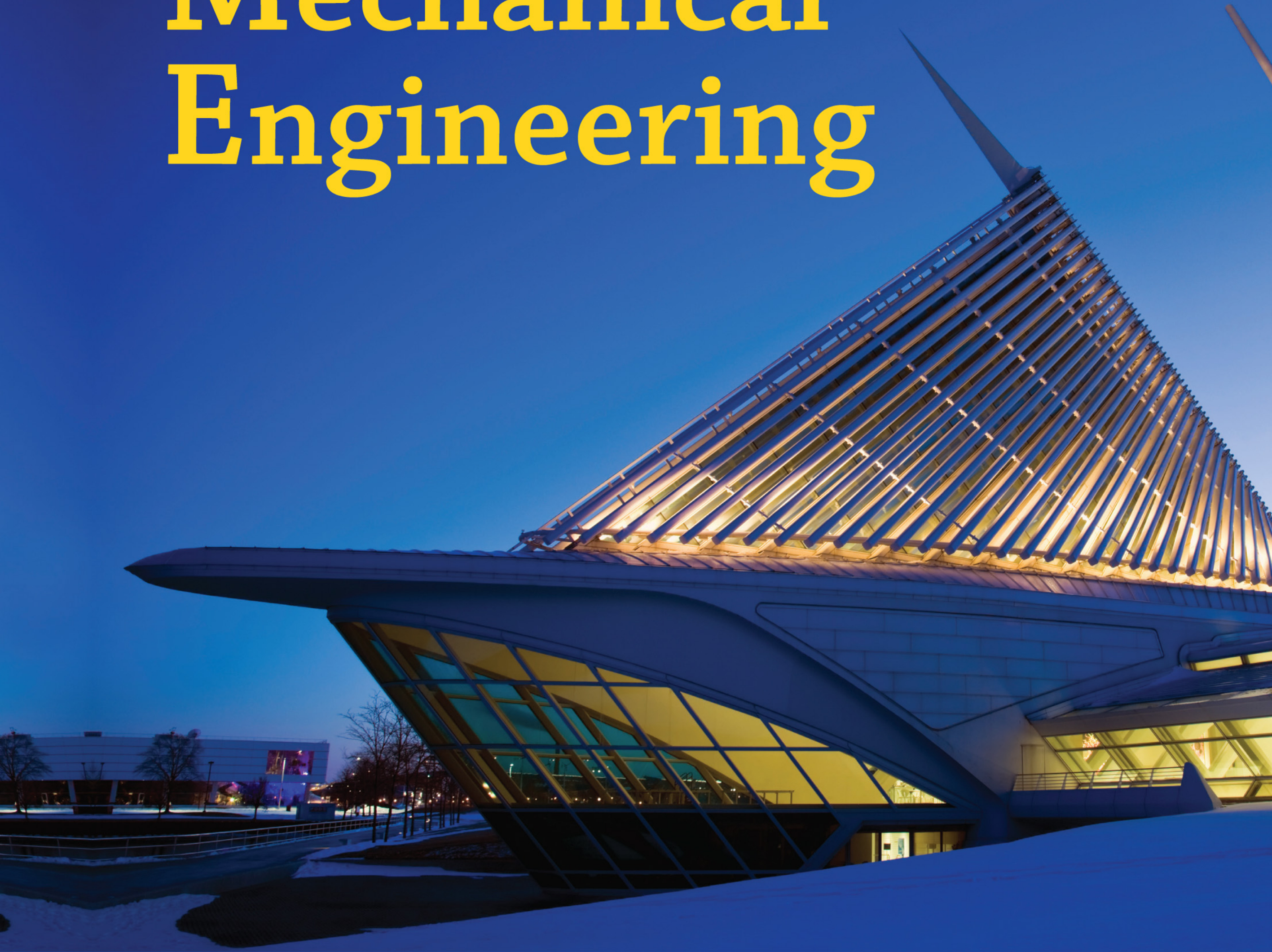
An Introduction to Mechanical Engineering



Fourth Edition

JONATHAN WICKERT | KEMPER LEWIS

Fourth Edition

An Introduction to Mechanical Engineering

Jonathan Wickert
Iowa State University

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Dedication

To Karen and Rebecca for their patience and encouragement throughout this project.

Jonathan Wickert

To the Lord for grace and to Laura, Kamryn, and Kaden for their overwhelming patience, support, and love.

Kemper Lewis

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Student's Preface

Purpose

This textbook will introduce you to the ever-emerging field of mechanical engineering and help you appreciate how engineers design the hardware that builds and improves societies all around the world. As the title implies, this textbook is neither an encyclopedia nor a comprehensive treatment of the discipline. Such a task is impossible for a single textbook, and, regardless, our perspective is that the traditional four-year engineering curriculum is just one of many steps taken during a lifelong education. By reading this textbook, you will discover the "forest" of mechanical engineering by examining a few of its "trees," and along the way you will be exposed to some interesting and practical elements of the profession called mechanical engineering.

Approach and Content

This textbook is intended for students who are in the first or second years of a typical college or university program in mechanical engineering or a closely related field. Throughout the following chapters, we have attempted to balance the treatments of technical problem-solving skills, design, engineering analysis, and modern technology. The presentation begins with a narrative description of mechanical engineers, what they do, and the impact they can have (Chapter 1). Seven "elements" of mechanical engineering are emphasized subsequently in Chapter 2 (Mechanical Design), Chapter 3 (Professional Practice), Chapter 4 (Forces in Structures and Machines), Chapter 5 (Materials and Stresses), Chapter 6 (Fluids Engineering), Chapter 7 (Thermal and Energy Systems), and Chapter 8 (Motion and Power Transmission). Some of the applications that you will encounter along the way include commercial space travel, 3-D printing, Boeing's 787 Dreamliner, medical device design, nanomachines, internal combustion engines, robotics, sports technology, advanced materials, micro-fluidic devices, automatic transmissions, and renewable energy.

What should you be able to learn from this textbook? First and foremost, you will discover who mechanical engineers are, what they do, what technical, social, and environmental challenges they solve with the technologies they create. Section 1.3 details a "top ten" list of the profession's achievements. By looking at this list, you will recognize how the profession has contributed to your day-to-day life and society around the world in general. Second, you will find that engineering is a practical endeavor with the objective of designing things that work, that are cost-effective to manufacture, that are safe to use, and that are responsible in terms of their environmental impact. Third, you will learn some of the calculations, estimates, and approximations that mechanical engineers can perform as they solve technical problems and communicate their results. To accomplish their jobs better and faster, mechanical engineers combine mathematics, science, computer-aided engineering tools, experience, and hands-on skills.

You will not be an expert in mechanical engineering after having read this textbook, but that is not our intention, and it should not be yours. If our objective has been met, however, you will set in place a solid foundation of problem-solving, design, and analysis skills, and those just might form the basis for your own future contributions to the mechanical engineering profession.

Instructor's Preface

Approach

This textbook is intended for a course that provides an introduction to mechanical engineering during either the freshman or sophomore years. Over the past decade, many colleges and universities have taken a fresh look at their engineering curricula with the objective of positioning engineering content earlier in their programs. Particularly for the freshman year, the formats vary widely and can include seminars on "who are mechanical engineers" and "what do they do," innovative design experiences, problem-solving skills, basic engineering analysis, and case studies. Courses at the sophomore level often emphasize design projects, exposure to computer-aided engineering, principles of engineering science, and a healthy dose of mechanical engineering hardware.

Core engineering-science courses (for example, strength of materials, thermodynamics, fluid mechanics, and dynamics) have evolved since the post–World War II era into their present, relatively mature, states. On the other hand, little if any standardization exists among introductory mechanical engineering courses. With limited discipline-specific instructional materials available for such courses, we believe that an important opportunity remains for attracting students, exciting them with a view of what to expect later in their program of study and in their future careers, and providing them with a foundation of sound engineering analysis, technical problem-solving, and design skills.

Objectives

While developing the fourth edition of this textbook, our objective has been to provide a resource that others can draw upon when teaching introductory mechanical engineering to first-year and second-year students. We expect that most such courses would encompass the bulk of material presented in Chapter 1 (The Mechanical Engineering Profession), Chapter 2 (Mechanical Design), and Chapter 3 (Technical Problem Solving and Communication Skills). Based on the level and contact hours of their particular courses, instructors can select additional topics from Chapter 4 (Forces in Structures and Machines), Chapter 5 (Materials and Stresses), Chapter 6 (Fluids Engineering), Chapter 7 (Thermal and Energy Systems), and Chapter 8 (Motion and Power Transmission). For instance, Section 5.5 on materials selection is largely self-contained, and it provides an introductory-level student with an overview of the different classes of engineering materials. Similarly, the descriptions in Sections 7.6 and 7.7 of internal-combustion engines and electrical power plants are expository in nature, and that material can be incorporated in case studies to demonstrate the operation of some important mechanical engineering hardware. Rolling-contact bearings, gears, and belt and chain drives are similarly discussed in Sections 4.6, 8.3, and 8.6.

This textbook reflects our experiences and philosophy for introducing students to the vocabulary, skills, applications, and excitement of the mechanical engineering profession. Our writing has been motivated in part by teaching introductory mechanical engineering courses at our respective universities. Collectively, these courses have included lectures, computer-aided design and manufacturing projects, product dissection laboratories (an example of which is discussed in Section 2.1), and team design projects (many of which have been adapted into the new open-ended design problems at the end of each chapter). A number of vignettes and case studies are also discussed to demonstrate for students the realism of what they are learning, including the "top ten" list of previous mechanical engineering achievements and a list of the top emerging fields in mechanical engineering both developed by the American Society of Mechanical Engineers (Section 1.3), the fourteen "grand challenges" from the National Academy of Engineering (NAE) (Section 2.1); design innovation, patents, and a summary of the recently updated patent protection system in the United States (Section 2.2); the design of the Boeing 787 Dreamliner (Section 2.3); the loss of the *Mars Climate Orbiter* spacecraft and the refueling error on Air Canada Flight 143 (Section 3.1); the Deepwater Horizon oil spill disaster (Section 3.6), the design of a heart implant (Section 4.5); the design of products and materials for extreme environments (Section 5.2); the design of advanced materials for innovation applications (Section 5.5); microfluidic devices (Section 6.2); blood flow in the human body (Section 6.5); sports technology (Sections 6.6 and 6.7); global energy consumption (Section 7.3); renewable energies (Section 7.5); internal combustion engines (Section 7.6); solar power generation and the development of innovative energy solutions through crowdsourcing (Section 7.7); nanomachines (Section 8.3); and advanced geartrains for next generation engines (Section 8.5).

The "Focus on . . ." boxes in each chapter are used to highlight some of these interesting topics and other emerging concepts in mechanical engineering.

Content

We certainly have not intended this textbook to be an exhaustive treatment of mechanical engineering, and we trust that it will not be read in that light. Quite the contrary: In teaching first-year and second-year students, we are ever conscious of the mantra that "less really is more." To the extent possible, we have resisted the urge to add just one more section on a particular subject, and we have tried to keep the material manageable and engaging from the reader's perspective. Indeed, many topics that are important for mechanical engineers to know are simply not included here; this is done intentionally (or, admittedly, by our own oversight). We are confident, however, that students will be exposed to those otherwise omitted subjects in due course throughout the remainder of their engineering curricula.

In Chapters 2 through 8, we have selected a subset of mechanical engineering "elements" that can be sufficiently covered for early students to develop useful design, technical problem-solving, and analysis skills. The coverage has been chosen to facilitate the textbook's use within the constraints of courses having various formats. While there is more material here than can be comfortably covered in a single semester, instructors should find a reasonable menu from which to choose. In particular, we have selected content that we have found to

1. Match the background, maturity, and interests of students early in their study of engineering
2. Expose students to the significance of mechanical design principles in the development of innovative solutions to technical challenges that face our global societies.
3. Help students think critically and learn good problem-solving skills, particularly with respect to formulating sound assumptions, making order-of-magnitude approximations, performing double-checks, and bookkeeping proper units
4. Convey aspects of mechanical engineering science and empiricism that can be applied at the freshman and sophomore levels
5. Expose students to a wide range of hardware, innovative designs, engineering technology, and the hands-on nature of mechanical engineering
6. Generate excitement through applications encompassing space flight, 3-D printing, Boeing's 787 Dreamliner, medical device design, nanomachines, engines, robotics, sports technology, consumer products, advanced materials, micro-fluidic devices, automotive transmissions, renewable energy generation, and more

To the extent possible at the freshman and sophomore levels, the exposition, examples, and homework problems have been drawn from realistic applications. You will find no masses on inclined planes or block-and-tackle systems in this textbook. Because we find engineering to be a visual and graphical activity, we have placed particular emphasis on the quality and breadth of the nearly three hundred photographs and illustrations, many of which were provided by our colleagues in industry, federal agencies, and academe. Our view has been to leverage that realism and motivate students through interesting examples that offer a glimpse of what they will be able to study in later courses and, subsequently, practice in their own careers.

New in the Fourth Edition

In preparing this fourth edition, we have made many of the types of changes that one would expect: Sections have been rewritten and reorganized, new material has been added, some material has been removed, new examples problems have been created, and small mistakes have been corrected. Over 20 new homework problems have been developed and over 30 new figures have been included. We are excited about the new homework problems as they are all open-ended problems whose solutions depends upon the set of assumptions made. While these problems do not have a single correct answer, there are better answers and worse answers. Therefore, students are challenged to consider their problem-solving approach, the validity of their assumptions, and the appropriateness of their answers. These new problems are included as the last homework problems in each chapter and have been developed to be used in group settings, including flipped classroom environments. These larger open-ended problems are denoted with an asterisk "*".

We have attempted to remain faithful to the philosophy of the first three editions by emphasizing the importance of the mechanical engineering profession to solving global problems, including new information in Chapter 1 on recent professional trends, technology development, traditional and emerging mechanical engineering career paths, and knowledge areas. Also, in Chapter 1, we update, in Figure 1.2, the energy range that mechanical engineers are creating devices or machines to produce and/or consume. We tighten the presentation of the top past accomplishments in mechanical engineering and add a discussion about the top emerging fields within mechanical engineering adapted from a recent report from ASME.

In Chapter 2, new material is included on global design patents, and the new patent law in the United States. The previous case studies from Chapter 2 and one from Chapter 6 have now been moved to the companion student website.

Throughout the book, we have continued the use of the improved pedagogical format comprising the problem's statement, approach, solution, and discussion. In particular, the discussion portion is intended to highlight why the numerical answer is interesting or why it makes intuitive sense. Symbolic equations are written alongside the numerical calculations. Throughout the textbook, the dimensions appearing in these calculations are explicitly manipulated and canceled in order to reinforce good technical problem-solving skills.

The "Focus on . . ." boxes contain topical material, either conceptual or applied, that broadens the textbook's coverage without detracting from its flow. New topics in the "Focus on . . ." boxes include the emerging career opportunities for mechanical engineers; product archaeology "digs"; global design teams; the types of engineering estimations used in predicting the oil flow rates during the Deepwater Horizon disaster; ineffective communication practices using illustrative technical charts; innovative design opportunities that arise from engineering failure analysis; design of devices for extreme environments; development of new engineering materials; the crowdsourcing of innovative solutions to global energy challenges; and the design of advanced automotive geartrains to address fuel economy standards.

As was the intent with the first three editions, we have attempted to make the fourth edition's content readily accessible to any student having a conventional secondary school background in mathematics and physics. We have not relied on any mathematics beyond algebra, geometry, and trigonometry (which is reviewed in Appendix B), and in particular, we have not used any cross-products, integrals, derivatives, or differential equations. Consistent with that view, we have intentionally not included a chapter that addresses the subjects of dynamics, dynamic systems, and mechanical vibration (ironically, my own areas of specialization). We remain focused on the earliest engineering students, many of whom will be studying calculus concurrently. Keeping those students in mind, we feel that the added mathematical complexity would detract from this textbook's overall mission.

Supplements

Supplements for instructors are available on the Instructor's Resource Center at sso.cengage.com.

- Case Studies: We have shifted some of the case studies in previous editions to the student website without any loss of content in the text. The case studies were longer design applications of the chapter concepts and as such, they function well as effective reference information for the students who want to explore the chapter concepts further.
- Instructor's Solutions Manual: As was the case with the first three editions, the fourth edition is also accompanied by a detailed Instructor's Solutions Manual. With the exception of some "open-ended" problems at the end of each chapter, the manual contains a solution to each of the numerical problems in this textbook. The description and style of these solutions (stating the problem, writing a brief approach, making appropriate assumptions, making sketches, carrying out calculations, keeping track of units and significant figures, checking one's work, discussing the validity of the solution, and so forth) are intended to guide students with respect to the formatting of their own work.
- Lecture Note PowerPoints: We have created PowerPoint presentations for each chapter that capture the primary teaching points, along with a number of the figures and tables from the chapters.

MindTap Online Course

The MindTap includes these additional features: Digital Digs, chapter study guides, and videos.

This textbook is also available online through Cengage Learning's MindTap, a personalized learning program. Students who purchase the MindTap have access to the book's multimedia-rich electronic Reader and are able to complete homework and assessment material online, on their desktops, laptops, or iPads. The new MindTap Mobile App makes it easy for students to study anywhere, anytime. Instructors who use a Learning Management System (such as Blackboard or Moodle) for tracking course content, assignments, and grading, can seamlessly access the MindTap suite of content and assessments for this course.

With MindTap, instructors can:

- Personalize the Learning Path to match the course syllabus by rearranging content or appending original material to the online content
- Connect a Learning Management System portal to the online course and Reader
- Highlight and annotate the digital textbook, then share their notes with students.

- Customize online assessments and assignments
- Track student engagement, progress and comprehension
- Promote student success through interactivity, multimedia, and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes in the digital Reader, study from and create their own Flashcards, highlight content for easy reference, and check their understanding of the material through practice quizzes and automatically-graded homework.

Acknowledgments

It would have been impossible to develop the four editions of this textbook without the contributions of many people and organizations, and at the outset, we would like to express our appreciation to them. Generous support was provided by the Marsha and Philip Dowd Faculty Fellowship, which encourages educational initiatives in engineering. Adriana Moscatelli, Jared Schneider, Katie Minardo, and Stacy Mitchell, who are now alumni of Carnegie Mellon University, helped to get this project off the ground by drafting many of the illustrations. The expert assistance provided by Ms. Jean Stiles in proofreading the textbook and preparing the *Instructor's Solutions Manual* was indispensable. We very much appreciate the many contributions she made.

Our colleagues, graduate students, and teaching assistants at Iowa State University, Carnegie Mellon and the University at Buffalo—SUNY provided many valuable comments and suggestions as we wrote the editions. We would specifically like to thank Adnan Akay, Jack Beuth, Paul Steif, Allen Robinson, Shelley Anna, Yoed Rabin, Burak Ozdoganlar, Parker Lin, Elizabeth Ervin, Venkataraman Kartik, Matthew Brake, John Collinger, Annie Tangpong, Matthew Iannacci, James Lombardo, Phil Odonkor, Erich Devendorf, Phil Cormier, Aziz Naim, David Van Horn, Brian Literman, and Vishwa Kalyanasundaram for their comments and help. We are likewise indebted to the students in our courses: Fundamentals of Mechanical Engineering (Carnegie Mellon), Introduction to Mechanical Engineering Practice (University at Buffalo—SUNY), and Design Process and Methods (University at Buffalo—SUNY). Their collective interest, feedback, and enthusiasm have always provided much-needed forward momentum. Joe Elliot and John Wiss kindly offered the engine dynamometer and cylinder pressure data to frame the discussion of internal-combustion engines in Chapter 7. Solutions to many of the homework problems were drafted by Brad Lisien and Albert Costa and we appreciate their hard work and conscientious effort.

In addition, the following reviewers of the first, second, third, and fourth editions were kind enough to let us benefit from their perspectives and teaching experience: Terry Berreen, Monash University; John R. Biddle, California State Polytechnic University at Pomona; Terry Brown, University of Technology (Sydney); Peter Burban, Cedarville University; David F. Chichka, George Washington University; Scott Danielson, Arizona State University; Amirhossein Ghasemi, University of Kentucky; William Hallett, University of Ottawa; David W. Herrin, University of Kentucky; Robert Hocken, University of North Carolina

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On all counts, we have enjoyed interacting with the editorial staff at Cengage Learning. As the textbook's publisher and developmental editor, Tim Anderson and Mona Zeftel were committed to developing a high-quality product, and it has been a continuing pleasure to collaborate with them. The fourth edition's production team included Jean Buttrom, Michelle Kunkler, Kristiina Paul, Alex Sham, and the staff of RPK Editorial Services. They managed production with skill and professionalism and with a keen eye for detail. To each, we express our thanks for a job well done.

Colleagues at the following industrial, academic, and governmental organizations were remarkably helpful and patient in providing us with photographs, illustrations, and technical information: General Motors, Intel, Fluent, General Electric, Enron Wind, Boston Gear, Mechanical Dynamics, Caterpillar, NASA, NASA's Glenn Research Center, W. M. Berg, FANUC Robotics, the U.S. Bureau of Reclamation, Niagara Gear, Velocity11, Stratasys, National Robotics Engineering Consortium, Lockheed-Martin, Algor, MTS Systems, Westinghouse Electric, Timken, Sandia National Laboratories, Hitachi Global Storage Technologies, Segway LLC, the U.S. Department of Labor, and the U.S. Department of Energy. We've surely not listed everyone who has helped us with this endeavor, and we apologize for any inadvertent omissions that we may have made.

About the Authors

Photo courtesy of Dave Gieseke

Jonathan Wickert

Jonathan Wickert serves as Senior Vice President and Provost at Iowa State University and is responsible for the university's educational, research, and extension and outreach programs. He previously served as department chair and dean at Iowa State, and before then was a member of the faculty at Carnegie Mellon University. Dr. Wickert received his B.S., M.S., and Ph.D. degrees in mechanical engineering from the University of California, Berkeley, and he was a postdoctoral fellow at the University of Cambridge. The Society of Automotive Engineers, the American Society for Engineering Education, and the Information Storage Industry Consortium have recognized Dr. Wickert for his teaching and research, and he was elected a fellow of the American Society of Mechanical Engineers and the National Academy of Inventors. As a researcher and consultant in the field of mechanical vibration, he has worked with companies and federal agencies on a diverse range of technical applications including computer data storage; the manufacture of sheet metal, fiberglass, polymers, and industrial chemicals; automotive brakes; radial flow gas turbines; and consumer products.

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Kemper Lewis

Kemper Lewis serves as Chair of the Mechanical and Aerospace Engineering Department at the University at Buffalo – SUNY where he also holds a faculty appointment as Professor. He teaches and conducts research in the areas of mechanical design, system optimization, and decision modeling. As a researcher and consultant, he has worked with companies and federal agencies on a wide range of engineering design problems including turbine engine product and process design; optimization of industrial gas systems; air and ground vehicle design; innovation in consumer product design; and manufacturing process control for thin film resistors, heat exchangers, and medical electronics. Dr. Lewis received his B.S. in mechanical engineering and B.A. in Mathematics from Duke University and his M.S., and Ph.D. degrees in mechanical engineering from the Georgia Institute of Technology. He has served as associate editor of the ASME Journal of Mechanical Design, on the ASME Design Automation Executive Committee, and on the National Academies Panel on Benchmarking the Research Competitiveness of the United States in Mechanical Engineering. Dr. Lewis has received awards in recognition of his teaching and research from the Society of Automotive Engineers, the American Society for Engineering Education, the American Institute of Aeronautics and Astronautics, and the National Science Foundation. He also was elected fellow of the American Society of Mechanical Engineers.

CHAPTER 1

The Mechanical Engineering Profession

CHAPTER OBJECTIVES

1-1 Describe some of the differences among engineers, mathematicians, and scientists.

1-2 Discuss the type of work that mechanical engineers do, list some of the technical issues they address, and identify the impact that they have in solving global, social, environmental, and economic problems.

1-3 Identify some of the industries and governmental agencies that employ mechanical engineers.

1-4 List some of the products, processes, and hardware that mechanical engineers design.

1-5 Recognize how the mechanical engineering profession's "top ten" list of achievements has advanced our society and improved day-to-day lives.

1-6 Understand the objectives and format of a typical curriculum for mechanical engineering students.

1.1 Overview

In this introductory chapter, we describe who mechanical engineers are, what they do, what their challenges and rewards are, what their global impact can be, and what their notable accomplishments have been. Engineering is the practical endeavor in which the tools of mathematics and science are applied to develop cost-effective solutions to the technological problems facing our society. Engineers design many of the consumer products that you use every day. They also create a large number of other products that you do not necessarily see or hear about because they are used in business and industrial settings. Nevertheless, they make important contributions to our society, our world, and our planet. Engineers develop the machinery that is needed to manufacture most products, the factories that make them, and the quality control systems that guarantee the product's safety and performance. Engineering is all about making useful things that work and impact lives.

The Elements of Mechanical Engineering

The discipline of mechanical engineering is concerned in part with certain “elements”:

- Design (Chapter 2)
- Professional Practices (Chapter 3)
- Forces (Chapter 4)
- Materials (Chapter 5)
- Fluids (Chapter 6)
- Energy (Chapter 7)
- Motion (Chapter 8)

Mechanical engineers invent machines and structures that exploit those elements in order to serve a useful purpose and solve a problem. Original design and the practical issue of making something that works are the themes behind any engineering endeavor. An engineer creates a machine or product to help someone solve a technical problem. The engineer might start from a blank sheet of paper, conceive something new, develop and refine it so that it works reliably, and—all the while—satisfy the constraints of safety, cost, and manufacturability.

Robotic welding systems (Figure 1.1), internal combustion engines, sports equipment, computer hard disk drives, prosthetic limbs, automobiles, aircraft, jet engines, surgical tools, and wind turbines are some of the thousands of technologies that mechanical engineering encompasses. It would not be much of an exaggeration to claim that, for every product you can imagine, a mechanical engineer was involved at some point in its design, materials selection, temperature control, quality assurance, or production. Even if a mechanical engineer didn’t conceive or design the product per se, it’s still a safe bet that a mechanical engineer designed the machines that built, tested, or delivered the product.

Mechanical engineering has been defined as the profession in which power-producing and power-consuming machines are researched, designed, and manufactured. In fact, mechanical engineers devise machines that produce or consume power over the remarkably wide scale shown in Figure 1.2, ranging from

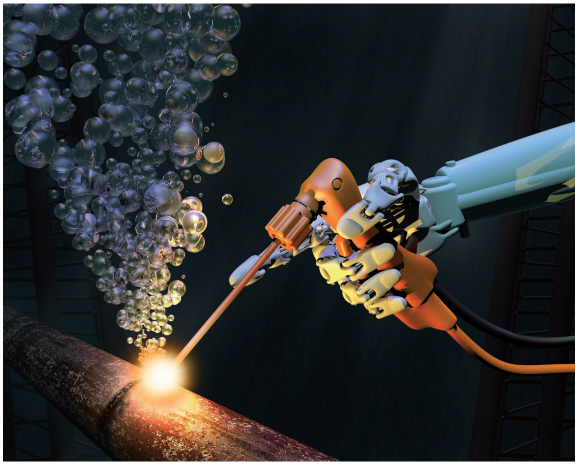

Figure 1.1

Robots are used in environments that require precise and repetitive tasks such as industrial assembly lines and in extreme environments like this deep sea repair on a corroded pipe.

Paul Fleet/Shutterstock.com

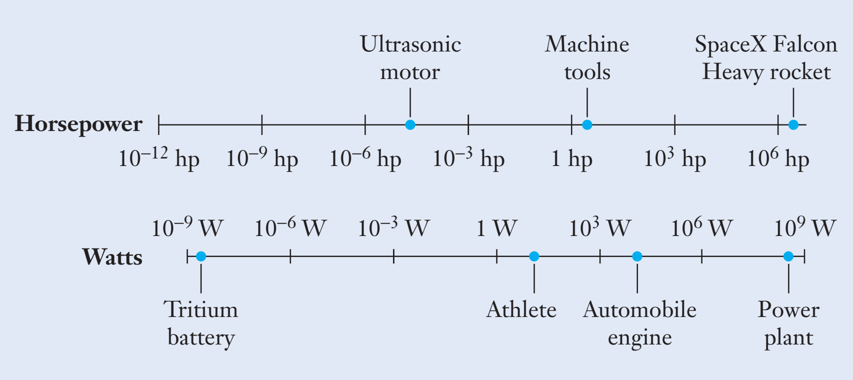

Figure 1.2

Mechanical engineers work with machines that produce or consume power over a remarkably wide range.

nanowatts (nW) to gigawatts (GW). Few professions require a person to deal with physical quantities across so many orders of magnitude (one quintillionfold or a factor of 1,000,000,000,000,000,000), but mechanical engineering does. At the lower end of the power range, batteries powered by the decay of the hydrogen isotope tritium can generate nanowatts of power for sensors, electronic equipment, and small precision ultrasonic motors, such as those used in a camera's autofocus lens. Moving upward in power level, an athlete using exercise equipment, such as a rowing machine or a stair climber, can produce up to several hundred watts (about 0.25–0.5 horsepower [hp]) over an extended period of time. The electric motor in an industrial drill press might develop 1000 W, and the engine on a sport utility vehicle is capable of producing about 100 times that amount of power. At the upper end of the scale, SpaceX's Falcon Heavy rocket (Figure 1.3) produces approximately 1,800,000 hp at liftoff. Finally, a commercial electrical power plant can generate one billion watts of power, which is an amount sufficient to supply a community of 800,000 households with electricity.

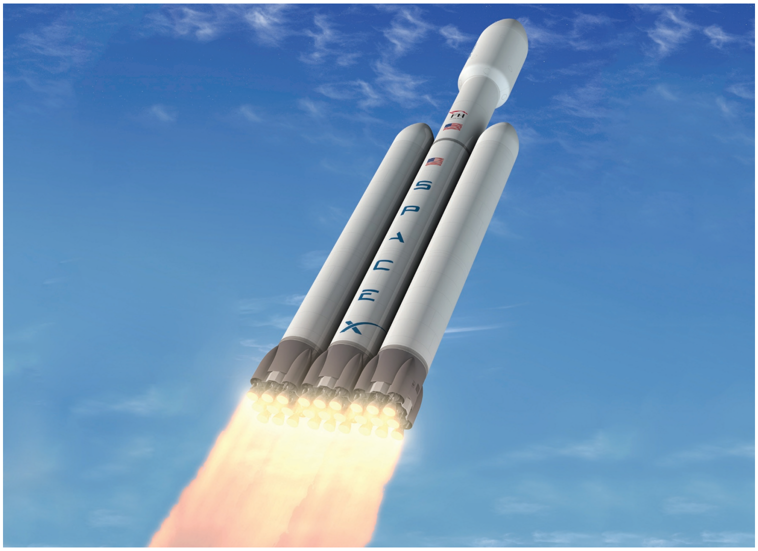

Figure 1.3

The Falcon Heavy rocket from SpaceX, which is able to lift into orbit the equivalent of a Boeing 737 jetliner loaded with passengers, crew, luggage, and fuel.

HO/Reuters/Landov

1.2 What Is Engineering?

The word "engineering" derives from the Latin root *ingeniere*, meaning to design or to devise, which also forms the basis of the word "ingenious." Those meanings are quite appropriate summaries of the traits of a good engineer. At the most fundamental level, engineers apply their knowledge of mathematics, science, and materials—as well as their skills in communications and business—to develop new and better technologies. Rather than experiment solely through trial and error, engineers are educated to use mathematics, scientific principles, and computer simulations (Figure 1.4) as tools to create faster, more accurate, and more economical designs.

In that sense, the work of an engineer differs from that of a scientist, who would normally emphasize the discovery of physical laws rather than apply those phenomena to develop new products. Engineering is essentially a bridge between scientific discovery and product applications. Engineering does not exist for the sake of furthering or applying mathematics, science, and computation by themselves. Rather, engineering is a driver of social and economic growth and an integral part of the business cycle. With that perspective, the U.S. Department of Labor summarizes the engineering profession as follows:

> *Engineers apply the theories and principles of science and mathematics to research and develop economical solutions to technical problems. Their work is the link between perceived social needs and commercial applications. Engineers design products, machinery to build those products, plants in which those products are made, and the systems that ensure the quality of the products and the efficiency of the workforce and manufacturing process. Engineers design, plan, and supervise the construction of buildings, highways, and transit systems. They develop and implement improved ways to extract, process, and use raw materials, such as petroleum and natural gas. They develop new materials that both improve the performance of products and take advantage of advances in technology. They harness the power of the sun, the Earth, atoms, and electricity for use in supplying*

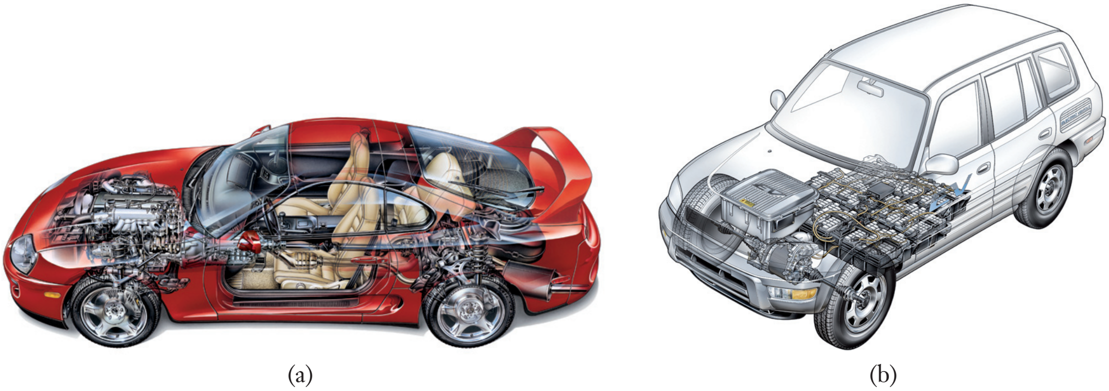

Figure 1.4

On a day-to-day basis, mechanical engineers use state-of-the-art cyber-enabled tools to design, visualize, simulate, and improve products.

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> *the Nation's power needs, and create millions of products using power. They analyze the impact of the products they develop or the systems they design on the environment and on people using them. Engineering knowledge is applied to improving many things, including the quality of healthcare, the safety of food products, and the operation of financial systems.*

Many students begin to study engineering because they are attracted to the fields of mathematics and science. Others migrate toward engineering careers because they are motivated by an interest in technology and how everyday things work or, perhaps with more enthusiasm, how not-so-everyday things work. A growing number of others are impassioned by the significant impact that engineers can have on global issues such as clean water, renewable energy, sustainable infrastructures, and disaster relief.

Regardless of how students are drawn to it, engineering is distinct from the subjects of mathematics and science. At the end of the day, the objective of an engineer is to have built a device that performs a task that previously couldn't have been completed or couldn't have been completed so accurately, quickly, or safely. Mathematics and science provide some of the tools and methods that enable an engineer to test fewer mock-ups by refining designs on paper and with computer simulations, before any metal is cut or hardware is built. As suggested by Figure 1.5, "engineering" could be defined as the intersection of activities related to mathematics, science, computer simulation, and hardware.

Approximately 1.5 million people are employed as engineers in the United States. The vast majority work in industry, and fewer than 10% are employed by federal, state, and local governments. Engineers who are federal employees are

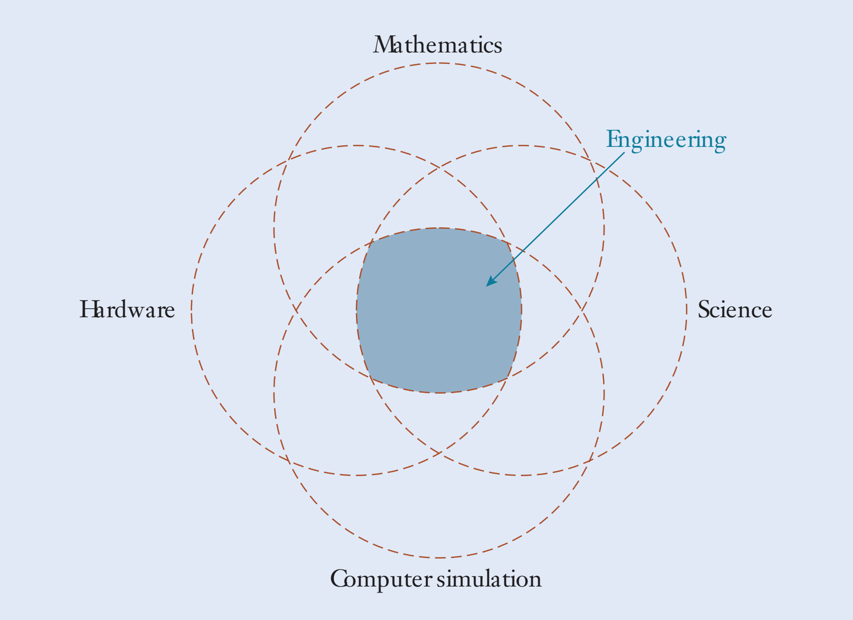

Figure 1.5

Engineers combine their skills in mathematics, science, computers, and hardware.

often associated with such organizations as the National Aeronautics and Space Administration (NASA) or the Departments of Defense (DOD), Transportation (DOT), and Energy (DOE). About 3–4% of all engineers are self-employed, working mostly in consulting and entrepreneurial capacities. Further, an engineering degree prepares students to work in a wide range of influential fields. In a recent list of the CEOs from the Standard & Poor's 500, 33% have undergraduate degrees in engineering, which is almost three times the number as those who earned business administration or economics degrees. Similar surveys showed that 28% of the CEOs in the Fortune 50 had an undergraduate engineering degree. Of the 13 major industry sectors, engineering was the most popular major for CEOs in nine of them:[1]

- Business services
- Chemicals
- Communications
- Electricity, gas, and sanitary
- Electronic components
- Industrial and commercial machinery
- Measuring instruments
- Oil and gas extraction
- Transportation equipment

This is understandable since engineers know that successful problem solving starts with effective information gathering and sound assumptions. They know how to process information to make decisions while taking into account unknown parameters. They also know when to isolate facts and emotions in their decisions while being incredibly innovative and intuitive.

Although engineering majors are well represented in top business leadership positions, their representation in top political and civic leadership positions is mixed. Currently, only 9 of the 540 members of the 114th United States Congress are engineers[2] down from 11 engineers in the 113th United States Congress.[3] However, eight of the nine members of a recent top civic leadership committee in China have engineering degrees.[4] In addition, the three most recent Presidents of China have all been engineers. While government service may not be your career ambition, leaders all over the world in all disciplines are realizing that a broad range of skills in both hard and soft sciences is necessary in a world where globalization and communication

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[1] Spencer Stuart, "Leading CEOs: A Statistical Snapshot of S&P 500 Leaders" (Chicago, 2008).

[2] Lucey, B., "By the Numbers: How well do you know the 114th Congress?" http://www.dailynewsgems.com/2015/01/by-the-numbers-how-well-do-you-know-the-114th-congress.html, January 25, 2015.

[3] "Engineers in Politics," https://www.asme.org/career-education/early-career-engineers/me-today/me-today-march-2013-issue/engineers-in-politics

[4] Norman R. Augustine, *Is America Falling off the Flat Earth*? (Washington, DC: The National Academies Press, 2007).

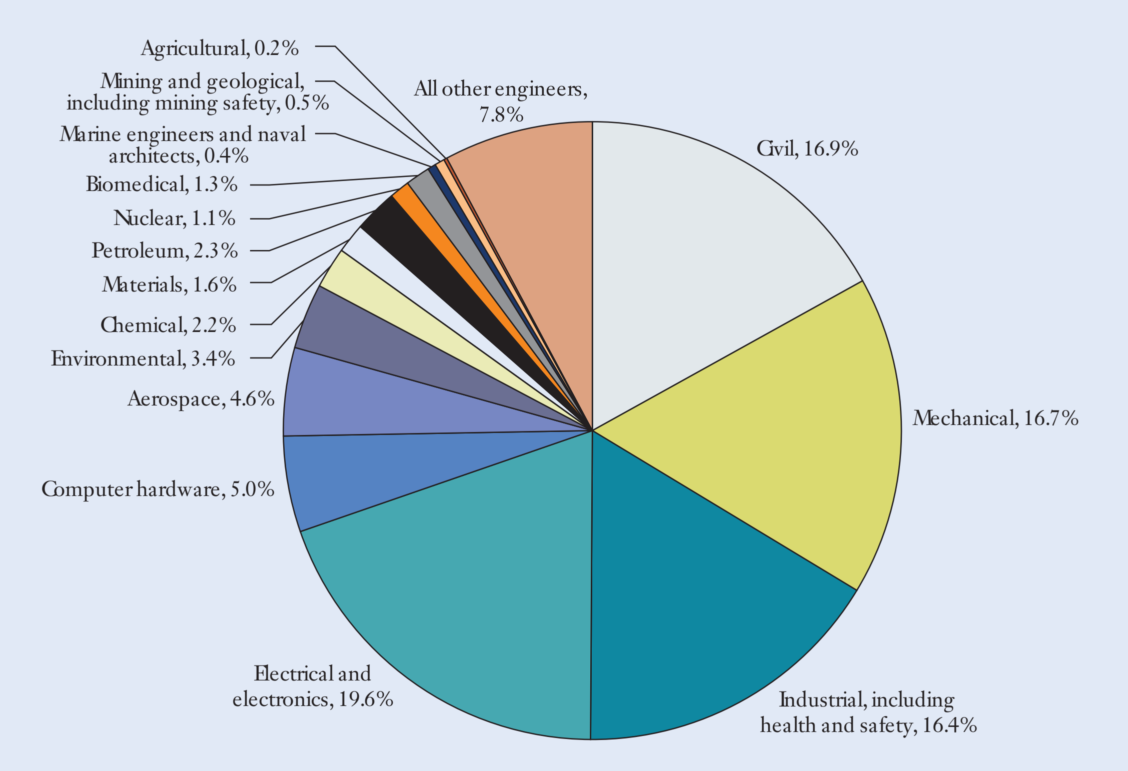

Figure 1.6

Percentages of engineers working in the traditional engineering fields and their specializations.

Based on data from the United States Department of Labor.

technologies are making geographic divisions increasingly irrelevant. As a result, the field of engineering is changing and this textbook encompasses many of these changes in how engineers need to view, model, analyze, solve, and disseminate the technical, social, environmental, economic, and civic challenges from a global perspective.

Most engineers, while earning a degree in one of the major branches, end up specializing. Though 17 engineering specialties are covered in the Federal Government's Standard Occupational Classification (SOC) system, numerous other specialties are recognized by professional societies. Further, the major branches of engineering have many subdivisions. For example, civil engineering includes the subdivisions of structural, transportation, urban, and construction engineering; electrical engineering includes the subdivisions of power, control, electronics, and telecommunications engineering. Figure 1.6 depicts the distribution of engineers in the major branches, as well as several other specializations.

Engineers develop their skills first through formal study in an accredited bachelor's degree program and later through advanced graduate studies and/or practical work experience under the supervision of accomplished and senior engineers. When starting a new project, engineers often rely on their reasoning, physical intuition, hands-on skills, and the judgment gained through previous technical experiences. Engineers routinely make approximate "back-of-the-envelope" calculations to answer such questions as, "Will a 10-hp engine be powerful enough to drive that air compressor?" or "How many *g*'s of acceleration must the blade in the turbocharger withstand?"

Lifelong learning

When the answer to a particular question isn't known or more information is needed to complete a task, an engineer conducts additional research using such resources as books, professional journals, and trade publications in a technical library; sites such as Google Scholar or CiteSeer; engineering conferences and product expositions; patents; and data provided by industry vendors. The process of becoming a good engineer is a *lifelong* endeavor, and it is a composite of education and experience. One can make a good argument that it is not possible to build a lifelong career on only the material that was learned in college. As technologies, markets, and economies quickly grow and evolve, engineers are constantly learning new approaches and problem-solving techniques and informing others of their discoveries.

Focus On

MECHANICAL ENGINEERING JOBS

As you begin your formal mechanical engineering education, keep the outcome of your degree in mind. As your education process continues, either formally with more degrees or informally with on the job training, the immediate outcome is a job that matches your skills, passions, and education. While you may have some perceptions about where mechanical engineers work, you may be surprised to find mechanical engineering opportunities in almost every company. For instance, a quick search reveals the following positions for candidates with a bachelor level degree in mechanical engineering.

Yeamake/Shutterstock.com

Google/Skybox Imaging

Description Summary: You will design in CAD our next generation satellite (a large, complex assembly) making sure parts fit properly together and the CAD model matures efficiently with the program; early layout in a lightweight model up through detailed models representing "as built." You will be responsible for small-to-medium CAD models, part sourcing, and assembly of support equipment. You will take responsibility of some subset of our environmental tests which include sine and random vibration testing, acoustics testing, shock testing, and mechanism characterization. You will contribute detailed design documentation including test plans and reports, test procedures, assembly drawings and assembly instructions as needed to the satellite or supporting equipment designs. You will own production design-work such as CAD updates incorporating lessons learned, drawing fixes, and clarification documents.

General Requirements:

- Collaborate with other engineers to establish the best solution or design
- Design mechanical parts with an acute awareness of manufacturability and strive for simplicity
- Plan complex tests on a critical piece of hardware

- Work hands-on in the machine shop to prototype, assemble completed designs, and run tests
- Experience with mechanical engineering fundamentals (thermodynamics, fluid dynamics, mechanics of materials)


360b/Shutterstock.com

Apple, Inc.

Description Summary: Lead the design, development and validation of sensor technologies including owning the end-to-end mechanical development and integration of a sensor module into a product, with responsibilities including:

- Brainstorming design concepts and executing design concepts in all phases of a development cycle
- Generating innovative designs with cross-functional teams while driving design towards Apple's cosmetic requirements
- Defining mechanical component outlines and assembly schemes
- Generating dimensional and tolerance analysis
- Participating in the development of new manufacturing processes
- Design validation and characterization from prototype bring-up to product testing

General Requirements:

- 3D CAD experience required
- Scientific method, experimental process, root cause analysis
- Applied knowledge in flex circuits, printed circuit boards, material science and basic chemistry is beneficial
- Excellent written and verbal communication skills and people skills; ability to interact with management, team members and external vendors
- Teamwork: the candidate must be able to communicate well with cross-functional team members, be able to efficiently collaborate with team members to achieve project goals, and contribute positively to the engineering community


Claudio Divizia/Shutterstock.com

Amazon

Description Summary: Given the rapid growth of our business, we can achieve Earth's biggest selection and still manage to offer lower prices every day to customers by providing cutting-edge automation technology and excellent decision support tools/services. If you are seeking an environment where you can drive innovation, want to apply state-of-the-art technologies to solve extreme-scale real world problems, and want to provide visible benefit to end-users in an iterative fast paced environment, the Amazon Prime Air Team is your opportunity. You will work with an interdisciplinary team to execute product designs from concept to production, including design, prototyping, validation, testing and certification. You will also work with manufacturing, supply chain, quality and outside vendors to ensure a smooth transition to production.

General Requirements:

- Experience designing and analyzing robust, mechanical systems
- Enjoy problem solving and possess practical knowledge of prototype design as well as production run manufacturing methods
- Experience with CREO with knowledge of robust part design, managing large assemblies and creating detailed documentation
- Strong hands on experience with the ability to craft simple proof-of-concept models in-house
- Thorough understanding and use of principles, theories and concepts in mechanical, aerospace, or robotics engineering and design

In this textbook, we cover a number of these skills to help you prepare to be a successful professional in the dynamic field of mechanical engineering.