of their employers, many mechanical engineers are being trained to understand the principles of marketing and sales, so that those principles can be incorporated into the design of the product.

Mechanical engineers are also finding employment in nontraditional engineering areas such as the environment and medicine. Mechanical engineers are now employed to design equipment to clean and preserve the environment and work with natural scientists such as biologists. Mechanical engineers are also employed in the Bioengineering industry, along with medical doctors, physical therapists, and other medical professionals in endeavors to analyze the human body, design and fabricate replacement limbs, and design and construct medical instrumentation.

As can be seen from the preceding paragraphs, mechanical engineers play an important role in society and find employment in a wide range of areas. Thus, it is very difficult to find an area of interest where mechanical engineers have not played an active role.

PROFESSIONAL SUCCESS

Mechanical engineers have a responsibility to society to design and build safe, reliable, and efficient machinery. Also, mechanical engineers need to consider what long-term impacts their designs have on the environment.

One area of concern is pollution. Global warming due to the release of green house gases is a hotly debated topic nowadays. However, there is evidence that the industrial age has resulted in polluted landscapes, air, and watersheds. With increasing emphasis on this topic, it is quite possible that endeavors to minimize or eliminate pollution may be a focus of your career.

The exhaust from the internal combustion automobile engine has been blamed for much of the release of greenhouse gases. Some efforts in the last 20 years have concentrated on reformulating gasoline so that it burns cleaner. In addition, mechanical engineers working on new automobile designs have developed lighter cars, which are more fuel efficient. They have also developed and are continuing to improve engines that run more efficiently and therefore pollute less.

2.3 BECOMING A MECHANICAL ENGINEER AND THE LIFELONG LEARNING PROCESS

The mechanical engineer has his or her roots in the millwright who worked in early industrial age industries, such as iron smelters, forges, and textile mills. Millwrights did not have any formal education. However, today, engineering practice requires that mechanical engineers attain formal training.

Formal training for a mechanical engineer is usually attained at a four-year accredited college or university. For the first two years, mechanical engineering students study calculus, chemistry, physics, statics, and dynamics. Many students take the courses covering this material at a two-year college and then transfer to a four-year university. In the last two years of study, students study specialized mechanical engineering topics in machinery, computer-aided design (CAD), computer-aided manufacturing (CAM), thermodynamics, fluid dynamics, materials, and manufacturing processes.

After four years of successful study, the graduate attains a bachelor of science (B.S.). Upon graduation, many students pursue graduate studies and obtain a master of science (M.S.) and a doctor of philosophy (Ph.D.). Some industries, such as the aerospace industry, have traditionally desired engineers with advanced degrees. Many companies are encouraging their employees to pursue graduate studies, and often they pay for their employees' tuition.

Learning for a mechanical engineer does not stop upon graduation, whatever the degree. Learning is a lifelong experience. Because mechanical engineers find employment in areas stressing technology and technology changes over time, it is important that the mechanical engineer continue the educational process throughout his or her career.

Beyond the formal education at a university, additional education occurs from the first day the mechanical engineer steps into his or her place of employment. This may involve specific methods used by the employer. Quite often, the employer will train the employee in areas that are too focused for study at the university level, but necessary in the job.

Mechanical engineering societies also play a role in the continued learning process by offering training seminars and opportunities to meet other engineers. The American Society of Mechanical Engineers (ASME) is the primary professional organization, but mechanical engineers also belong to other societies. Some of these societies are listed in Table 2-1 along with their Internet Web addresses.

TABLE 2-1 Web Site Addresses for Organizations with Mechanical Engineer Members

Organization	Address
American Astrononautical Society	www.aas.org
American Institute of Aeronautics and Astronautics	www.aiaa.org
American Society for Testing and Materials	www.astm.org
American Society of Heating, Refrigeration, and Air-Conditioning Engineers	www.ashrae.org
American Society of *Mechanical Engineer*s	www.asme.org
Society of Automotive Engineers	www.sae.org
Society of Manufacturing Engineers	www.sme.org
Society of Petroleum Engineers	www.spe.org

Many universities will have student chapters of these societies. Participation in one or more of these societies is encouraged, because it helps to build ties with the profession. The societies often sponsor student design competitions, which can be very rewarding and fun. The cost for a student to join one of the societies is usually very low.

2.4 APPROACHING AND SOLVING AN ENGINEERING PROBLEM

Mechanical engineers are problem solvers. The mechanical engineer uses techniques honed during training to evaluate a physical system, model the system using known principles, and solve for the unknowns. To be a successful mechanical engineer, you must develop these problem-solving skills early in your academic career.

Students tend to have difficulty with word problems. The following sequences of steps may be used to approach and solve such problems:

1. Read through the problem statement at least twice.
2. Identify the known and unknown quantities. The known quantities are used to solve the problem for the unknown quantities.
3. Sketch a diagram of the problem. This will help you to see what the problem is all about.
4. Translate the words in the problem to a mathematical statement. In doing this, look for key words that convey the concepts of the problem. For example, "twice b" implies $2b$; "is," "was," and "becomes" all mean "=."
5. Solve for the unknowns using the appropriate mathematical techniques.
6. Check your answer to see if it is mathematically correct.

Example 2.1 What number added to nine is four times the number?

SOLUTION

Step 2

The problem is actually looking for an unknown number. Let this number be called x.

Step 4

We determine the necessary equation by recognizing that "added to" means " + ," "is" means " = ," and "times" means " × ." Thus, we have

$$x + 9 = 4x.$$

Step 5

We can solve this equation using simple algebra

$$x + 9 = 4x.$$

$$(1 - 4)x = -9$$

$$\therefore x = 3.$$

Step 6

We check our result by substituting the number back into the original expression:

$$3 + 9 = 4(3)$$

$$12 = 12.$$

PRACTICE!

Find two numbers such that their difference is five and whose sum is also five.

PROFESSIONAL SUCCESS

A good engineer always checks to see if the results obtained from a calculation makes sense. This goes beyond checking for calculation errors by substituting the number back in to the original expression, as was done in step 6 of *** ” on page 27 ***. It also involves considering whether the result makes physical sense. This is especially true when using complicated computer programs such as finite-element programs to solve for unknown quantities. For example, suppose that a study is undertaken to determine the loads on the structure of a new building due to a heavy snowfall. One would expect that a large amount of snow on the roof of the building would cause the structure of the building to be compressed. Now suppose that after running a computer program you find that the net result is for the building to extend in height! Obviously, something is wrong and the results obtained are impractical at best. At this point, you would need to discard the solution and investigate exactly what went wrong.

2.5 SUMMARY

Studying at an accredited college or university helps the student attain formal training to become a mechanical engineer. The topics studied range from math and science to specialized courses in mechanical engineering. Many students, upon graduation, seek advanced degrees.

Whatever the degree, learning for a mechanical engineer does not stop upon graduation. Learning is a lifelong experience. Often, a mechanical engineer is trained on the job with respect to special tasks necessary to complete his or her duties. Also, because mechanical engineers work with technology that is ever changing, the successful engineer must keep abreast of the current state of technology.

Mechanical engineers are problem solvers who are employed in a wide variety of areas. They work in a team environment, often with professionals from other disciplines. Mechanical engineers work in many industries, often developing everyday products. They are also employed in government, doing research, and in academia, teaching the next generation of engineers. Thus, mechanical engineers play an important role in society.

KEY TERMS

Lifelong Learning   mechanical engineer   solving problems

Problems

For Question 1, Question 2, Question 3, Question 4, and Question 5, ask an instructor or a mechanical engineer to discuss the topics presented. Then, for each topic, write a paragraph that includes the ideas discussed by the professional, detailing what role each topic plays in mechanical engineering. Also, include comments on the types of engineering problems that the engineer might face and have to solve related to the topic.

1. How are principles from fluid mechanics used in the design of automobiles to reduce fuel consumption?
2. How is the theory of solid mechanics used to design structural components such as automobile and aircraft panels? What are some of the assumptions in the development of this theory? How do these assumptions influence analysis and design of these structural components?
3. What principles from the theory of thermodynamics are used to design fossil-fuel power generation plants? What parameters from the theory of thermodynamics influence the efficiency of these plants?
4. How is the theory heat transfer used to design mechanisms to efficiently remove heat from small engines?
5. What mechanisms are used in the design of a recliner? What are the principles of dynamics that are used in the design of these mechanisms?

For Question 6, Question 7, Question 8, and Question 9, use the steps in Section 2.3 to solve the word problems.

6. Find a number whose triple is eight more than the result of adding the original number plus five.
7. Find two consecutive integers whose sum is three times the smaller number.
8. What number added to 10 is the same as one-third the number.
9. A box is to be constructed from cardboard so that each face is a square. Suppose that the total surface area of the box is 2000 cm^2. What is the size of each face?

3

Engineers and the Real World

SECTIONS

- 3.1 Society's View of Engineering
- 3.2 How Engineers Learn From Mistakes
- 3.3 The Role of Failure in Engineering Design: Case Studies
- 3.4 Preparing for Failure in Your Own Design
- Key Terms
- References

OBJECTIVES

- 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

3.1 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 destined for 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. No TV show or movie has ever highlighted an engineer as the main character. Rather, engineers are always portrayed as either the brains behind some villain's master plot or the nerdy fellow 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 tout the faults of 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. The reason the public views engineers with apprehension may be due to the following fact: *Engineers do the 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 out of his hip pocket, flip open the cover, and talk to anyone in the world was pure science fiction. Now this scenario is a reality. You can go out today, buy a tiny, relatively inexpensive cell phone that fits in your pocket, and call anyone in the world who has a telephone.

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 that safely brought the astronauts back to earth.

As an engineer-to-be, you will 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 in town 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 as residents who will be most able to 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 newspaper in the Midwest ran a story about a father who got 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 in the town.

Misconception: Although the cell phone instruments themselves are wireless, the signals are sent to nearby cell-phone towers where they are routed thereafter to the telephone network by wires. In rural communities, these wires are most certainly overhead wires that would be 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 is made to resonate in the presence of a magnetic field. The physics involved 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 Web site *napster.com*. Amidst the discussion, an editorial appeared in a college 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.

Radio advertisement for a Palm VII: The Palm Pilot™ has become a favorite personal digital assistant for many individuals. The Palm VII model includes cell-phone like capability that forms a wireless link to a subscriber Web provider. An advertisement that aired in 2001 featured a wayward sole who gets locked in a meat freezer and uses his wireless Palm VII to send an e-mail message asking for help.

Misconception: Meat lockers are invariably made with solid 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: The Avon 3-Day Breast Cancer walk is an annual spring fund-raising event that takes place in many cities around the United States. 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 Boston 2000 event, which included about 2,500 walkers, the entire local cell network crashed after several hundred walkers and several hundred picker-uppers 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 only a few dozen channel frequencies and local lines 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 break 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 on used in photocopiers ("xerox" machines) except that in the latter, a broad flash of bright light it used to condition the drum to hold toner particles in the desired places.

3.2 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. Having decided to enter the design competition, 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 out 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 3.1. 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!

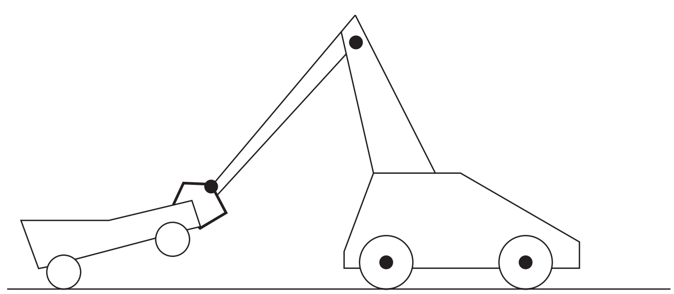

Figure 3.1 Hypothetical, impossible-to-build car design includes an articulated arm.

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*.

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 an electronic circuit or machine doesn't work because stray 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 after failure provides an important path to optimizing the final product and gives engineers needed time to correct deficiencies and work out *bugs* .[1]

A more realistic version of the paragraph appearing at the start of this section might resemble the following:

> 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. Eventually, 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 that they return to the machine shop 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 available in the computer lab, 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 of Figure 3.2 for their offensive strategy.

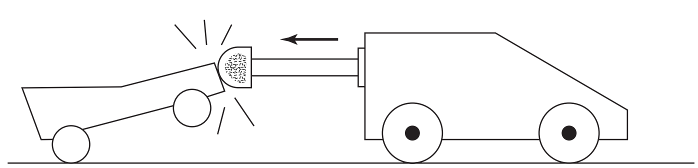

Figure 3.2 More realistic battering ram design as an offensive strategy.

[1] The term "bug" was coined by Adm. Grace Hopper in 1945. In the early days of computers, logic gates were made from electromechanical relay switches rather than transistors. A moth flew inside one such computer, got stuck between two relay contacts, and prevented seemingly closed relay contacts from making a true connection. The computer malfunctioned because of the "bug."

3.3 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 judgement. 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.

The failure examples to follow all had dire consequences. Each occurred once the product was in use, long after the initial design, test, and evaluation phases. 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 failure to avoid them was 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. Indeed, 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.

3.3.1 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, support 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 support 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. 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 3.3. After several hours, the bridge crumbled as if it were made from dry clay; not a piece remained between the two main center spans.

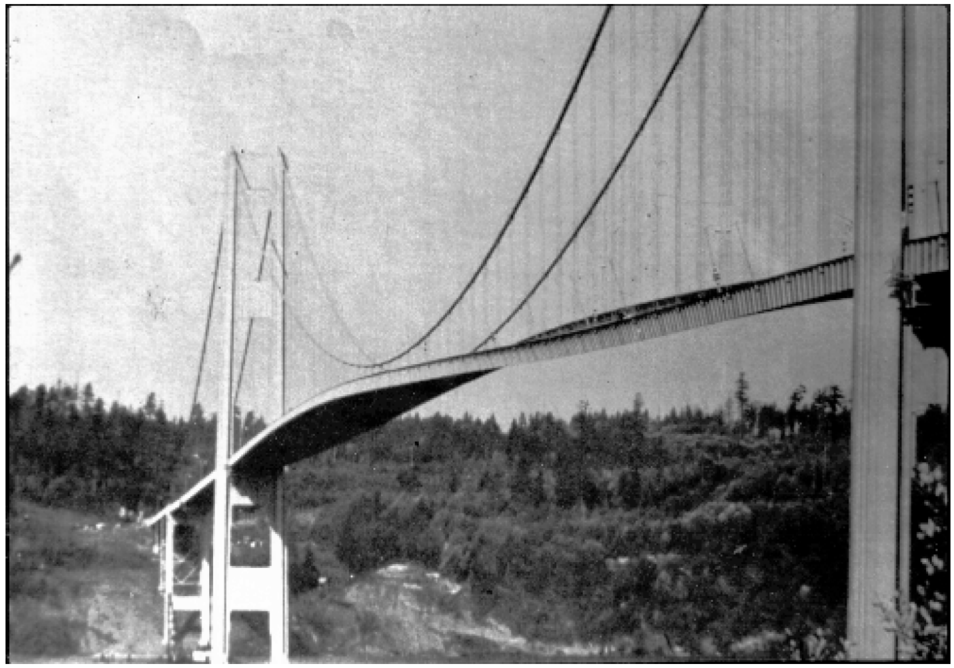

Figure 3.3 The Tacoma Narrows Bridge in torsional vibration.

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.

3.3.2 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 been built before. Its roof was made from a space frame structure of interconnected rods and ball sockets, much like a child's construction toy. Hundreds of rods were interconnected in a visually appealing geodesic pattern like the one shown in Figure 3.4. 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 slow large-mainframe computers.

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 judgement and intuition gleaned from years of construction practice. Instead, they relied on computer models of their new space frame design. 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 text-

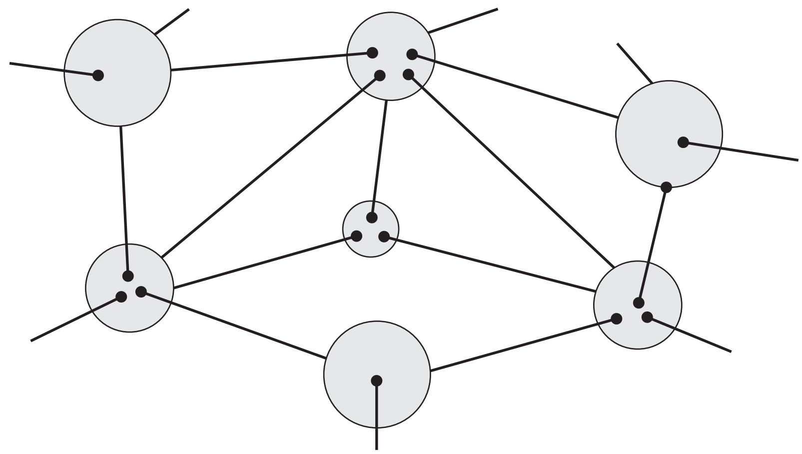

Figure 3.4 Geodesic, rod-and-ball socket construction.

books. Not one of the programmers had ever actually built a roof truss. All failed to include basic derating factors at the structural joints to account for the slight changes in layout (e.g., minor variations in angles, lengths, and torsion) that occur when a complex structure is actually built. The design engineers trusted the output of computer models that never had been fully tested on actual construction. Under normal roof load, many ball-and-socket joints were stressed beyond their calculated limits. The addition of a heavy snow load to the roof load proved too much for the structure to bear.

3.3.3 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 3.5]. 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 operated in cold weather, and on that particular day, it was about 28°F (–2°C), a very cold day for Florida. The frozen 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. 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 3.6, the engineers had relied on a standard design technique for rockets. The Challenger's booster rockets, however, were much larger than any on which O-rings had been used before. 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 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

Figure 3.5 The Space Shuttle *Challenger* explodes during launch. (Photo courtesy of RJS Associates.)

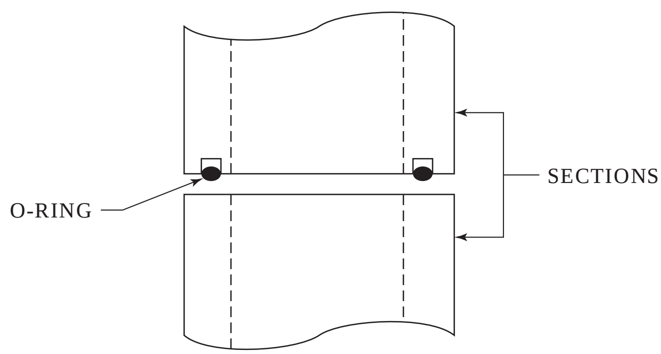

Figure 3.6 Schematic depiction of O-ring seals.

of appropriate 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. The decision by NASA to award the contract to the Utah company resulted in a multisection, O-ring-sealed booster rocket whose smaller pieces would 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 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 were compromised into a less-than-desirable design concept that had never before been attempted on something so large.

3.3.4 Case 4: Kansas City Hyatt

If you've ever been inside a Hyatt hotel, you know that their internal architectures are very unique. The typical Hyatt hotel has cantilevered floors that form an inner trapezoidal atrium, and the walkways and halls are open, inviting structures. There's nothing quite like the inside of a Hyatt. 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 3.7.

Each box beam was to be held up 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 structure as specified was not a realistic structure 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 having no threads. Threading reduces the diameter of a rod, so it's impossible to get a nut to the middle of a rod unless the rod is threaded for at least half its length. In order to construct the walkway as specified, each rod would have to be threaded along about 20 feet of its length, 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 3.8.

The problem with this modification is that the nut (A) at the lower end of the upper rod now had to support the weight of *both* walkways. A good analogy would be 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 grabbed the ankles of the upper climber instead of the rope, 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 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

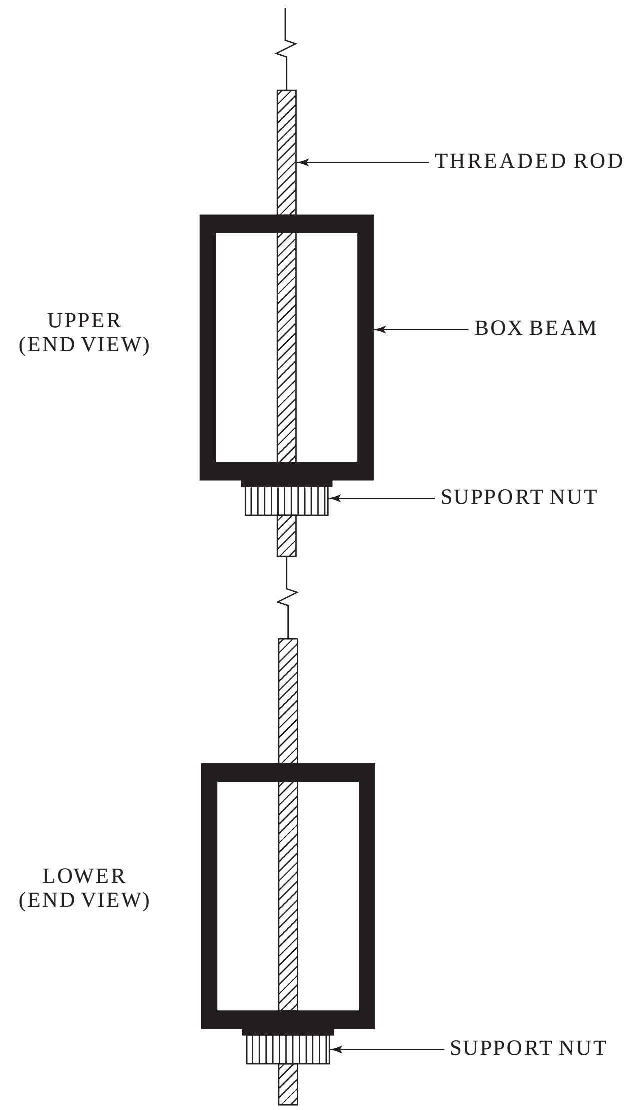

Figure 3.7 Kansas City Hyatt walkway support structure as designed.

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 as a way of gaining a feeling for how things are made in the real world.

Regardless of who was at fault, the design also left little room for *safety margins*. It's 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 a safety margin of a factor of two or more, 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.

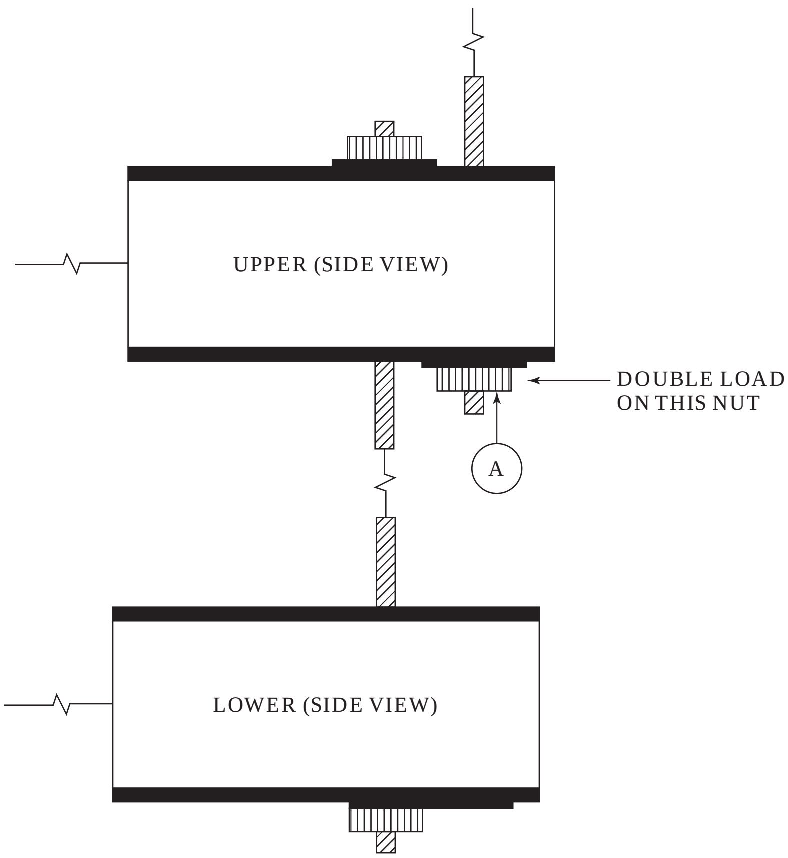

Figure 3.8 Kansas City Hyatt walkway support structure as actually built.

The construction supervisor, unaware of the structural implications, but wishing to see the job to completion, ordered a small, seemingly innocent, but ultimately fatal, change in the construction method. Had but one of the design engineers ever spent time working on a construction site, this shortcoming might have been discovered. Errors such as the one that occurred at the Kansas City Hyatt can be prevented by including workers from all phases of construction in the design process, ensuring adequate communication between all levels of employees, and adding far more than minimal safety margins where public safety is at risk.

3.3.5 Case 5: Three Mile Island

Three Mile Island was a large nuclear power plant in Pennsylvania (see Figure 3.9). It was the sight of the worst nuclear accident in the United States and nearly comparable to the total meltdown at Chernobyl, Ukraine. Fortunately, the incident at Three Mile Island resulted in only a near miss at a meltdown, but it also led to the shutting down and trashing of a billion-dollar electric power plant and significant loss of electrical generation capacity on the power grid in the eastern United States.

On the day of the accident, a pressure buildup occurred inside the reactor vessel. It was normal procedure to open a relief valve in such situations 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. The designer of the electrical control

Figure 3.9 Three Mile Island power plant.

system had made one critical mistake. As suggested by the schematic diagram shown in Figure 3.10, indicator lights in the control room lit up when power was applied to or removed from the valve actuator coil, but the control panel gave no indication about the *actual* position of the valve. After a 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 room indicated the valve to be closed, it was actually stuck open. The mechanical spring responsible for closing the valve did not have enough force to overcome the sticking force. While the operators, believing the valve to be closed, tried to diagnose the problem, 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.

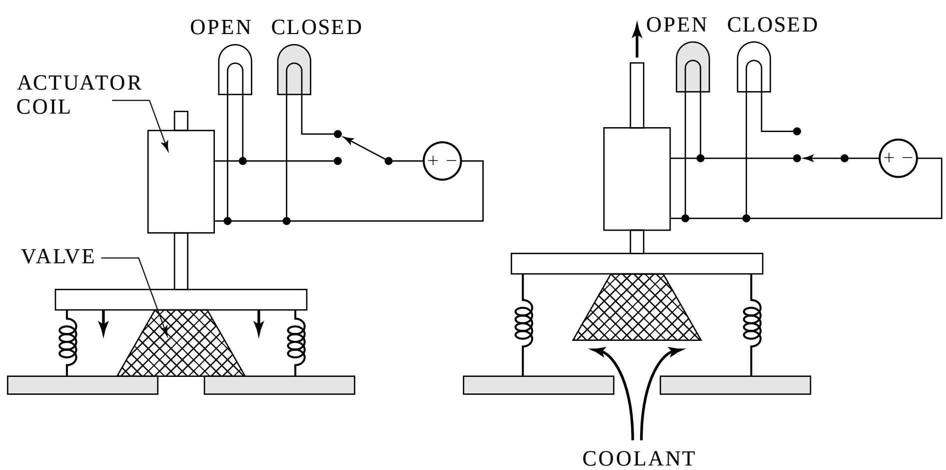

Figure 3.10 Valve indicator system as actually designed.

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, would be during an emergency when the need for absolutely accurate information would be 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 been one that included an independent sensor that unambiguously verified the true position of the valve, as suggested by the diagram of Figure 3.11.

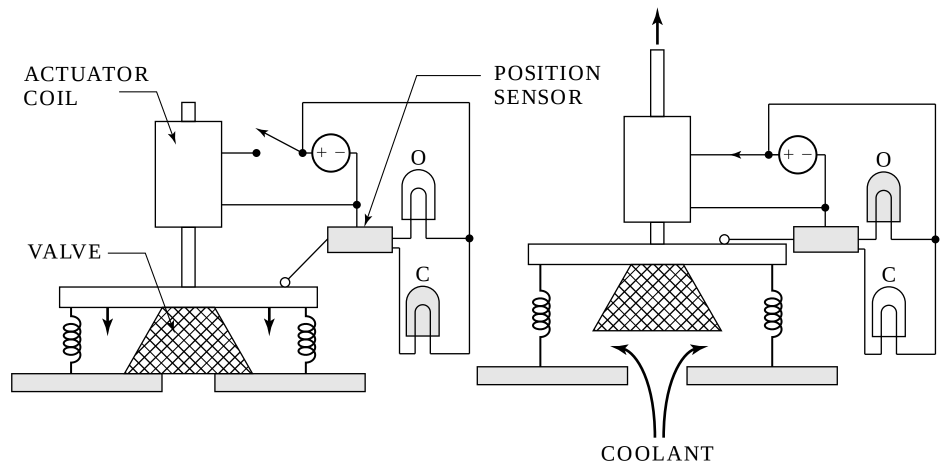

Figure 3.11 Valve indicator system as it should have been designed and built.

3.3.6 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 commonplace 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 anticipating 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 designed by engineers. Critical information, being needed most during crisis situations, 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.

3.3.7 Case 7: Hubble Telescope

The Hubble is an orbiting telescope that 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 optic mirror that compensated for aberrations. The repairs were carried out 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, less-well-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's 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 not possible in the case of the Hubble), a system should be developed and tested in as many different environmental conditions as possible if a chance exists that those conditions will be encountered in the field.

3.3.8 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 of the wreckages 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 rivets holding in the windows developed fatigue cracks, which, after many pressurization and depressurization cycles, grew into large, full-blown cracks in the fuselage. This mode of failure is depicted in Figure 3.12.

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 depressur-

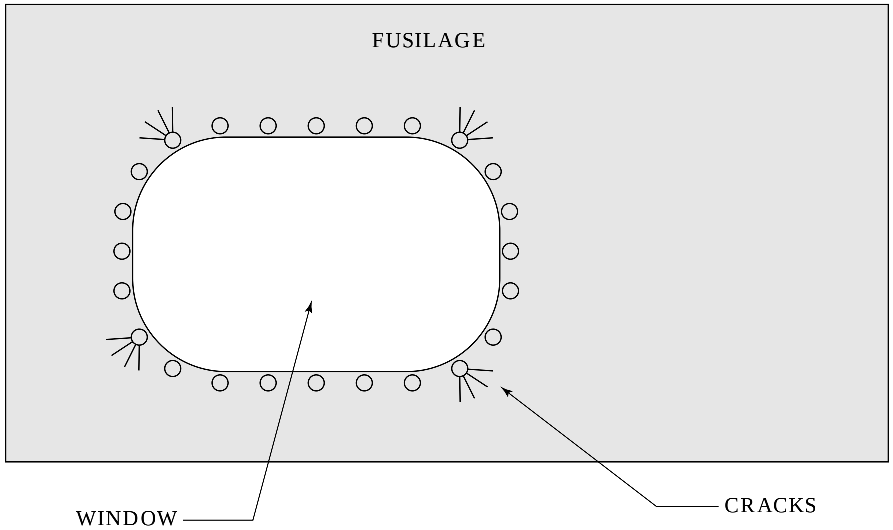

Figure 3.12 Stress cracks around the window rivets of the De Haviland Comet.

ization 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.

3.4 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 what's wrong, 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 bring a product to market 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, including automobiles, computers, and software, develop problems soon after they are released. If you purchase one of these items during the 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.

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KEY TERMS

bugs
flaws
safety margins
failure

Problems

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.

Look up and write a synopsis of the following classic engineering failure incidents:

2. Exxon Bayway refinery, Linden, New Jersey (1990)
3. General Electric rotary compressor refrigerators (1990)
4. Green Bank radio telescope (1989)
5. Union Carbide chemical leak, Bhopal, India (1984)
6. Korean Airlines Flight 007 (1983)
7. Interstate 95 Bridge, Mianus River, Connecticut (1983)
8. Alexander L. Kielland oil platform, North Sea (1980)
9. American Airlines DC-10 (1979)
10. Skylab (1979)
11. The New York City Power Blackout (1976)
12. The windows in the John Hancock Tower, Boston, Massachusetts (1976)
13. Big Ben, London (1976)
14. Bay Area Rapid Transit (BART) (1973)
15. Point Pleasant Bridge, Ohio River, Ohio-West Virginia (1967)
16. The Apollo 1 capsule fire (1967)
17. The Great Northeast Power Blackout (1965)