Foundations of ENGINEERING

Foundations of ENGINEERING

THIRD EDITION

Mark T. Holtzapple
W. Dan Reece
Texas A&M University

Mc Graw Hill

FOUNDATIONS OF ENGINEERING, THIRD EDITION

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LCR 27 26 25 24 23 22

ISBN 978-1-260-25393-1 (bound edition)
MHID 1-260-25393-7 (bound edition)
ISBN 978-1-260-58815-6 (loose-leaf edition)
MHID 1-260-58815-7 (loose-leaf edition)

Portfolio Manager: *Beth Bettcher*
Product Developer: *Erin Kamm*
Marketing Manager: *Shannon O'Donnell*
Content Project Managers: *Maria McGreal, Tammy Juran*
Buyer: *Laura Fuller*
Content Licensing Specialist: *Lorraine Buczek*
Cover Image: *WitR/iStock/Getty Images*
Compositor: *Aptara®, Inc.*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

Library of Congress Cataloging-in-Publication Data

Names: Holtzapple, Mark Thomas, author. | Reece, W. Dan, author.
Title: Foundations of engineering / Mark T. Holtzapple, W. Dan Reece, Texas A&M University.
Description: Third edition. | New York, NY : McGraw Hill Education, [2023] | Includes bibliographical references and indexes.
Identifiers: LCCN 2021034911 (print) | LCCN 2021034912 (ebook) | ISBN 9781260253931 (hardcover; acid-free paper) | ISBN 9781260588156 (spiral bound; acid-free paper) | ISBN 9781260588163 (pdf) | ISBN 9781264161546 (ebook other)
Subjects: LCSH: Engineering.
Classification: LCC TA145 .H59 2023 (print) | LCC TA145 (ebook) | DDC 620—dc23
LC record available at https://lccn.loc.gov/2021034911
LC ebook record available at https://lccn.loc.gov/2021034912

mheducation.com/highered

CONTENTS

To the Professor xiii

To the Student xvii

Acknowledgments xxii

SECTION ONE:

INTRODUCTION TO ENGINEERING

CHAPTER 1

THE ENGINEER

1.1 What Is an Engineer? 2
Box: *Engineer:* Origins of the Word 3
1.2 The Engineer as Problem Solver 3
1.3 The Need for Engineering 3
Box: The Trebuchet: An Engine of War 4
1.4 The Technology Team 5
Box: A Few Words on Diversity 6
Box: Elijah McCoy: Mechanical Engineer and Inventor 7
1.5 Engineering Disciplines and Related Fields 7
Box: Josephine Garis Cochrane: Inventor of the Dishwasher 8
Box: Ancient Egypt: From Engineer to God 10
1.6 Engineering Functions 15
1.7 How Much Formal Education Is Right for You? 16
1.8 The Engineer as a Professional 17
Box: The Roman Republic and Empire: Paving the World 18
Box: China Through the Ages: Walls, Words, and Wells 20
1.9 The Engineering Design Method 21
1.10 Traits of a Successful Engineer 24
1.11 Creativity 26
1.12 Traits of a Creative Engineer 30
1.13 Summary 36
Glossary 36

CHAPTER 2

ENGINEERING ETHICS

2.1 Interaction Rules 38
2.2 Settling Conflicts 41
2.3 Moral Theories 43
2.4 The Ethical Engineer 46
2.5 Resource Allocation 47
Box: Prisoner's Dilemma 48
2.6 Case Studies 51
Box: Risk on the Road 53
2.7 Summary 65
Glossary 68

CHAPTER 3

PROBLEM SOLVING

3.1 Types of Problems 69
3.2 Problem-Solving Approach 70
Box: A Word About Units 71
3.3 Problem-Solving Skills 72
3.4 Techniques for Error-Free Problem Solving 73
3.5 Estimating 78
3.6 Creative Problem Solving 81
3.7 Summary 96
Glossary 100

CHAPTER 4

UNDERSTANDING AND USING COMPUTERS

4.1 A Brief History of Computers 102
Box: Augusta Ada: The Mother of the Computer 105
Box: Grace Hopper: Computer Pioneer 106
4.2 Design Concepts in Digital Computers 106
4.3 Getting Started 114
4.4 Creating Computer Programs 120
4.5 Summary 129
Glossary 130

CHAPTER 5

INTRODUCTION TO DESIGN

5.1 The Engineering Design Method 133
Box: Paul MacCready, Engineer of the Century 134
Box: The Color TV War 141
5.2 First Design Example: Improved Paper Clip 145
5.3 Second Design Example: Robotic Hand for Space Shuttle 150
Box: Amount vs. Rate 157

5.4 Third Design Example: Zero-Emission Vehicle (Advanced Topic) 158
5.5 Summary 169
Glossary 170

CHAPTER 6
ENGINEERING COMMUNICATIONS
6.1 Preparation 173
6.2 Oral Presentations 176
6.3 Writing 182
6.4 Summary 195
Glossary 197

SECTION TWO:
MATHEMATICS

CHAPTER 7
NUMBERS
7.1 Number Notation 200
7.2 Simple Error Analysis 201
Box: Trouble with Hubble 204
7.3 Significant Figures 205
7.4 Summary 208
Glossary 210

CHAPTER 8
TABLES AND GRAPHS
8.1 Dependent and Independent Variables 211
8.2 Tables 211
8.3 Graphs 213
8.4 Linear Equations 219
8.5 Power Equations 220
8.6 Exponential Equations 223
8.7 Transforming Nonlinear Equations into Linear Equations 224
8.8 Interpolation and Extrapolation 226
8.9 Linear Regression 229
8.10 Summary 233
Glossary 237

CHAPTER 9
STATISTICS
9.1 Statistical Quality Control 239
9.2 Sampling 240
9.3 Descriptive Statistics 240
9.4 Histograms 245
9.5 Normal Distribution and Standard Normal Distribution 247
9.6 Summary 249
Glossary 253

SECTION THREE: ENGINEERING FUNDAMENTALS

CHAPTER 10
NEWTON'S LAWS

10.1 Analysis of Motion 256
10.2 Theory of Relativity (Advanced Topic) 267
10.3 Forces 271
10.4 Newton's First Law 276
10.5 Newton's Second Law 277
Box: Galileo Galilei: The First Physicist 278
10.6 Newton's Third Law 282
Box: Historical Perspective on the Laws of Motion 284
10.7 Relativistic Momentum and Mass and Energy Changes (Advanced Topic) 285
10.8 Example Applications of Newton's Laws 287
10.9 Planetary Motion 293
10.10 Care and Feeding of Formulas 295
10.11 Summary 297
Glossary 299

CHAPTER 11
INTRODUCTION TO THERMODYNAMICS

11.1 Forces of Nature 301
11.2 Structure of Matter 301
11.3 Temperature 302
11.4 Pressure 302
11.5 Density 303
Box: Temperature Scales 304
Box: Absolute Zero 304
11.6 States of Matter 305
Box: Pressure Scales 307
Box: Classical Greece: Philosophical Engineering 307
11.7 Equilibrium Conditions 308
11.8 Amount of Substance 309
11.9 Gas Laws 309
11.10 Real Gases (Advanced Topic) 312
11.11 Energy 313
Box: Dollars and Energy 314
Box: The Caloric Theory of Heat 319
Box: Concepts of Work 320
11.12 Reversibility 320
11.13 Thermodynamic Laws 321
Box: Musings on the Second Law of Thermodynamics 323
11.14 Heat Capacity 324
Box: Origins of the First Law 324
Box: Origins of the Second Law 325
Box: James Watt: Master Mechanic 326

11.15 Summary 327
Glossary 330

CHAPTER 12
INTRODUCTION TO RATE PROCESSES
12.1 Rate 332
12.2 Flux 333
12.3 Driving Force 333
12.4 Heat 334
12.5 Fluid Flow 335
12.6 Electricity 337
Box: AC/DC 339
12.7 Diffusion 340
12.8 Resistance 341
Box: Electrical Superconductors 344
12.9 Summary 344
Glossary 348

CHAPTER 13
SI SYSTEM OF UNITS
13.1 Historical Background 349
13.2 Dimensions and Units 350
13.3 SI Units 351
Box: Born in Revolution 351
Box: Comparison of a Green and Blue Laser Pointer 359
13.4 SI Prefixes 362
13.5 Customary Units Recognized by SI 364
13.6 Rules for Writing SI Units (Reference) 365
13.7 Summary 369
Glossary 371

CHAPTER 14
UNIT CONVERSIONS
14.1 What Does it Mean to “Measure” Something? 373
Box: The Right and Lawful Rood 374
14.2 Conversion Factors 374
14.3 Mathematical Rules Governing Dimensions and Units 375
14.4 Systems of Units 377
14.5 The Datum 382
14.6 Pressure 383
14.7 Temperature 386
14.8 Changing the System of Units in an Equation 389
14.9 Dimensional Analysis (Advanced Topic) 390
14.10 Summary 392
Box: Why Do Golf Balls Have Dimples? 393
Glossary 396

CHAPTER 15

INTRODUCTION TO STATICS AND DYNAMICS

15.1 Statics of Particles 399
15.2 Statics of Rigid Bodies 403
Box: Leonardo da Vinci: Renaissance Visionary 414
15.3 Strength of Materials 414
Box: Stress Is a Momentum Flux 418
15.4 Dynamics (Advanced Topic) 419
Box: Safety Factors in the Man-Made and Natural Worlds 420
15.5 Summary 427
Glossary 430

CHAPTER 16

INTRODUCTION TO ELECTRICITY

16.1 Fundamentals of Electricity 431
16.2 Fundamentals of Magnetism 435
16.3 Conductors, Semiconductors, and Insulators 437
16.4 Electromagnetic Radiation 441
16.5 Circuit Components 444
Box: Shuji Nakamura: Inventor of the Blue and Green LED 454
16.6 Circuit Analysis 463
Box: The Transistor—Invention of the Century 465
16.7 Circuits 467
16.8 Electronic Circuit Construction 483
Box: Pioneers of the Integrated Circuit 486
16.9 Summary 487
Glossary 490

SECTION FOUR:

ENGINEERING ACCOUNTING

CHAPTER 17

ACCOUNTING

17.1 Systems: Subsets of the Universe 497
17.2 Intensive and Extensive Quantities 499
17.3 State and Path Quantities 500
17.4 Classification of Quantities 502
17.5 State Properties of Matter 503
17.6 Special Types of Systems 503
17.7 Universal Accounting Equation 507
Box: A Word about Signs 509
Box: Let's be Clear! 513
17.8 Types of Equations 513
17.9 Summary 514
Glossary 517

CHAPTER 18
ACCOUNTING FOR MASS
18.1 Conservation of Mass 519
Box: Fire Stuff 521
18.2 Generation and Consumption of Mass (Advanced Topic) 522
18.3 Chemical Reactors (Advanced Topic) 524
18.4 Summary 528
Glossary 530

CHAPTER 19
ACCOUNTING FOR CHARGE
19.1 Accounting for Charge 531
19.2 Accounting for Charge in Chemical Reactions 533
19.3 Accounting for Charge in Nuclear Reactions 539
19.4 Electric Circuits 540
19.5 Summary 543
Box: Facts about Fax 543
Box: Pioneers in Electricity 544
Glossary 547

CHAPTER 20
ACCOUNTING FOR LINEAR MOMENTUM
20.1 Review of Newton's Laws 548
20.2 Conservation of Linear Momentum 549
Box: How Do Wings Work? 557
20.3 Systems Without Net Linear Momentum Input 558
20.4 Summary 559
Glossary 561

CHAPTER 21
ACCOUNTING FOR ANGULAR MOMENTUM
21.1 Measures of Rotary Motion 562
21.2 Centripetal and Centrifugal Forces 566
21.3 Angular Momentum for Particles 570
21.4 Angular Momentum for Rigid Bodies (Advanced Topic) 571
21.5 Torque 575
21.6 Conservation of Angular Momentum 576
21.7 Systems Without Net Momentum Input 580
21.8 Summary 582
Glossary 585

CHAPTER 22
ACCOUNTING FOR ENERGY
22.1 Energy Accounting 586
22.2 Path Energies 587

22.3 State Energies 598
22.4 Total Energy Conservation 613
22.5 Fluid Flow (Advanced Topic) 617
Box: How Do Wings Work? 621
Box: How Do Propellers Work? 621
22.6 Energy Conversion 622
22.7 Sequential Energy Conversion 625
Box: Metabolic Energy 627
22.8 Summary 628
Glossary 632

CHAPTER 23

ACCOUNTING FOR ENTROPY

23.1 Reversibility and Irreversibility 634
23.2 Entropy 644
Box: Discovery of Entropy 645
Box: Entropy and Disorder (advanced) 648
Box: Entropy and Information 651
23.3 Accounting for Entropy 659
23.4 Summary 665
Glossary 669

CHAPTER 24

ACCOUNTING FOR MONEY

24.1 Micro- and Macroeconomics 670
24.2 Interest and Investment Costs 672
24.3 Present Worth and Discount 677
24.4 Annuities 679
24.5 Perpetuities and Capitalized Costs 684
24.6 Discount Factors and Compounding Factors 687
24.7 Inflation 691
24.8 A Quick Look at Other Topics 692
24.9 Summary 693
Glossary 696

APPENDIX A
Unit Conversion Factors 699

APPENDIX B
NSPE Code of Ethics for Engineers 712

APPENDIX C
z Table 718

APPENDIX D
Summary of Some Engineering Milestones 720

Topic Index 726
Biographical Index 737

TO THE PROFESSOR

Traditional engineering courses—such as courses on heat transfer, circuits, and fluids—are fairly well defined. In contrast, there is no general agreement on the content of freshman engineering courses. Current freshman engineering texts choose from a range of topics including professionalism, creativity, ethics, design, technical writing, graphing, systems of units, engineering science, and problem solving. All of these topics are important aspects of the freshman engineering experience, but we found no one text that adequately encompassed them all. Therefore, we decided to write our own text to fill the void.

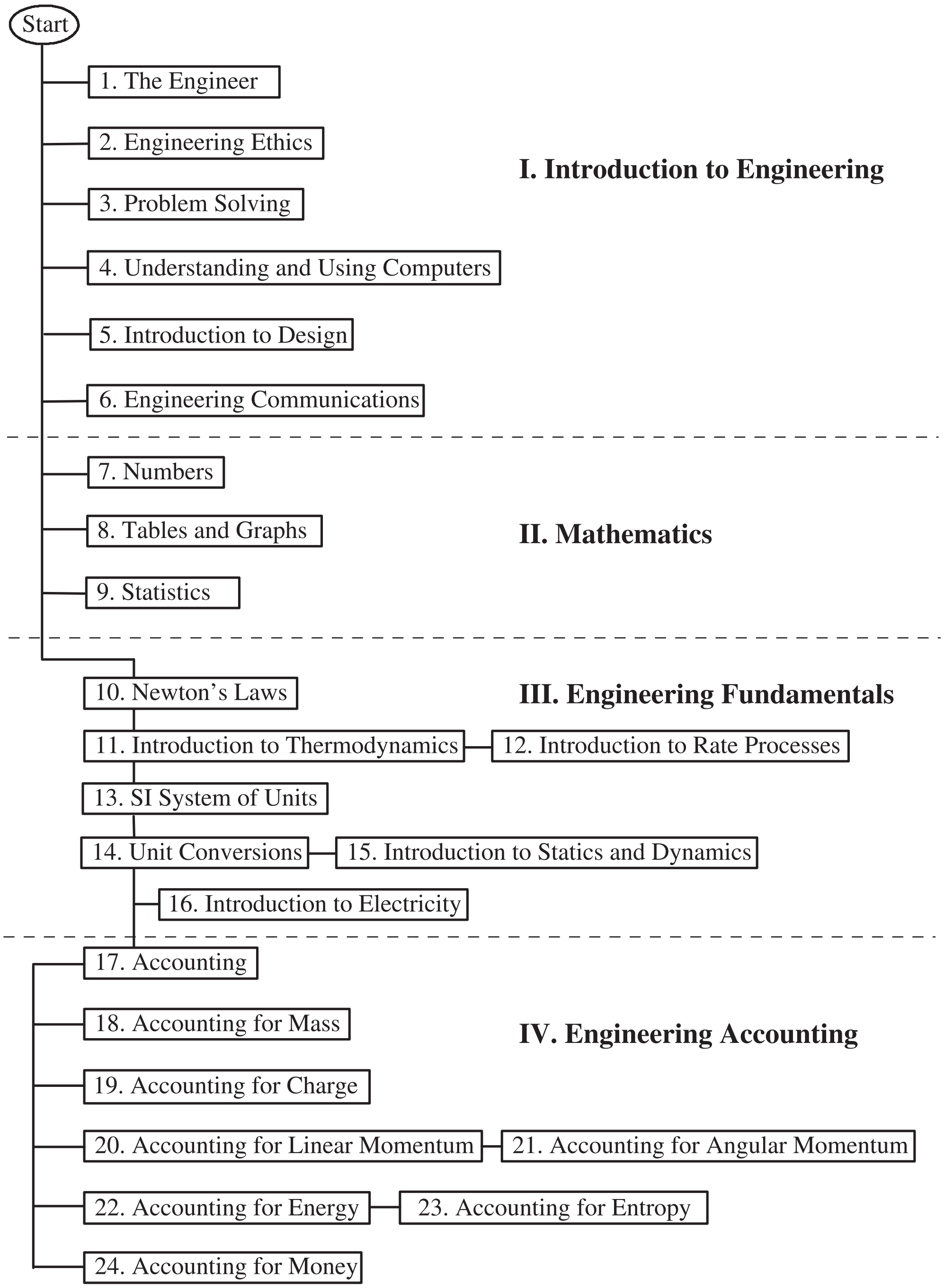
Many freshman engineering texts describe specific engineering disciplines, such as mechanical or electrical engineering, and give sample problems involving statics or electrical circuits. Given the increasing number of new engineering disciplines (e.g., biochemical engineering) and the increasingly interdisciplinary nature of engineering (e.g., mechatronics), we feel this discipline-specific approach is inadequate. Instead, we feel a more unified approach is required, with less emphasis on traditional disciplines. The goals of our text are listed here:

- *Excite the student about engineering.* Most practicing engineers find their work to be very exciting and creative. However, freshmen must struggle with the rigors of their science and mathematics classes, so they may be unaware of the pleasures that await them. We hope to stimulate the students' interest in engineering by describing engineering history, challenging them with "brain teaser" problems, and explaining the creative process.
- *Provide a strong foundation in engineering fundamentals.* Engineering has grown beyond the traditional disciplines (e.g., civil, mechanical, and electrical engineering) and now includes nontraditional disciplines (e.g., biomedical, environmental, and nuclear engineering). The common threads through all these disciplines are fundamental physical and mathematical laws.
- *Cultivate problem-solving skills.* The most important engineering skill is the ability to solve problems. We describe many heuristic approaches to creative problem solving as well as a systematic approach to solving well-defined engineering problems.
- *Challenge advanced students.* Students who have good high school backgrounds will have been exposed to calculus and physics. To stimulate their interest in engineering, advanced topics are sprinkled throughout the book.

- *Integrate computing with other engineering topics.* This book contains numerous sample computer programs illustrating a variety of engineering applications. This will help the student realize that computing is not a separate topic, but is a tool used by engineers to solve problems.
- *Provide reference material.* Most students will not purchase handbooks until later in their engineering careers. This book provides unit conversion factors and material properties so that students have the resources to solve real-world problems.
- *Provide information the student is unlikely to encounter elsewhere.* Often, important engineering information that does not fit neatly into advanced courses is put into a freshman engineering course. Thus, this text includes information such as statistics, grammatical rules for the SI system, and graphing rules.
- *Connect with their high school experience.* Many students may be concerned about possible gaps between their actual knowledge and the knowledge college professors expect of them. Touching upon topics with which they are already familiar will ease their anxiety and improve their confidence.
- *Review high school mathematics.* Most freshman engineering students no longer have their high school mathematics textbooks, nor is high school mathematics discussed in college calculus textbooks. For students who need to refresh their mathematics skills, the book's website, http://www.mhhe.com/holtzapple, offers a mathematics supplement complete with practice problems.
- *Connect with their freshman science and mathematics courses.* Some students may perceive that their freshman science and mathematics classes are a hazing process, and may not understand that these courses form the backbone of engineering. We purposely incorporate topics they see in other courses to show the connection with engineering.
- *Provide "soak time" for difficult topics.* Learning is a process that requires repetition. A few difficult topics that students will encounter in later engineering courses (e.g., thermodynamics, rate processes) are introduced here at a very simple level. This allows them to become acquainted with the ideas, so their next detailed exposure is easier.
- *Introduce the design process.* To help freshmen experience the joy of engineering, we think it is necessary to assign a design problem during their first semester. To support this notion, early in the text, we introduce design.
- *Emphasize the importance of communication skills.* Too often, engineers are criticized for lacking communication skills. To help overcome this problem, we provide information on both oral and written communication that will be immediately useful to freshmen during their design project.

The topics in *Foundations of Engineering* are presented in a sequential manner, so it can be read from front cover to back cover with each new topic building on previously presented topics. Although the book is designed so that it **can** be read from cover to cover, this does not imply that it **must** be read from cover to cover. The accompanying figure indicates how the chapters fit together.

The "road map" in the accompanying figure shows that Chapters 1 through 9 are independent; if you decide to skip these chapters, it will not seriously affect the students' understanding of later chapters. In contrast, Chapters 10, 11, 13, and 14 are interdependent and must be covered in sequence. Chapters 12 and 15 are optional, but if covered, they must



Relationship of book chapters.

be after Chapters 11 and 14, respectively. Chapter 17 sets the stage for all the later chapters and therefore must be covered if the later chapters are taught. Chapters 18, 19, 20, 22, and 24 are independent. If Chapters 21 and 23 are covered, they must be done after Chapters 20 and 22, respectively.

In our experience, many students who have the potential to make excellent engineers have a poor command of high school mathematics. Whether they have forgotten it or never learned it, the information is lost to them because they no longer have their high school mathematics texts. To overcome this problem, the book's website includes a review of high school mathematics. At Texas A&M University, we require students to do mathematics homework problems, but do not take class time to discuss these topics because they review high school material. Each chapter with mathematical content informs students of the mathematical prerequisites needed to fully understand the chapter, and directs them to the appropriate section on the website.

If your freshman engineering course is taught in two semesters, it is possible to use the entire book. However, if you are teaching a one-semester course, it is unlikely you will be able to cover all the material. In this case, we suggest that you give the students a "guide map" through the book, indicating which sections you consider to be core testable material and which sections are offered for enrichment purposes only. All the sections are conveniently numbered, so it is possible to be very explicit about what you expect the students to read.

This book is designed to be used in conjunction with a computer programming text. There are computer problems in almost every chapter that can be used to integrate students' computing knowledge with other engineering topics. Also, this book may be used in conjunction with an engineering graphics text. Obviously one of the most important tools for practicing engineers is the ability to read and create engineering drawings. We mention the importance of graphics several places in our text, but provide no real examples because this subject is very broad and is covered very well by other texts.

McGraw Hill maintains a website at www.mhhe.com/holtzapple that provides supplemental teaching materials. Please visit the site; we're sure you'll find it useful.

We hope that you and your students enjoy using this book. We will happily receive suggestions for improvements that may be incorporated into future editions.

Mark T. Holtzapple W. Dan Reece

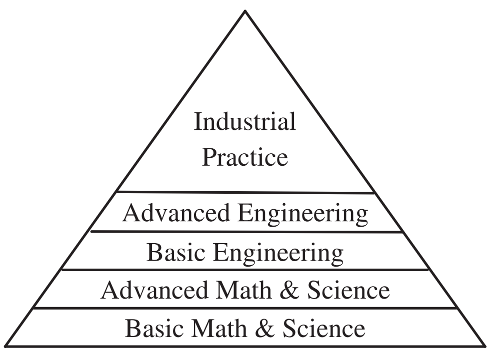
TO THE STUDENT

The engineering profession blossomed in Egypt with the construction of irrigation systems, roads, and pyramids by the first civil engineers. Regardless of the engineering discipline you decide to follow, you can visualize your engineering studies as a construction project in which you are building your knowledge.

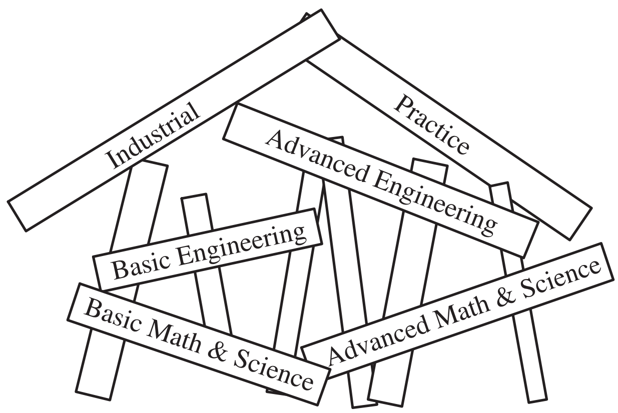
If you are wise, you will construct a pyramid, a well-proven structure that can withstand millennia of weathering. A pyramid is strong because it has a wide foundation. Your wide foundation requires a firm grasp of mathematics and science, which cannot be achieved by memorizing formulas or learning rote procedures. Instead, your objective should be to become "educated" and to *understand*.

Unfortunately, some students take the "plug-and-chug" approach to their engineering studies. They mistakenly believe that real-world engineers mindlessly plug numbers into handbook formulas with little understanding of the underlying principles. They view the required science and mathematics courses as a hazing process to separate the weak from the strong. Students with this attitude are constructing a rickety shack that will blow down in the first strong wind. They will be incapable of solving difficult problems and probably will make no significant engineering contributions to society.

In writing this text, our purpose is to begin your engineering education by providing a firm foundation for your later studies. This is a huge task, so our book is necessarily



The Educated Engineer



The "Plug-and-Chug" Engineer

long and detailed. In fact, it is unlikely that you will be able to cover the entire book in a single semester. Your professor will decide which of the many topics will be covered in your particular course. However, your professor's decisions should not preclude you from reading on your own. All of the topics in this text should be covered at some point in your studies.

We have divided the book into four sections:

- *Introduction to Engineering:* This is an overview of the engineering professions and the skills required to become a good engineer.
- *Mathematics:* We touch on a few mathematical concepts that you are not likely to encounter in your calculus class.
- *Engineering Fundamentals:* We feel the topics discussed here are absolutely fundamental to engineering education. You will be introduced to topics such as thermodynamics, rate processes (e.g., heat transfer, electricity), and Newton's laws. Unit conversions are given particular attention because this topic is so important.
- *Engineering Accounting:* We have cast the basic conservation laws (e.g., conservation of energy or mass) as a simple "accounting" procedure. We feel that accounting is a unifying concept that transcends the individual engineering disciplines. Here, you have the opportunity to apply your new skills to a variety of problems. The fundamental accounting principles are applied to such quantities as mass, energy, linear momentum, and angular momentum.

In case your high school mathematics is rusty, the book's website, at http://www.mhhe.com/holtzapple includes a mathematics supplement which reviews topics such as algebra, mathematical notation, probability, geometry, trigonometry, logarithms, polynomials, zeros of equations, and calculus. Each chapter with mathematical content informs you of the mathematical prerequisites needed to fully understand the chapter, and directs you to the appropriate section on the website.

The website also contains useful supplemental learning materials. Please visit the site; we're sure you'll find it useful.

We think of our book as a smorgasbord of delightful delicacies. There are so many delicacies, it is impossible for you to eat them all in a single sitting. However, with many sittings, it is possible for you to enjoy them all.

As many topics as we cover in this book, we still do not attempt to cover everything you will need to know. For several topics of major importance to engineers, particularly engineering graphics and the details of computing, we expect that you are receiving training from other texts. Both topics are essential to the practicing engineer. Even a simple engineering drawing passes more information than several volumes of words alone. Computers have revolutionized engineering. What took hours of drudgery just 20 years ago can now be done in seconds by using personal computers and software.

As shown in the "pyramid of learning" depicted earlier, all engineering disciplines use knowledge gained in mathematics and science courses. In addition, an important foundation of engineering is communications. One of the most important functions of engineers is to present their findings clearly and succinctly, both orally or in writing. It is no accident that English and technical writing are included in your engineering studies! The ability to convey ideas well comes only with hard work, practice, and constructive feedback; this may be the most important skill you have to learn.

We recommend that you hold onto this book. It has many useful charts, tables, conversion factors, and formulas that you will find invaluable in your later studies. Also, the topics are covered in a friendly, unified approach. If you are having troubles grasping a concept in your later studies, we hope you will take this book off your shelf and read—or reread—the appropriate chapters.

Mark T. Holtzapple W. Dan Reece

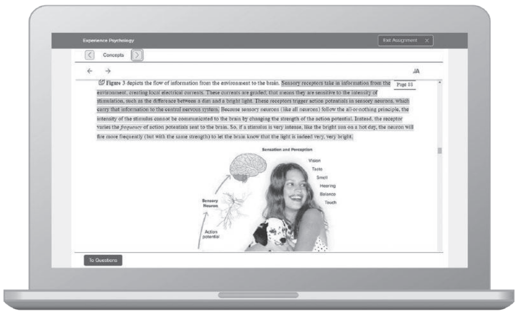
McGraw Hill connect®

Instructors: Student Success Starts with You

Tools to enhance your unique voice

Want to build your own course? No problem. Prefer to use an OLC-aligned, prebuilt course? Easy. Want to make changes throughout the semester? Sure. And you'll save time with Connect's auto-grading too.

65%
Less Time Grading



Laptop: McGraw Hill; Woman/dog: George Doyle/Getty Images

Study made personal

Incorporate adaptive study resources like SmartBook® 2.0 into your course and help your students be better prepared in less time. Learn more about the powerful personalized learning experience available in SmartBook 2.0 at **www.mheducation.com/highered/connect/smartbook**

Affordable solutions, added value

Make technology work for you with LMS integration for single sign-on access, mobile access to the digital textbook, and reports to quickly show you how each of your students is doing. And with our Inclusive Access program you can provide all these tools at a discount to your students. Ask your McGraw Hill representative for more information.

Padlock: Jobalou/Getty Images

Solutions for your challenges

A product isn't a solution. Real solutions are affordable, reliable, and come with training and ongoing support when you need it and how you want it. Visit **www.supportateverystep.com** for videos and resources both you and your students can use throughout the semester.

Checkmark: Jobalou/Getty Images

SUPPORT AT every step

Students: Get Learning that Fits You

Effective tools for efficient studying

Connect is designed to help you be more productive with simple, flexible, intuitive tools that maximize your study time and meet your individual learning needs. Get learning that works for you with Connect.

Study anytime, anywhere

Download the free ReadAnywhere app and access your online eBook, SmartBook 2.0, or Adaptive Learning Assignments when it's convenient, even if you're offline. And since the app automatically syncs with your Connect account, all of your work is available every time you open it. Find out more at **www.mheducation.com/readanywhere**

"I really liked this app—it made it easy to study when you don't have your textbook in front of you."

- Jordan Cunningham, Eastern Washington University

Calendar: owattaphotos/Getty Images

Everything you need in one place

Your Connect course has everything you need—whether reading on your digital eBook or completing assignments for class, Connect makes it easy to get your work done.

Learning for everyone

McGraw Hill works directly with Accessibility Services Departments and faculty to meet the learning needs of all students. Please contact your Accessibility Services Office and ask them to email accessibility@mheducation.com, or visit **www.mheducation.com/about/accessibility** for more information.

Top: Jenner Images/Getty Images, Left: Hero Images/Getty Images, Right: Hero Images/Getty Images

ACKNOWLEDGMENTS

A project of this size cannot be completed without assistance from many individuals. Dan Turner, the undergraduate dean at the Dwight Look College of Engineering at Texas A&M, initiated this project to provide a text for our introductory engineering course *Engineering Problem Solving and Computing*. He provided financial support and organized internal reviews of the manuscript. Karan Watson, who followed Dan Turner, provided invaluable support and encouragement for this project.

Curtis Johnson, an undergraduate nuclear engineering student at Texas A&M, provided assistance with computers and graphics. We are deeply indebted to him. The secretarial support from Brenda Mooney is much appreciated. Also, we thank Seth Adelson, a graduate chemical engineering student, for providing some historical descriptions of engineering and for creating some key computer programs.

Bill Bassichis is commended for giving a very thorough and helpful review of our physics chapters. Mike Rabins and Ed Harris, who jointly work on an NSF-supported engineering ethics project, were enormously helpful in their critical review of the ethics chapter. John Fleming deserves our praise for his very careful review of the manuscript. We also appreciate Larry Piper's and Jim Morgan's efforts in coordinating many of the activities that went into the book.

Charles Glover is thanked for the countless hours we spent discussing the accounting principles used widely in this text. He is a key player in an NSF-sponsored project to create a unifying framework for all engineering disciplines. His insight and deep thinking are essential to this book.

As mentioned earlier, Dan Turner organized a review of the manuscript by the following individuals: Lee Carlson, Glen Williams, Mac Lively, Alberto Garcia, Larry Piper, Skip Fletcher, Ray James, Tom Tielking, Mike McDermott, Ron Hart, Richard Griffin, Gerald Miller, Pierce Cantrell, Aaron Cohen, Vincent Sweat, and Kaylan Annamalai. We are grateful for their helpful comments.

It took thousands of hours to write this book, mostly during the evenings and weekends. We thank our families for graciously providing us with this time.

LIST OF REVIEWERS

Third Edition

Ali Abdul-Aziz	Kent State University
Azize Akcayoglu	Florida State University
Narendra Chaganti	The University of Alabama
George Concepcion	Rockland Community College
Alejandro Gutierrez	University of California, Merced
Adam Harris	Central Piedmont Community College
Clive Woods	University of South Alabama
Ahmed Zaki	Brown University

Second Edition

Sven Bilén	The Pennsylvania State University
Jerome N. Borowick	California State Polytechnic University, Pomona
John T. Demel	The Ohio State University
Lawrence J. Genalo	Iowa State University
Robert J. Gustafson	The Ohio State University
Mark Hernandez	University of Colorado–Boulder
William E. Howard	Milwaukee School of Engineering
Jean C. Malzahn Kampe	Virginia Polytechnic Institute
Andrew Lau	The Pennsylvania State University
Gary A. Pertmer	University of Maryland

Raymond H. Russell	University of Texas–Austin
David R. Thompson	Oklahoma State University
Ronald L. Thurgood	Utah State University

First Edition

Barry Crittenden	Virginia Polytechnic Institute
John T. Demel	The Ohio State University
James Garrett	Carnegie Mellon University
Jeff Kantor	University of Notre Dame
Rajiv J. Kapdia	Mankato State University
James L. Kelly	University of Virginia
Hillel Kumin	University of Oklahoma
James Morgan	Texas A&M University
William Park	Clemson University
Joey Parker	University of Alabama
Harry J. Ploehn	University of South Carolina
Larry G. Richards	University of Virginia
David N. Rocheleau	University of South Carolina
Sheryl Sorby	Michigan Technological University
Linda L. Vahala	Old Dominion University
Gretchen L. Van Meer	Northern Illinois University
Thomas Walker	Virginia Polytechnic Institute
Daniel White	University of Alaska Fairbanks
Steve Yurgartis	Clarkson University

ABOUT THE AUTHORS

Mark T. Holtzapple

Mark T. Holtzapple is Professor of Chemical Engineering at Texas A&M University. In 1978, he received his BS in chemical engineering from Cornell University. In 1981, he received his PhD from the University of Pennsylvania. His PhD research focused on developing a process to convert fast-growing poplar trees into ethanol fuel.

After completing his formal education, in 1981 Mark joined the U.S. Army and helped develop a portable backpack cooling device to alleviate heat stress in soldiers wearing chemical protective clothing.

After completing his military service, in 1986 Mark joined the Department of Chemical Engineering at Texas A&M University. It quickly became apparent that he had a passion for teaching: within a 2-year period he won nearly every major teaching award offered at Texas A&M, including Tenneco Meritorious Teaching Award, General Dynamics Excellence in Teaching Award, Dow Excellence in Teaching Award, and two awards offered by the Texas A&M Association of Former Students. Mark particularly has a passion for teaching freshman engineering students. He wrote this book to excite students about engineering and to help lay a solid foundation for their future studies.

In addition to his role as an educator, Mark is a prolific inventor. He is developing technologies that desalinate water, store electricity, capture carbon dioxide from flue gas, and store carbon dioxide in building materials. For fun, he is developing a novel flying car. He is also developing a high-efficiency, low-pollution Brayton cycle engine suitable for automotive use. In addition, he is developing technologies for converting waste biomass into useful products, such as animal feeds, industrial chemicals, and fuels. To recognize his contributions in biomass conversion, in 1996 he received the Presidential Green Chemistry Challenge Award offered by the president and vice president of the United States.

W. Dan Reece

Dr. Reece is a retired professor from the Nuclear Engineering Department and is the former Director of the Nuclear Science Center at Texas A&M University. He received his Bachelor of Chemical Engineering, Master of Science in Nuclear Engineering, and PhD in Mechanical Engineering all at the Georgia Institute of Technology. He has worked as an analytical chemist, a chemical engineer, and a staff scientist at the Pacific Northwest National Laboratory, before his current positions at Texas A&M.

Much of Dr. Reece's research is in the area of radiation monitoring, novel uses of radiation in medicine, and the health effects of radiation. Like Dr. Holtzapple, he has a passion for teaching and has won a Distinguished Teaching Award from the Texas A&M Association of Former Students. Dr. Reece taught many topical courses in dosimetry and health physics, has an active consulting business, and, whenever his schedule allows him free time, enjoys backpacking, playing tennis, and running. His greatest enjoyment comes from his children, his students, and the advances in medicine and worker protection he has helped to make.

SECTION ONE

INTRODUCTION TO ENGINEERING

This book is divided into four sections. This first section addresses the question of what exactly are engineers, and what do they do? In this section we will explore the various disciplines within engineering, some history of engineering, and what characteristics are usually present in good engineers. Next, we examine engineering professionalism and engineering ethics. Lastly, we will look at the most basic activities of engineering: solving problems, using computers, designing things, and communicating findings.

Mathematical Prerequisite

- Geometry (Appendix I, Mathematics Supplement)

CHAPTER 1

The Engineer

Nearly all the manmade objects that surround you result from the efforts of engineers. Just think of all that went into making the chair upon which you sit. Its metal components came from ores extracted from mines designed by mining engineers. The metal ores were refined by metallurgical engineers in mills that civil and mechanical engineers helped build. Mechanical engineers designed the chair components as well as the machines that fabricated them. The polymers and fabrics in the chair were probably derived from oil that was produced by petroleum engineers and refined by chemical engineers. The assembled chair was delivered to you in a truck that was designed by mechanical, aerospace, and electrical engineers, in plants that industrial engineers optimized to make best use of space, capital, and labor. The roads on which the truck traveled were designed and constructed by civil engineers.

Obviously, engineers play an important role in bringing ordinary objects to market. In addition, engineers are key players in some of the most exciting ventures of humankind. For example, the Apollo program was a wonderful enterprise in which humankind was freed from the confinement of earth and landed on the moon. It was an engineering achievement that captivated the United States and the world. Some pundits say the astronauts never should have gone to the moon, simply because all other achievements pale in comparison; however, we say that even more exciting challenges await you and your generation.

1.1 WHAT IS AN ENGINEER?

Engineers are individuals who combine knowledge of science, mathematics, and economics to solve technical problems that confront society. It is our practical knowledge that distinguishes engineers from scientists, for they too are masters of science and mathematics. Our emphasis on the practical was eloquently stated by the engineer A. M. Wellington (1847–1895), who described engineering as "the art of doing . . . well with one dollar, which any bungler can do with two."

Although engineers must be very cost-conscious when making ordinary objects for consumer use, some engineering projects are not governed strictly by cost considerations. President Kennedy promised the world that the Apollo program would place a man on the moon prior to 1970. Our national reputation was at stake and we were trying to prove our technical prowess to the Soviet Union in space, rather than on the battlefield. Cost was a secondary consideration; landing on the moon was the primary consideration. Thus, engineers can be viewed as problem solvers who assemble the necessary resources to achieve a clearly defined technical objective.

Engineer: Origins of the Word

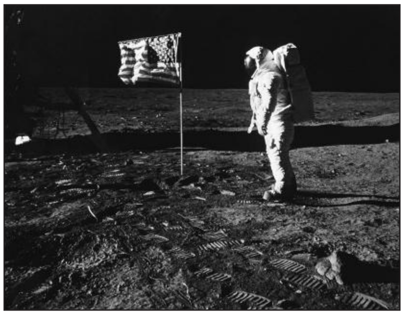
The root of the word *engineer* derives from *engine* and *ingenious*, both of which come from the Latin root *in generare*, meaning "to create." In early English, the verb *engine* meant "to contrive" or "to create."

The word *engineer* traces to around A.D. 200, when the Christian author Tertullian described a Roman attack on the Carthaginians using a battering ram described by him as an *ingenium*, an ingenious invention. Later, around A.D. 1200, a person responsible for developing such ingenious engines of war (battering rams, floating bridges, assault towers, catapults, etc.) was dubbed an *ingeniator.* In the 1500s, as the meaning of "engines" was broadened, an engineer was a person who made engines. Today, we would classify a builder of engines as a mechanical engineer, because an engineer, in the more general sense, is "a person who applies science, mathematics, and economics to meet the needs of humankind."

1.2 THE ENGINEER AS PROBLEM SOLVER

Engineers are problem solvers. Given the historical roots of the word engineer (see box above), we can expand this to say that engineers are *ingenious* problem solvers.

In a sense, all humans are engineers. A child playing with building blocks who learns how to construct a taller structure is doing engineering. A secretary who stabilizes a wobbly desk by inserting a piece of cardboard under the short leg has engineered a solution to the problem.



Fulfilling President Kennedy's promise, the United States landed on the moon in 1969.
NASA Kennedy Space Center (NASA-KSC)

Early in human history, there were no formal schools to teach engineering. Engineering was performed by those who had a gift for manipulating the physical world to achieve a practical goal. Often, it would be learned through apprenticeship with experienced practitioners. This approach resulted in some remarkable accomplishments. Appendix D summarizes some outstanding engineering feats of the past.

Current engineering education emphasizes mathematics, science, and economics, making engineering an "applied science." Historically, this was not true; rather, engineers were largely guided by intuition and experience gained either personally or vicariously. For example, many great buildings, aqueducts, tunnels, mines, and bridges were constructed prior to the early 1700s, when the first scientific foundations were laid for engineering. Engineers often must solve problems without even understanding the underlying theory. Certainly, engineers benefit from scientific theory, but sometimes the solution is required before the theory can catch up to the practice. For example, theorists are still trying to fully explain high-temperature superconductors while engineers are busy forming flexible wires out of these new materials that may be used in future generations of electrical devices.

1.3 THE NEED FOR ENGINEERING

Appendix D describes how humankind's needs have been met by engineering throughout history. As you prepare for a career in engineering, you should be aware of the problems you will face. Here, we look briefly at some of the challenges in our future.

1.3.1 Resource Stewardship and Utilization

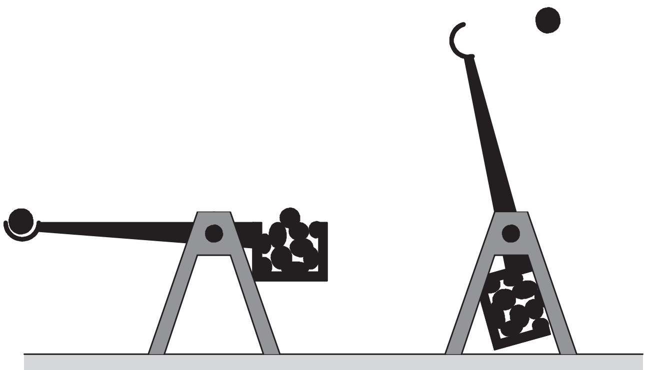
The history of engineering can be viewed as "humans versus nature." Humans made progress when they overcame some of nature's terrors by redirecting rivers, paving land, felling trees, and mining the earth. In view of our large population (about 8 billion), we can claim victory.

The Trebuchet: An Engine of War

The trebuchet (pronounced *tray-boo-shay*) pictured below is an ancient "engine" of war. It consists of a long beam that rotates about a fixed fulcrum. One end of the beam has a cup or sling into which the projectile is placed. At the other end is a counterweight that, when released, causes the beam to rotate and throw the projectile into the air.

The trebuchet was invented in China about 2200 years ago and reached the Mediterranean about 1400 years ago. It could throw objects weighing up to 1 ton great distances; in fact, it was used even after the invention of the cannon, because its range was greater than that of early artillery. A modern trebuchet constructed in England could throw a 476-kg car (without engine) 80 meters using a 30,000-kg counterweight. Ancient machines threw stones, dead horses, and even diseased human corpses as a form of biological warfare.

As is often the case, practice preceded theory; trebuchets were constructed and used long before their theory was understood. Many modern concepts, such as force vectors and work (a force exerted over a distance), are thought to have been developed by engineers seeking to improve trebuchet performance. The trebuchet is an example of military necessity causing advances in scientific understanding, a process that is still occurring.



Adapted from: P. E. Chevedden, L. Eigenbrod, V. Foley, and W. Soedel, "The Trebuchet," *Scientific American*, July 1995, pp. 66–71.

The rising wave of environmentalism results from our recognition that a fundamental change is now required. We can no longer be nature's adversary, but must become its caretaker. We have become so powerful, we literally can eliminate whole ecosystems either deliberately (e.g., by felling rain forests) or inadvertently (e.g., by releasing pollution into the water and air). Many scientists are also concerned that human activity may result in changing weather patterns due to the release of "greenhouse gases" such as carbon dioxide, methane, chlorofluorocarbons, and nitrogen oxides. Some chlorine-containing gases are implicated in the destruction of the ozone layer, which protects plants and animals from damaging ultraviolet light.

Although we humans have become extremely powerful, we still depend upon nature to provide the basics of life, such as food and oxygen. These basics do not come easily. NASA has spent millions of dollars to develop regenerative life support systems for use on the moon or Mars that allow people to live independently of earth's life support system. The research continues because the problem is so challenging.

"Sustainable development" is a recent economic philosophy that recognizes humans' right to live and improve their standard of living, while simultaneously protecting the environment. This philosophy attempts to reshape our economy to achieve sustainability. For example, basing our energy sources on fossil fuels is not sustainable. Eventually they will run out, or the pollution resulting from their use will make the planet uninhabitable. Sustainable development would require the use of renewable energy sources such as solar, wind, and biomass fuels, or "infinite" energy sources such as fission (with breeder reactors) or fusion. Resource conserving, recycling, and nonpolluting technologies are also essential to sustainable development.

In modern times, many resources are used once and then thrown away. This "one-pass" approach is increasingly unacceptable, because of the finite nature of our resources and because discarded resources cause pollution. Instead, engineers must develop a cyclical approach in which resources are reused. Some products are now designed to be dismantled when their useful life is completed. They are constructed of metals and polymers that can be reformed into new products.

All processes, including the cyclical processes developed by future engineers, are driven by energy. Because energy production expends resources and causes pollution, it is incumbent upon engineers to develop energy-efficient processes. Many of our current processes use energy inefficiently and can be greatly improved by future engineers.

Unavoidably, all processes produce waste. In the future, many engineers will be required to design processes that minimize wastes, produce wastes that can be converted to useful products, or convert the wastes to forms that can be safely stored.

1.3.2 Global Economy

During World War II, while much of the world economy was destroyed, the U.S. economy remained intact. For a few decades immediately following the war, the U.S. economy was very strong with high export levels. Foreign nations wanted our goods—not because they were of superior quality, but because there were few alternatives. In fact, the quality of many U.S. goods actually deteriorated due to sloppy manufacturing practices, adopted because our industry was not challenged by competition.

Today, the world economy is completely different. The economies of the world have long since recovered from the war. Many nations are capable of producing goods that are equal or superior to the quality of U.S. goods. After the war, a product labeled "Made in Japan" was assumed to be of poor quality; today, this label is an indication that the product is well made and affordable.

In a free market, consumers are able to buy products from all over the world. When they select products made in other countries, it represents a loss of jobs for the United States. American industry is meeting this challenge by instituting "quality" into the corporate culture. A company that is committed to quality must identify their customers, learn their requirements, and transform its manufacturing and management practices to create products that meet the customers' needs and expectations.

Because labor is generally less expensive overseas, many labor-intensive products cannot be economically manufactured in the United States using current technology. However, if engineers develop manufacturing methods that use machines to replace labor, then many of these products can be made in the United States.

Another way for the United States to compete is by developing high-technology products. A major U.S. competitive advantage is our very strong science base. We have a very healthy scientific enterprise in this nation. By translating the latest scientific research into consumer products, we can maintain a competitive edge.

1.4 THE TECHNOLOGY TEAM

Modern technical challenges are seldom met by the lone engineer. Technology development is a complex process involving the coordinated efforts of a technology team consisting of:

A Few Words on Diversity

To fully describe a person, the list of traits might include intellectual ability, personality, creativity, educational level, hobbies, hair color, skin color, body weight, height, age, physical strength, gender, religion, ethnic background, sexual orientation, nationality, language, parental upbringing, and so forth. The list is long, and there are so many variations within each trait that certainly every person is unique.

Because humanity is so diverse, you can be assured that the teammates on your technology team will be different from you. This diversity will be a source of either strength or weakness, depending upon how you respond to it.

Diversity is a source of strength when people with various backgrounds and abilities all work together on the technical problem. The benefits of diversity have long been recognized; hence the expression "two heads are better than one." This simple statement recognizes the fact that a single person may not have all the skills necessary to solve a complex problem, but collectively, the needed skills are there. Also, a diverse team has a useful variety of viewpoints. For example, although traditional automobile design teams have been strictly male, women have recently joined these teams. The female teammates have introduced a new perspective to automobile design, making the cars safer and more appealing to women, who constitute about 50% of the car-buying public.

Diversity is a source of weakness if teammates are so different that they cannot communicate, or they mistrust each other and cannot work together toward a common end. This potential weakness results from two common human tendencies: tribalism and overgeneralization. *Tribalism* refers to the fact that during most of human history, people have lived in tribes composed of similar members. When outsiders entered the tribal land, they were often treated with suspicion because they were potential enemies. *Overgeneralization* refers to the fact that in their attempt to understand the world, humans make generalizations from specific observations—but sometimes the generalizations go too far. For example, if Laura were watching a basketball game, she would observe that the team is composed primarily of tall people. After the game, if Laura were to meet Greg, who happens to be seven feet tall, she might assume that Greg plays basketball, when, in fact, he has no interest in the game. Tribalism and overgeneralization prevent people from dealing with each other as individuals; instead, perceived attributes of a group are automatically assigned to an individual. Not acknowledging the true character of a co-worker makes a working relationship impossible.

To gain strength from diversity and avoid potential pitfalls, it is important that the technology team share a common set of core values that allow it to work together. Some sample core values are shown below:

- Teammates are rewarded on the basis of hard work, not politics.
- Teammates are treated with respect.
- Teammates are treated as unique persons with their own skills, talents, abilities, and perspectives.

Adopting these core values, and others, will allow the team to function in harmony and gain strength from diversity.

- *Scientists,* who study nature in order to advance human knowledge. Although some scientists work in industry on practical problems, others have successful careers publishing results that may not have immediate practical applications. Typical degree requirement: BS, MS, PhD.
- *Engineers,* who apply their knowledge of science, mathematics, and economics to develop useful devices, structures, and processes. Typical degree requirement: BS, MS, PhD.
- *Technologists,* who apply science and mathematics to well-defined problems that generally do not require the depth of knowledge possessed by engineers and scientists. Typical degree requirement: BS.
- *Technicians,* who are generally supervised by engineers and scientists to accomplish specific tasks such as drafting, laboratory procedures, and model building. Typical degree requirement: two-year associate's degree.
- *Artisans,* who have the manual skills (welding, machining, carpentry) to construct devices specified by scientists, engineers, technologists, and technicians. Typical degree requirement: high school diploma plus experience.

Elijah McCoy: Mechanical Engineer and Inventor

Elijah McCoy was born in the early 1840s in Colchester, Ontario, Canada. His parents were former slaves who escaped from Kentucky via the Underground Railroad, a network of individuals who helped slaves reach freedom.

At that time, educational opportunities for blacks were limited, so at age 15, McCoy's parents sent him to study in Scotland, where he achieved the title "master mechanic and engineer." He returned to North America and settled in Detroit, Michigan. During the 1860s, it was difficult for blacks to obtain jobs in the professions, so his first job was a fireman/oilman on the Michigan Central Railroad. As a fireman, he shoveled coal into the firebox. As an oilman, he lubricated the machinery, which had to be stopped for that purpose, causing delays and reducing efficiency. This experience inspired his first patent (U.S. Patent 129,843, issued July 12, 1872), for a device that lubricated machinery while in motion. This lubricating device was so superior to the competition that some engineers would ask if machinery was equipped with *the real McCoy,* a popular American expression meaning *the real thing.* Interestingly, this expression originated in an 1856 advertising slogan *the real MacKay,* used to promote a Scottish brand of whiskey.

During his life, McCoy developed 57 patents. They were issued in the United States, Great Britain, Canada, France, Germany, Austria, and Russia. Among them were an ironing board and a lawn sprinkler.

In 1920, he established the Elijah McCoy Manufacturing Company to manufacture and sell his numerous inventions. He died nine years later in 1929. To honor his achievements as an inventor, he was inducted into the National Inventors Hall of Fame in 2001.

Adapted from the following websites:

www.princeton.edu/~mcbrown/display/mccoy.html
web.mit.edu/www/inventorsI-Q/mccoy.html
www.inventorsmuseum.com/elijahmccoy.htm
www.invent.org/book/book-text/mccoy.htm
www.uselessknowledge.com/word/mccoy.shtml

Successful teamwork results in accomplishments larger than can be produced by individual team members. There is a magic when a team coalesces and each member builds off of the ideas and enthusiasm of teammates. For this magic to occur and to produce output that surpasses individual efforts, several characteristics must be present:

- Mutual respect for the ideas of fellow team members.
- The ability of team members to transmit and receive the ideas of the team.
- The ability to lay aside criticism of an idea during early formulation of solutions to a problem.
- The ability to build on initial or weakly formed ideas.
- The skill to accurately criticize a proposed solution and analyze for both strengths and weaknesses.
- The patience to try again when an idea fails or a solution is incomplete.

1.5 ENGINEERING DISCIPLINES AND RELATED FIELDS

At this point in your engineering career, you may not have selected a major. Does your future lie in mechanical engineering, chemical engineering, electrical engineering, or other engineering fields? Once you have made your selection, you will have decided upon your engineering *discipline.* To help in this decision, we briefly describe the major engineering disciplines and some related fields.

Josephine Garis Cochrane: Inventor of the Dishwasher

In 1839, Josephine Garis was born into an industrious family. Her father, John Garis, was a civil engineer who supervised mills along the Ohio River and drained swamps to develop Chicago during the 1850s. Her great-grandfather, John Fitch, built a steamboat of his own design that served Philadelphia in 1786.

In 1853, at age 19, Josephine Garis married William Cochran, a handsome 27-year-old man who became wealthy in the dry goods business. Josephine was an independent woman—although she took her husband's name, she insisted on ending it with an *e*.

The young socialite couple was popular and had many friends, whom they entertained frequently with elaborate dinner parties using family heirloom china. The servants who washed the china were careless and broke too many plates, so Josephine decided to wash and dry the dishes herself. She soon concluded that this activity wasted her precious time, so she resolved to design a machine that would wash the dishes for her. Within a half hour, she decided that the machine should hold the dishes in a rack and high-pressure water would scrub them clean.

Shortly thereafter, in 1883, Josephine's husband died. Although he was a wealthy man, he had spent more than he earned, leaving her destitute. Nonetheless, with the help of mechanic George Butters, she built the first dishwasher in the shed behind her home, a site now marked with a historical marker. Powered by a hand pump, it cleaned dishes using streams of soapy water. Friends and neighbors came to see the contraption. They were delighted and encouraged her to pursue it further. On December 28, 1886, Mrs. Cochrane received her first patent on the dishwasher.

Because it was expensive, she decided to market her dishwasher to institutions, rather than homes. The Palmer House, a famous Chicago hotel, was her first customer. Her dishwasher could wash and dry 240 dishes within 2 minutes.

Because she had no capital, she hired a contractor to build the units. Relations were strained; the contractor would often ignore her ideas because she had no formal mechanical training and because she was a woman. Further, the contractor took most of the profits, even though she had the brains, patents, entrepreneurial talent, and sales orders. She was not able to raise capital from investors because they refused to invest in a company headed by a woman.

In 1893, nine of her Garis-Cochran dishwashers cleaned dirty dishes at the World's Columbian Exposition, a large fair held in Chicago. Judges awarded her machine the highest prize, stating it had the "best mechanical construction, durability and adaptation to its line of work." The resulting publicity generated more orders. By 1898, Mrs. Cochrane had saved enough money to open her own manufacturing facility and no longer depend on a contractor to build her machines. George Butters became the foreman and oversaw the three employees. Finally, she could work with people who respected her and did not challenge her ideas. Her dishwashers were acclaimed by hotels and other institutions because they saved labor, reduced breakage, and sanitized the dishes. Josephine had succeeded and lived to see her business thrive.

After her death in 1913, the company continued to manufacture dishwashers of her design. In 1926, the company was purchased by Hobart, a manufacturer of well-engineered appliances. Hobart changed the name of the dishwasher subsidiary to KitchenAid, which finally introduced a home dishwasher in the 1940s. Later, KitchenAid was acquired by Whirlpool, a major home appliance manufacturer.

Adapted from: J. M. Fenster, "The Woman Who Invented the Dishwasher," *American Heritage of Invention & Technology,* vol. 15, no. 2, pp. 54–61, Fall 1999.

Figure 1.1 shows when the major engineering disciplines were born. Nearly all disciplines are thought to have evolved from civil engineering. Note that all engineering disciplines require extensive knowledge of physics, whereas chemical and materials engineering require extensive knowledge of physics and chemistry. Some recent disciplines (biochemical and biomedical) require extensive knowledge of physics, chemistry, and biology.

1.5.1 Civil Engineering

Civil engineering is generally considered the oldest engineering discipline—its works trace back to the Egyptian pyramids and before. Many of the skills possessed by civil engineers (e.g., building walls, bridges, roads) are extremely useful in warfare, so these engineers worked on both military and civilian projects. To distinguish those engineers who work on civilian projects from those who work on military projects, the British engineer John Smeaton coined the term *civil engineer* in about 1750.

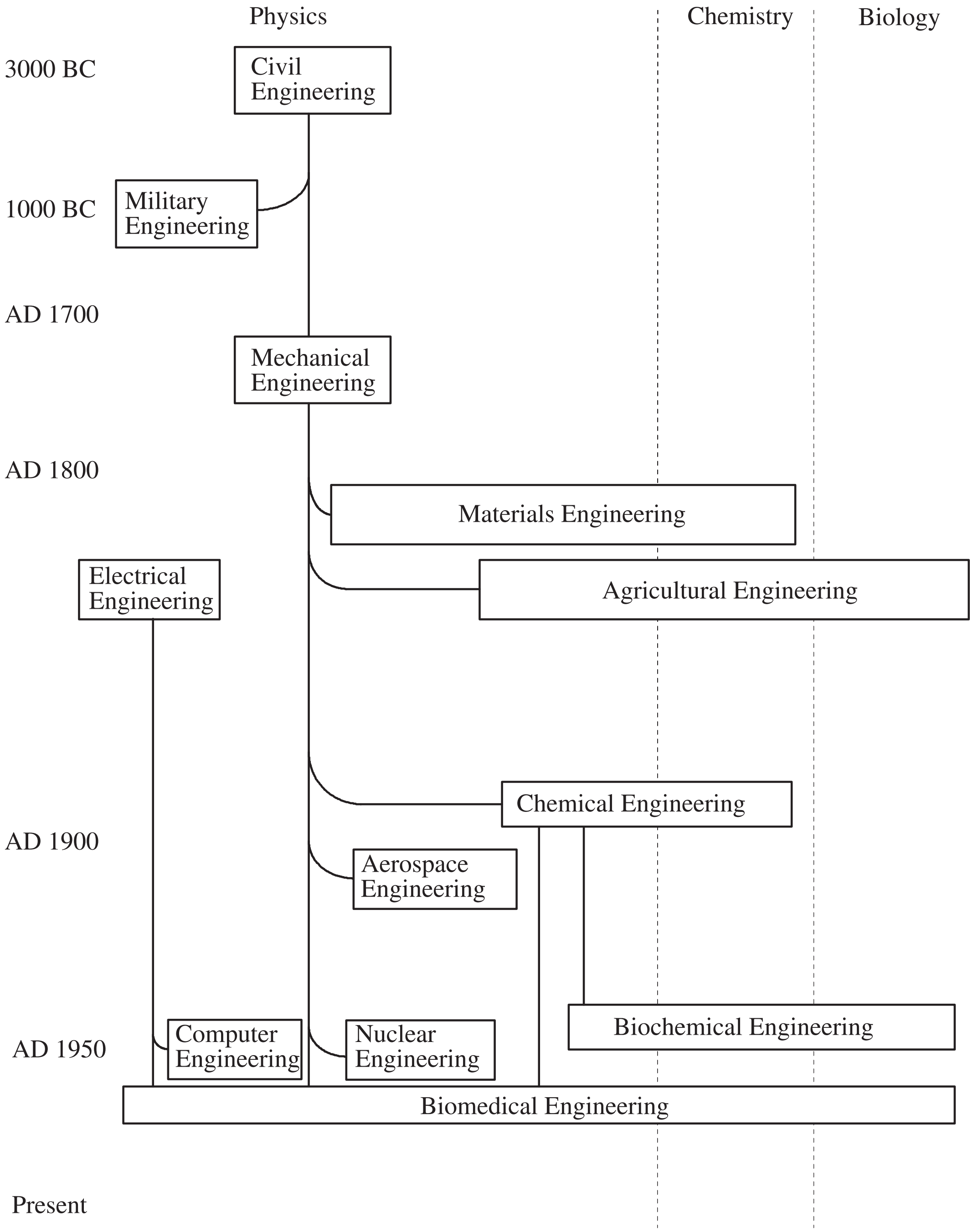


FIGURE 1.1
Birth of engineering disciplines (birth dates are approximate).

Ancient Egypt: From Engineer to God

Egyptian civilization ascended from the Late Stone Age, around 3400 B.C., with vigorous advancements in several engineering fields. While we can still see the spectacular construction feats of the Pyramid Age (3000–2500 B.C.), the ancient Egyptians also pioneered other engineering fields. As hydraulic engineers, they manipulated the Nile River for agricultural and commercial purposes; as chemical engineers, they produced dyes, cement, glass, beer, and wine; as mining engineers, they extracted copper from the Sinai Peninsula for use in the bronze tools that built the pyramids.

One of the key players of this period was Imhotep, known today as "The Father of Stone Masonry Construction." Imhotep served the pharaoh Zoser as chief priest, magician, physician, and head engineer. Most archaeologists credit Imhotep with designing and building the first pyramid, a stepped tomb for Zoser at Sakkara, around 2980 B.C. This pyramid consists of six stages, each 30 feet high, built from local limestone, and hewn with copper chisels. While only 200 feet high (the height of an 18-story building), this unique structure served as a prototype for the Great Pyramid at Giza, constructed 70 years later, which covers four city blocks in area and originally stood 480 feet high.

Imhotep acquired an extensive reputation as a sage, and in later centuries was recognized as the Egyptian god of healing. Although Egyptian civilization saw great engineering progress during the Pyramid Age, 2000 years of stagnation and decline followed.

Hypostyle Hall of Karnak Temple in Luxor, Egypt.
Tatiana-GV/iStock/Getty Images

Courtesy of Seth Adelson, graduate student.

Civil engineers are responsible for constructing large-scale projects such as roads, buildings, airports, dams, bridges, harbors, canals, water systems, and sewage systems.

1.5.2 Mechanical Engineering

Mechanical engineering was practiced concurrently with civil engineering because many of the devices needed to construct great civil engineering projects were mechanical in nature. During the Industrial Revolution (1750–1850), wonderful machines were developed: steam engines, internal combustion engines, mechanical looms, sewing machines, and more. Here we saw the birth of mechanical engineering as a discipline distinct from civil engineering.

Mechanical engineers make engines, vehicles (automobiles, trains, planes), machine tools (lathes, mills), heat exchangers, industrial process equipment, power plants, consumer items (typewriters, pens), and systems for heating, refrigeration, air conditioning, and ventilation. Mechanical engineers must know structures, heat transfer, fluid mechanics, materials, and thermodynamics, among many other things.

1.5.3 Electrical Engineering

Soon after physicists began to understand electricity, the electrical engineering profession was born. Electricity has served two main functions in society: the transmission of power and of information. Those electrical engineers who specialize in power transmission design and build electric generators, transformers, electric motors, and other high-power equipment. Those who specialize in information transmission design and build radios, televisions, computers, antennae, instrumentation, controllers, and communications equipment.

Electronic equipment can be **analog** (meaning the voltages and currents in the device are *continuous* values) or **digital** (meaning only *discrete* voltages and currents can be attained by the device). As analog equipment is more susceptible to noise and interference than digital equipment, many electrical engineers specialize in digital circuits.

Modern life is largely characterized by electronic equipment. Daily, we rely on many electronic devices—televisions, telephones, computers, calculators, and so on. In the future, the number and variety of these devices can only increase.

1.5.4 Chemical Engineering

By 1880, the chemical industry was becoming important in the U.S. economy. At that time, the chemical industry hired two types of technical persons: mechanical engineers and industrial chemists. The chemical engineer combined these two persons into one. The first chemical engineering degree was offered at the Massachusetts Institute of Technology (MIT) in 1888.

Chemical engineering is characterized by a concept called *unit operations.* A unit operation is an individual piece of process equipment (chemical reactor, heat exchanger, pump, compressor, distillation column). Just as electrical engineers assemble complex circuits from component parts (resistors, capacitors, inductors, batteries), chemical engineers assemble chemical plants by combining unit operations together.

Chemical engineers process raw materials (petroleum, coal, ores, corn, trees) into refined products (gasoline, heating oil, plastics, pharmaceuticals, paper). Biochemical engineering is a growing subdiscipline of chemical engineering. Biochemical engineers combine biological processes with traditional chemical engineering to produce food and pharmaceuticals and to treat wastes.

1.5.5 Industrial Engineering

In the late 1800s, industries began to use "scientific management" techniques to improve efficiency. Early pioneers in this field did time-motion studies on workers to reduce the amount of labor required to produce a product. Today, industrial engineers develop, design, install, and operate integrated systems of people, machinery, and information to produce either goods or services. Industrial engineers bridge engineering and management.

Industrial engineers are famous for designing and operating assembly lines that optimally combine machinery and people. However, they can also optimize train or plane schedules, hospital operations, banks, or overnight package delivery services. Industrial engineers who specialize in human factors design products (e.g., hand tools, airplane cockpits) with the human user in mind.

1.5.6 Aerospace Engineering

Aerospace engineers design vehicles that operate in the atmosphere and in space. It is a diverse and rapidly changing field that includes four major technology areas: aerodynamics, structures and materials, flight and orbital mechanics and control, and propulsion. Aerospace engineers help design and build high-performance flight vehicles (e.g., aircraft, missiles, and spacecraft) as well as automobiles. Also, aerospace engineers confront problems associated with wind effects on buildings, air pollution, and other atmospheric phenomena.

1.5.7 Materials Engineering

Materials engineers are concerned with obtaining the materials required by modern society. Materials engineers may be further classified as:

- *Geological engineers,* who study rocks, soils, and geological formations to find valuable ores and petroleum reserves.
- *Mining engineers,* who extract ores such as coal, iron, and tin.
- *Petroleum engineers,* who find, produce, and transport oil and natural gas.
- *Ceramic engineers,* who produce ceramic (i.e., nonmetallic mineral) products.
- *Plastics engineers,* who produce plastic products.
- *Metallurgical engineers,* who produce metal products from ores or create metal alloys with superior properties.
- *Materials science engineers,* who study the fundamental science behind the properties (e.g., strength, corrosion resistance, conductivity) of materials.

1.5.8 Agricultural Engineering

Agricultural engineers help farmers efficiently produce food and fiber. This discipline was born with the McCormick reaper. Since then, agricultural engineers have developed many other farm implements (tractors, plows, choppers, etc.) to reduce farm labor requirements. Modern agricultural engineers apply knowledge of mechanics, hydrology, computers, electronics, chemistry, and biology to solve agricultural problems. Agricultural engineers may specialize in food and biochemical engineering; water and environmental quality; machine and energy systems; and food, feed, and fiber processing.

1.5.9 Nuclear Engineering

Nuclear engineers design systems that employ nuclear energy, such as nuclear power plants, nuclear ships (e.g., submarines and aircraft carriers), and nuclear spacecraft. Some nuclear engineers are involved with nuclear medicine; others are working on the design of fusion reactors that potentially will generate limitless energy with minimal environmental damage.

1.5.10 Architectural Engineering

Architectural engineers combine the engineer's knowledge of structures, materials, and acoustics with the architect's knowledge of building esthetics and functionality.

1.5.11 Biomedical Engineering

Biomedical engineers combine traditional engineering fields (mechanical, electrical, chemical, industrial) with medicine and human physiology. They develop prosthetic devices (e.g., artificial limbs), artificial kidneys, pacemakers, and artificial hearts. Recent developments will enable some deaf people to hear and some blind people to see. Biomedical engineers can work in hospitals as clinical engineers, in medical centers as medical researchers, in medical industries designing clinical devices, in the FDA evaluating medical devices, or as physicians providing health care.

1.5.12 Computer Science and Engineering

Computer science and engineering evolved from electrical engineering. Computer scientists understand both computer software and hardware, but they emphasize software. In contrast, computer engineers understand both computer software and hardware but emphasize hardware. Computer scientists and engineers design and build computers ranging from supercomputers to personal computers, network computers together, write operating system software that regulates computer functions, or write applications software such as word processors and spreadsheets. Given the increasingly important role of computers in modern society, computer science and engineering are rapidly growing professions.

1.5.13 Engineering Technology

Engineering technologists bridge the gap between engineers and technicians. Engineering technologists typically receive a 4-year BS degree and share many courses with their engineering cousins. Their course work evenly emphasizes both theory and hands-on applications, whereas the engineering disciplines described above primarily emphasize theory with less emphasis on hands-on applications. Engineering technologists can acquire specialties such as general electronics, computers, and mechanics. With their skills, engineering technologists perform such functions as designing and building electronic circuits, repairing faulty circuits, maintaining computers, and programming numerically controlled machine shop equipment.

1.5.14 Engineering Technicians

Engineering technicians typically receive a 2-year associate's degree. Their education primarily emphasizes hands-on applications with less emphasis on theory. They are involved in product design, testing, troubleshooting, and manufacturing. Their specialties include the following: electronics, drafting, automated manufacturing, robotics, and semiconductor manufacturing.

1.5.15 Artisans

Artisans often receive no formal schooling beyond high school. Typically, they learn their skills by apprenticing with experienced artisans who show them the "tricks of the trade." Artisans have a variety of manual skills such as machining, welding, carpentry, and equipment operation. Artisans are generally responsible for transforming engineering ideas into reality; therefore, engineers often must work closely with them. Wise engineers highly value the opinions of artisans, because artisans frequently have many years of practical experience.

1.5.16 Engineering Employment Statistics

Table 1.1 shows the number of engineers employed in the United States. Approximately 1.7 percent of all employees are engineers.

TABLE 1.1
Number of engineers and other professions in the United States

Engineering	Total	Men	Women
Civil	296,415	260,835	35,580
Mechanical	235,040	218,615	16,425
Electrical	181,095	166,735	14,360
Industrial	176,575	140,375	36,200
Aerospace	111,435	99,810	11,625
Chemical	53,875	44,190	9,680
Computer hardware	47,555	41,925	5,630
Materials	33,025	30,260	2,765
Environmental	25,495	18,525	6,970
Petroleum	22,045	18,925	3,120
Biomedical	12,910	10,900	2,010
Marine	10,185	9,115	1,070
Mining	7,925	7,015	915
Nuclear	6,180	5,075	1,105
Agricultural	1,780	—	—
Others	457,085	400,170	56,915
Total	1,678,620	1,472,470	204,370
Computers and Mathematics			
Software developers	1,085,705	886,910	198,800
Computer systems analysts	431,495	258,025	173,470
Computer programmers	358,785	283,500	75,285
Web developers	129,610	87,215	42,395
Information security analysts	72,830	58,875	13,955
Computer scientists	15,920	12,770	3,150
Mathematicians	1,290	1,035	255
Other Professionals			
Lawyers	890,650	568,465	322,185
Physicians	743,005	489,670	253,335
Pharmacists	213,205	96,765	116,435
Architects	154,410	117,970	36,440
Dentists	93,295	66,000	27,295
Scientists			
Chemists	73,010	46,920	26,095
Biologists	61,515	33,630	27,885
Physicists	9,735	7,670	2,070
Total Workers (full-time, >25 years old)	99,399,500	56,659,885	42,739,615
Total Population	322,941,311	158,887,125	164,054,186

Source: U.S. Census (2016)

1.6 ENGINEERING FUNCTIONS

Regardless of their discipline, engineers can be classified by the functions they perform:

- *Research engineers* search for new knowledge to solve difficult problems that do not have readily apparent solutions. They require the greatest training, generally an MS or PhD degree.
- *Development engineers* apply existing and new knowledge to develop prototypes of new devices, structures, and processes.
- *Design engineers* apply the results of research and development engineers to produce detailed designs of devices, structures, and processes that will be used by the public.
- *Production engineers* are concerned with specifying production schedules, determining raw materials availability, and optimizing assembly lines to mass produce the devices conceived by design engineers.
- *Testing engineers* perform tests on engineered products to determine their reliability and suitability for particular applications.
- *Construction engineers* build large structures.
- *Operations engineers* run and maintain production facilities such as factories and chemical plants.
- *Sales engineers* have the technical background required to sell technical products.
- *Managing engineers* are needed in industry to coordinate the activities of the technology team.
- *Consulting engineers* are specialists who are called upon by companies to supplement their in-house engineering talent.
- *Teaching engineers* educate other engineers in the fundamentals of each engineering discipline.

To illustrate the roles of engineering disciplines and functions, consider all the steps required to produce a new battery suitable for automotive propulsion. (The probable engineering discipline is in parentheses and the engineering function is in italics.) A *research engineer* (chemical engineer) performs fundamental laboratory studies on new materials that are possible candidates for a rechargeable battery that is lightweight but stores much energy. The *development engineer* (chemical or electrical engineer) reviews the results of the research engineer and selects a few candidates for further development. She constructs some battery prototypes and tests them for such properties as maximum number of recharge cycles, voltage output at various temperatures, effect of discharge rate on battery life, and corrosion. If the development engineer lacks expertise in corrosion, the company would temporarily hire a *consulting engineer* (chemical, mechanical, or materials engineer) to solve a corrosion problem. When the development engineer has finally amassed sufficient information, the *design engineer* (mechanical engineer) designs each battery model that will be produced by the company. He must specify the exact composition and dimension of each component and how each component will be manufactured. A *construction engineer* (civil engineer) erects the building in which the batteries will be manufactured and a *production engineer* (industrial engineer) designs the production line (e.g., machine tools, assembly areas) to mass produce the new battery. *Operations engineers* (mechanical or industrial engineers) operate the production line and ensure that it is properly maintained. Once the production line is operating, *testing engineers* (industrial or electrical engineers) randomly select batteries and test them to ensure that they meet company specifications. *Sales engineers* (electrical or mechanical engineers) meet with automotive companies to explain the advantages of their company's battery and answer technical questions. *Managing engineers* (any discipline) make decisions about financing plant expansions, product pricing, hiring new personnel, and setting company goals. All of these engineers were trained by *teaching engineers* (many disciplines) in college.

In this example, the engineering disciplines that satisfy each function are unique to the project. Other projects would require the coordinated efforts of other engineering disciplines. Also, the disciplines selected for this project are an idealization. A company might not have the ideal mix of engineers required by a project and would expect its existing engineering staff to adapt to the needs of the project. After many years, engineers become cross trained in other disciplines, so it becomes difficult to classify them by the disciplines they studied in college. An engineer who wishes to stay employed must be adaptable, which means being well acquainted with the fundamentals of other engineering disciplines.

1.7 HOW MUCH FORMAL EDUCATION IS RIGHT FOR YOU?

Knowledge is expanding at an exponential rate. It is impossible to fully grasp engineering in a 4-year BS degree. Although you will continue learning on the job, your experience there will tend to be narrowly focused on the needs of the company.

As you proceed through your engineering studies, you should ask yourself, How much more formal education do I need? The answer depends upon your ultimate career objectives. Many of the job functions described above can be performed adequately with a BS degree. However, others—like the research engineer and the development engineer—generally require an MS or a PhD. These individuals are engaged in the early stages of product development. More education is required because they must solve more challenging technical problems.

If you think that you would enjoy the technical challenges met by advanced-degree engineers, do not let the educational costs dissuade you. Most graduate schools provide financial assistance to their students in the form of a stipend. Although the stipend does not equal the pay received in industry, it is usually enough to live a comfortable life. Because people with advanced degrees generally earn higher salaries (Figure 1.2), the short-term financial loss may eventually be recouped. Financial gain should not be your primary motivation for obtaining an advanced degree, however. You should consider it only if you would enjoy a job with greater technical challenges.

Some BS engineering students decide to continue formal education in other fields such as law, medicine, or business. The engineering curriculum provides an excellent background for these other fields because it develops excellent discipline, work habits, and thinking skills.

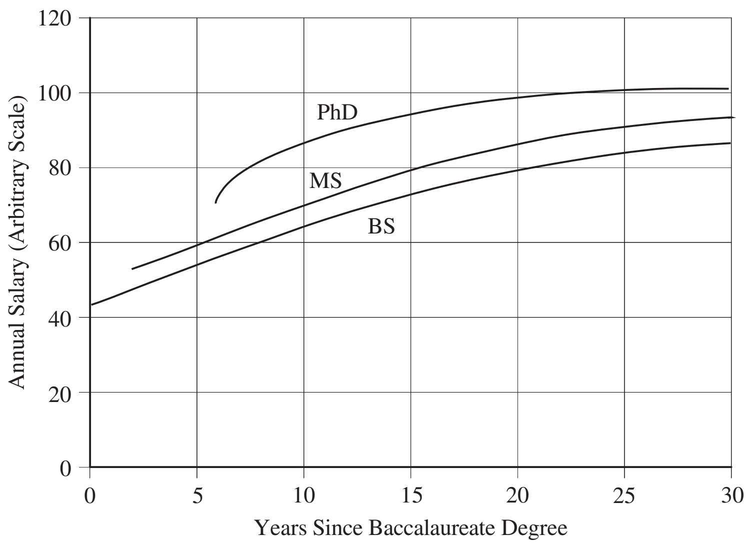


FIGURE 1.2

Median salaries for engineers with different levels of education.

Source: Engineering Workforce Commission of the American Association of Engineering Societies, *Engineers: A Quarterly Bulletin on Careers in the Profession* 1, no. 3 (July 1995).

1.8 THE ENGINEER AS A PROFESSIONAL

Historically, a professional was simply a person who professed to be "duly qualified" in a given area. Often, these professionals professed adherence to the monastic vows of a religious order. So, being a professional meant not only mastering a body of knowledge, but also abiding by proper standards of conduct.

In the modern world, our concept of a professional has become more formalized. We consider a **professional** to have the following traits:

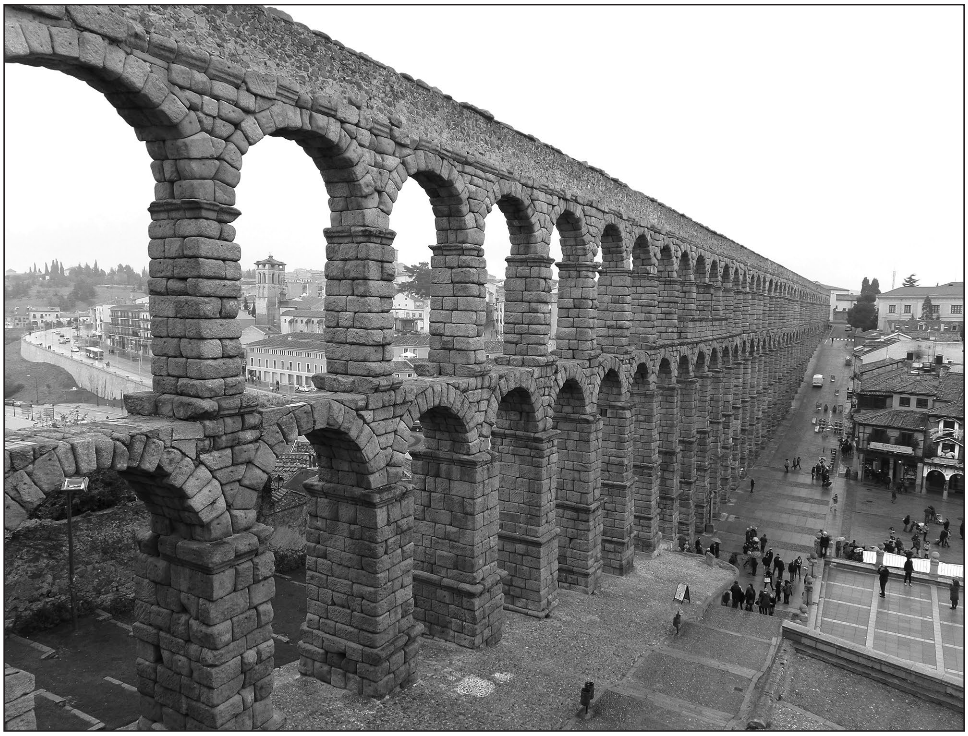
- *Extensive intellectual training*—all professions require many years of schooling, at the undergraduate or post-graduate level.
- *Pass qualifying exam*—professionals must demonstrate that they master a common body of knowledge.
- *Vital skills*—the skills of professionals are vital to the proper functioning of society.
- *Monopoly*—society gives professionals a monopoly to practice in their respective fields.
- *Autonomy*—society entrusts professionals to be self-regulated.
- *Code of ethics*—the behavior of professionals is regulated by self-imposed codes.

Engineering, architecture, medicine, law, dentistry, and pharmacy are examples of professions; they are some of the most prestigious occupations in our society.

1.8.1 Engineering Education

Since 1933, engineering education has been accredited by the Accrediting Board for Engineering and Technology (ABET). The primary purpose of accreditation is to ensure that graduates from engineering programs are adequately prepared to practice

The Roman Republic and Empire: Paving the World



Roman aqueduct in Segovia, Spain.
lovelypeace/123RF

Over a period of 800 years, the city-state of Rome grew from a crowded Latin settlement to the nerve center of an empire stretching from present-day Scotland to Israel. To maintain the stability of their vast realm, the Romans implemented many public works, using contemporary technology to supply water, remove sewage, allow transportation, traverse rivers, and provide entertainment.

Scientific achievement under Roman rule was minimal; the Romans were not interested in theory. Applying simple principles with plenty of cheap materials and slave labor gave satisfactory results. For example, early Roman builders used the semicircular arch, an architectural concept developed by the Etruscans (a non-Indo-European people from northern Italy), to construct the magnificent aqueducts that supplied Rome with water. Although many earlier peoples had used concrete, Roman engineers manufactured an improved mixture, yielding a building material as hard and as waterproof as natural rock. With this improved concrete, they built well-planned cities with apartment buildings, or *insulae* ("islands"), that rose five stories high and provided central heating.

The Roman network of roads, beginning with the famed Via Appia in central Italy and then expanding outward into the Empire, was originally intended for military use. To defend its borders and continue its expansion, the Empire required rapid transportation of soldiers over a hard surface with sure footing. Roman engineers built their roads to last; they used simple instruments with plumb bobs to keep the surfaces level, and they often laid down four or five layers, 4 feet thick and 20 feet wide.

Courtesy of Seth Adelson, graduate student.

engineering. Although schools can offer nonaccredited engineering programs, graduates from these schools may have difficulty finding employment.

When an engineering program is evaluated by ABET, the evaluation team assesses the quality of the students, faculty, facilities, and curriculum. The curriculum must include (1) general education courses, (2) 1 year of college-level mathematics and basic sciences, and (3) $1\frac{1}{2}$ years of engineering science and design. The curriculum must culminate with a major design experience.

Rather than prescribing a list of courses, ABET allows each engineering department to design its own curriculum that allows students to meet specified goals. During the evaluation of an engineering program, ABET determines if the graduates have the following skills:

a. An ability to apply knowledge of mathematics, science, and engineering.
b. An ability to design and conduct experiments, as well as to analyze and interpret data.
c. An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.
d. An ability to function on multidiscipline teams.
e. An ability to identify, formulate, and solve engineering problems.
f. An understanding of professional and ethical responsibility.
g. An ability to communicate effectively.
h. The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.
i. A recognition of the need for, and an ability to engage in, life-long learning.
j. A knowledge of contemporary issues.
k. An ability to use techniques, skills, and modern engineering tools necessary for engineering practice.

1.8.2 Registered Professional Engineer

Each state has the power to license and register professional engineers. The purpose is to protect the public by ensuring minimum standards through testing, experience, and letters of recommendation. In 1907, the need to license engineers was made evident in Wyoming. Chaos resulted when homesteaders surveyed their own water rights and declared themselves as the surveying engineer. Today, all states have an engineering board that licenses and registers engineers.

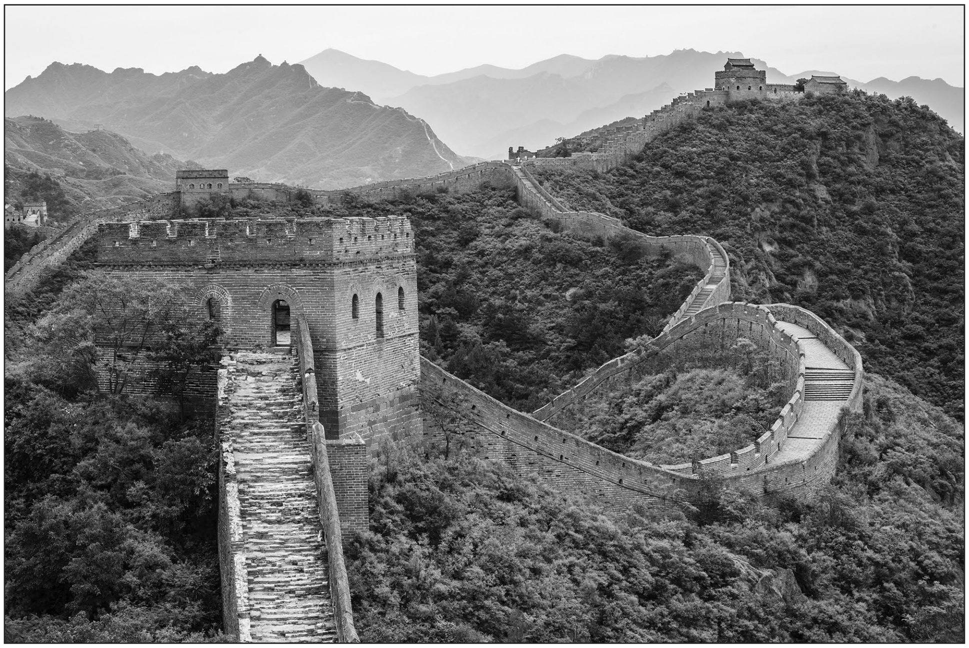
An engineer does not need a license to practice engineering, but those who do have licenses have more career opportunities. Many industrial and government positions can only be filled by licensed engineers.

Although each state has its own licensing regulations, the procedure is generally as follows:

1. Obtain a degree from an institution recognized by the state engineering board. This requirement is automatically satisfied if the institution is accredited by ABET.
2. Successfully complete the Fundamentals of Engineering examination. This is a 6-hour exam on discipline specifics, as well as fundamentals in chemistry, mathematics, structures, electronics, economics, and other subjects. The title “Engineer in Training” (EIT) is given to engineering graduates who pass the exam.
3. Work 4 years as an engineer.
4. Obtain letters of recommendation.
5. Successfully complete the Principles and Practice examination, which is an 8- to 10-hour exam on the engineer’s discipline.

Both exams are prepared by the National Council of Examiners for Engineering and Surveying (NCEES) and are offered throughout the country at about the same time. If you wish to become a registered professional engineer, you should plan to take the Fundamentals exam during your last semester of college, when the knowledge is still fresh in your mind.

China Through the Ages: Walls, Words, and Wells



Great Wall of China.
axz700/Shutterstock

No discussion of ancient engineering feats is complete without mention of the Great Wall of China. Construction began in the third century B.C., under the rule of the brutal emperor Qin Shi Huang Di (a title meaning "First Divine Autocrat of the Qin Dynasty"). The emperor's goal was to secure China from the murderous Huns of northern Asia. To this end, he forced hundreds of thousands of Chinese peasants, men and women, to leave their homes and fields and join the building effort. Though not completed during Qin's lifetime, the Wall eventually grew to a length of over 2200 miles, including the spurs and branches. If placed in America, it would stretch from New York City to Des Moines, Iowa. Materials and dimensions vary over the entire length, but the Wall is largely constructed of clay bricks, 25 feet thick at the base and rising 30 feet high. Watchtowers are spaced every few hundred yards. The Wall has been rebuilt by various rulers throughout history, even into the 19th century.

Later Chinese engineering accomplishments, though not quite as large, are equally remarkable. In the 1st century A.D., the courtly eunuch Cai Lun concocted paper from tree bark, hemp, rags, and fishnets. Later, development of the printing press in the 9th through the 12th centuries made the Chinese the first publishers as well as the first to circulate printed currency.

Pioneering the chemical industry, engineers of the landlocked Sichuan province in central China collected brine from deep wells for salt production as early as the 11th century A.D. Salt accounted for the bulk of the local economy for over 800 years. Using bamboo cables to drill and bamboo pipes to collect, the wells grew from 100 to 1000 meters deep as technology improved. As early as the 16th century, the Sichuanese learned to store the natural gas that also came from the wells, and used it to fire the brine boilers.

Courtesy of Seth Adelson, graduate student.

1.8.3 Professional Societies

Most professions have professional societies. The American Medical Association (for physicians) and the American Dental Association (for dentists) serve the interests of those professions. Similarly, we engineers have professional societies that serve our interests. The first engineering professional society was the Institute of Civil Engineers, founded in Britain in 1818. The first American professional society was the American Society of Civil Engineers, founded in 1852. Since then, many other professional societies have been founded (Table 1.2).

TABLE 1.2
Internet addresses of major professional societies

AAES	American Association of Engineering Societies	www.aaes.org
NSPE	National Society of Professional Engineers	www.nspe.org
IEEE	The Institute of Electrical and Electronics Engineers	www.ieee.org
ASCE	American Society of Civil Engineers	www.asce.org
ASME	The American Society of Mechanical Engineers	www.asme.org
AIChE	American Institute of Chemical Engineers	www.aiche.org
IISE	Institute of Industrial and Systems Engineers	www.iienet.org
AIAA	American Institute of Aeronautics and Astronautics	www.aiaa.org
ACM	Association for Computing Machinery	www.acm.org
AIME	American Institute of Mining, Metallurgical and Petroleum Engineering	www.aimehq.org
ASABE	American Society of Agricultural and Biological Engineers	www.asabe.org
ANS	American Nuclear Society	www.ans.org
BMES	Biomedical Engineering Society	www.bmes.org
MAES	Society of Mexican American Engineers and Scientists	www.mymaes.org
NSBE	National Society of Black Engineers	www.nsbe.org
SWE	Society of Women Engineers	www.swe.org

The primary function of professional societies is to exchange information between members. This is accomplished in such ways as publishing technical journals, holding technical conferences, maintaining technical libraries, teaching continuing education courses, and providing employment statistics (salaries, fringe benefits) so members can assess their compensation. Some professional societies will assist members to find jobs or advise government in technical matters related to their profession.

As a student, you are highly encouraged to get involved with student chapters of professional societies in your discipline. They provide many benefits, such as group meetings that allow you to interact with industry, fellow students, and faculty. If you become a student officer, the leadership experience will be invaluable to your future success. Many student chapters arrange for plant trips so you can learn about the "real world" of engineering. Also, student chapters have social gatherings where you can become better acquainted with your peers.

1.9 THE ENGINEERING DESIGN METHOD

In high school, you probably have been exposed to the **scientific method:**

1. Develop *hypotheses* (possible explanations) of a physical phenomenon.
2. Design an experiment to critically test the hypotheses.
3. Perform the experiment and analyze the results to determine which hypothesis, if any, is consistent with the experimental data.
4. Generalize the experimental results into a law or theory.
5. Publish the results.

Although engineers use knowledge generated by the scientific method, they do not routinely use the method; that is the domain of scientists. The goals of scientists and engineers are different. Scientists are concerned with discovering what *is,* whereas engineers are concerned with designing what *will be.* To achieve our goals, engineers use the **engineering design method,** which is, briefly stated:

1. Identify and define the problem.
2. Assemble a design team.
3. Identify constraints and criteria for success.
4. Search for solutions.
5. Analyze each potential solution.
6. Choose the "best" solution.
7. Document the solution.
8. Communicate the solution to management.
9. Construct the solution.
10. Verify and evaluate the performance of the solution.

This method is described in much greater detail in Chapter 5, "Introduction to Design."

Your engineering education will focus primarily on **analysis.** The hundreds (or thousands) of homework and exam problems you will work during your studies are all designed to sharpen your analytical skills.

In their analysis of physical systems, engineers use **models.** A model represents the real system of interest. Depending upon the quality of the model, it may, or may not, be an accurate representation of reality.

1.9.1 Qualitative Models

A **qualitative model** is a simple relationship that is easily understood. For example, if you were designing a grandfather clock, the *period* of the pendulum—the time it takes to swing back and forth—would be a critical design issue because the pendulum regulates the clock (Figure 1.3). By observing a swinging rock tied to a string, you may notice that longer strings lengthen the period. A simple relationship such as this is very useful to the engineer; however, it is generally insufficient for rigorous analysis. We usually require more quantitative information. To build the clock, we need to know the exact period for a given pendulum length.

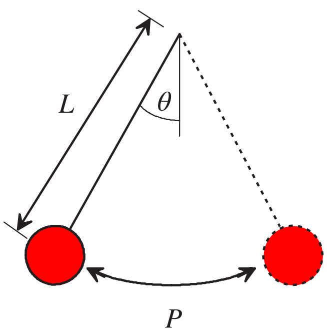


FIGURE 1.3
Pendulum.

1.9.2 Mathematical Models

Because engineering usually needs quantitative values, we transform these qualitative ideas about string length into mathematical formulas. For small displacement angles θ (less than about 15°), physics tells us that the period P of the pendulum (the time it takes to return to its original starting position) can be calculated by the simple formula

$$P = 2\pi\sqrt{\frac{L}{g}} = \frac{2\pi}{\sqrt{g}}\sqrt{L} = k\sqrt{L} \tag{1-1}$$

where L is the pendulum length (measured from the pivot point to the center of the pendulum mass), g is the acceleration due to gravity (9.8 m/s^2), and k is a proportionality constant. This relationship tells us "exactly" how the period changes with length.

Actually, this mathematical relationship is not exact; it applies only for small angles θ. Even at small angles, there is some error in the model. This simple mathematical model neglects factors such as air drag, friction at the pivot point, and the buoyancy of the swinging mass in air. Because air density changes with height above the earth, a complete model would have to account for this effect, even though the mass changes height by only a few centimeters. This simple model assumes that g, the acceleration due to gravity, is a constant. In fact, g decreases at distances farther from the center of the earth. Again, a complete model would have to account for the slight changes in g as the pendulum swings back and forth. A complete model should include the effects of electrical eddy currents generated in the metal pendulum as it swings through the earth's magnetic field. Because light exerts a slight pressure on objects, the complete model would have to account for the effect of light pressure.

You can see from this discussion that a complete model of the pendulum is hopelessly complex. Engineers rarely are able to develop complete mathematical models. However, even incomplete mathematical models may be extremely useful for design purposes, so we use them. A good engineer designs the final product so adjustments can be made to correct for minor effects not considered in the model, or to accommodate slight variations in the manufacturing process. In the case of the grandfather clock, the pendulum could have an adjustment screw that slightly changes its length.

Once a mathematical model of the system has been developed, the complete power of mathematics is at the disposal of the engineer to manipulate the mathematical description of the system. Insofar as the mathematical model is a reasonably accurate description of reality, the mathematical manipulations will also result in equations that approximate reality.

1.9.3 Digital Computer Models

Mathematical models may be programmed and solved using digital computers. In our pendulum example, we could write a computer program that calculates the position of the pendulum as time progresses. At each position, we could calculate the air density, the buoyancy forces, the acceleration due to gravity, the light-pressure forces, the air drag, and the pivot-point friction. The computer model would use all of this information to calculate the next position. All of this information would then be recalculated, allowing the next position to be determined. This may sound like a lot of work. It is. The amount of modeling effort expended depends upon how accurately the period must be known. Perhaps it would be better to use the simpler model and, using an adjustment screw on the pendulum, calibrate it against an electronic clock.

1.9.4 Analog Computer Models

Electronic circuits can be configured to simulate physical systems. Before digital computers became widely available, analog computers were frequently used. Today, they are rarely used because digital computers are more versatile and powerful.

1.9.5 Physical Models

Some systems are extremely complex and require physical models. For example, wind tunnel models of the space shuttle were constructed to determine its flight characteristics.

Engineers use a physical model of the Mississippi River to understand the effect of silt deposits and rainfall on its flow rate. Chemical engineers build a pilot plant to test a chemical process before the industrial-scale plant is constructed.

1.10 TRAITS OF A SUCCESSFUL ENGINEER

All of us would like to be successful in our engineering careers, because it brings personal fulfillment and financial reward. (For most engineers, financial reward is not the highest priority. Surveys of practicing engineers show that they value exciting and challenging work performed in a pleasant work environment over monetary compensation.) As a student, you may feel that performing well in your engineering courses will guarantee success in the real engineering world. Unfortunately, there are no guarantees in life. Ultimate success is achieved by mastering many traits, of which academic prowess is but one. By mastering the following traits, you will increase your chances of achieving a successful engineering career:

- *Interpersonal skills.* Engineers are typically employed in industry where success is necessarily a group effort. Successful engineers have good interpersonal skills. Not only must they effectively communicate with other highly educated engineers, but also with artisans, who may have substantially less education, or other professionals who are highly educated in other fields (marketing, finance, psychology, etc.).
- *Communication skills.* Although the engineering curriculum emphasizes science and mathematics, some practicing engineers report that they spend up to 80% of their time in oral and written communications. Engineers generate engineering drawings or sketches to describe a new product, be it a machine part, an electronic circuit, or a crude flowchart of new computer code. They document test results in reports. They write memos, manuals, proposals to bid on jobs, and technical papers for trade journals. They give sales presentations to potential clients and make oral presentations at technical meetings. They communicate with the workers who actually build the devices designed by engineers. They speak at civic groups to educate the public about the impact of their plant on the local economy, or address safety concerns raised by the public.
- *Leadership.* Leadership is one of the most desired skills for success. Good engineering leaders do not follow the herd; rather, they assess the situation and develop a plan to meet the group's objectives. Part of developing good leadership skills is learning how to be a good follower as well.
- *Competence.* Engineers are hired for their knowledge. If their knowledge is faulty, they are of little value to their employer. Performing well in your engineering courses will improve your competence.
- *Logical thinking.* Successful engineers base decisions on reason rather than emotions. Mathematics and science, which are based upon logic and experimentation, provide the foundations of our profession.
- *Quantitative thinking.* Engineering education emphasizes quantitative skills. We transform qualitative ideas into quantitative mathematical models that we use to make informed decisions.
- *Follow-through.* Many engineering projects take years or decades to complete. Engineers have to stay motivated and carry a project through to completion. People who need immediate gratification may be frustrated in many engineering projects.
- *Continuing education.* An undergraduate engineering education is just the beginning of a lifetime of learning. It is impossible for your professors to teach all relevant current

knowledge in a 4-year curriculum. Also, over your 40-plus-year career, knowledge will expand dramatically. Unless you stay current, you will quickly become obsolete.

- *Maintaining a professional library.* Throughout your formal education, you will be required to purchase textbooks. Many students sell them after the course is completed. If that book contains useful information related to your career, it is foolish to sell it. Your textbooks should become personalized references with appropriate underlining and notes in the margins that allow you to quickly regain the knowledge years later when you need it. Once you graduate, you should continue purchasing handbooks and specialized books related to your field. Recall that you will be employed for your knowledge, and books are the most ready source of that knowledge.
- *Dependability.* Many industries operate with deadlines. As a student, you also have many deadlines for homework, reports, tests, and so forth. If you hand homework and reports in late, you are developing bad habits that will not serve you well in industry.
- *Honesty.* As much as technical skills are valued in industry, honesty is valued more. An employee who cannot be trusted is of no use to a company.
- *Organization.* Many engineering projects are extremely complex. Think of all the details that had to be coordinated to construct your engineering building. It is composed of thousands of components (beams, ducting, electrical wiring, windows, lights, computer networks, doors, etc.). Because they interact, all those components had to be designed in a coordinated fashion. They had to be ordered from vendors and delivered to the construction site sequentially when they were required. The activities of the contractors had to be coordinated to install each item when it arrived. The engineers had to be organized to construct the building on time and within budget.
- *Common sense.* There are many commonsense aspects of engineering that cannot be taught in the classroom. A lack of common sense can be disastrous. For example, a library was recently built that required pilings to support it on soft ground. (A *piling* is a vertical rod, generally made from concrete, that goes deep into the ground to support the building that rests on it.) The engineers very carefully and meticulously designed the pilings to support the weight of the building, as they had done many times before. Although the pilings were sufficient to hold the building, the engineers neglected the weight of the books in the library. The pilings were insufficient to carry this additional load, so the library is now slowly sinking into the ground.
- *Curiosity.* Engineers must constantly learn and attempt to understand the world. A successful engineer is always asking, Why?
- *Involvement in the community.* Engineers benefit themselves and their community by being involved with clubs and organizations (Kiwanis, Rotary, etc.). These organizations provide useful community services and also serve as networks for business contacts.
- *Creativity.* From their undergraduate studies, it is easy for engineering students to get a false impression that engineering is not creative. Most courses emphasize **analysis,** in which a problem has already been defined and the "correct" answer is being sought. Although analysis is extremely important in engineering, most engineers also employ **synthesis,** the act of creatively combining smaller parts to form a whole. Synthesis is essential to design, which usually starts with a loosely defined problem for which there are many possible solutions. The creative engineering challenge is to find the best solution to satisfy the project goals (low cost, reliability, functionality, etc.). Many of the technical challenges facing society can be met only with creativity, for if the solutions were obvious, the problems would already be solved.

1.11 CREATIVITY

Imagination is more important than knowledge.
Albert Einstein

If the above quotation is correct, you should expect your engineering education to start with Creativity 101. Although many professors do feel that creativity is important in engineering education, creativity *per se* is not taught. Why is this?

- Some professors feel that creativity is a talent students are born with and cannot be taught. Although each of us has different creative abilities—just as we have different abilities to run the 50-yard dash—each of us *is* creative. Often, all the student needs is to be in an environment in which creativity is expected and fostered.
- Other professors feel that because creativity is hard to grade, it should not be taught. Although it is important to evaluate students, not everything a student does must be subjected to grading. The students' education should be placed above the students' evaluation.
- Other professors would argue that we do not completely understand the creative process, so how could we teach it? Although it is true we do not completely understand creativity, we know enough to foster its development.

Rarely is creativity directly addressed in the engineering classroom. Instead, the primary activity of engineering education is the transfer of knowledge to future generations that was painstakingly gained by past generations. (Given the vast amount of knowledge, this is a Herculean task.) Further, engineering education emphasizes the proper manipulation of knowledge to correctly solve problems. Both these activities support analysis, not synthesis. The "analysis muscles" of an engineering student tend to be well developed and toned. In contrast, their "synthesis muscles" tend to be flabby due to lack of use. Both analysis and synthesis are part of the creative process; engineers cannot be productively creative without possessing and manipulating knowledge. But it is important to realize that if you wish to tone your "synthesis muscles," it may require activities outside the engineering classroom.

Table 1.3 lists some creative professions, of which engineering is one. Although the goals of authors, artists, and composers are many, most have the desire to communicate. However, the constraints placed upon their communication are not severe. The author e.e. cummings is well known for not following grammatical conventions. We have all

TABLE 1.3
Creative professions

Profession	Goals	Constraints
Author	Communication, exploration of emotions, development of characters	Language
Artist	Communication, creation of beauty, experimentation with different media	Visual form
Composer	Communication, creation of new sounds, exploration of potential of each instrument	Musical form
Engineer	Simplicity, increased reliability, improved efficiency, reduced cost, better performance, smaller size, lighter weight, etc.	Physical laws and economics

been to art galleries in which a blob passes for art. The musician John Cage composed a musical piece entitled 4′ 33″ in which the audience listens to random ambient noise (e.g., the air handling system, coughs, etc.) for 4 minutes and 33 seconds.

The goals of engineers differ from those of the other creative professions (Table 1.3). To achieve these goals, we are constrained by physical laws and economics. Unlike other creative professions, we are not free to ignore our constraints. What success would an aerospace engineer achieve by ignoring gravity? Because we must work within constraints to achieve our goals, engineers must exhibit tremendous creativity.

Of those engineering goals listed in Table 1.3, one of the most important is simplicity. Generally, a simple design tends to satisfy the other goals as well. The engineer's desire to achieve simplicity is known as the *KISS* principle: "Keep It Simple, Stupid."

Although the creative process is not completely understood, we present here our own ideas about the origins of creativity. People can crudely be classified into *organized thinkers, disorganized thinkers,* and *creative thinkers.* Imagine we tell each of these individuals that "paper manufacture involves removing lignin (the natural binding agent) from wood, to release cellulose fibers that are then formed into paper sheets." Figures 1.4 through 1.6 show how each thinker might store the information.

The organized thinker has a well-compartmentalized mind. Facts are stored in unique places, so they are easily retrieved when needed. The papermaking fact is stored under "organic chemistry," because lignin and cellulose are organic chemicals.

The disorganized thinker has no structure. Although the information may be stored in multiple places, his mind is so disorganized that the information is hard to retrieve when needed. The disorganized thinker who needed to recall information about papermaking would not have a clue where to find it.

The creative thinker is a combination of organized and disorganized thinkers. The creative mind is ordered and structured, but information is stored in multiple places so that when the information is needed, there is a higher probability of finding it. When creative people learn, they attempt to make many connections, so the information is stored in different places and is linked in a variety of ways. In the papermaking example, they might store the information under "organic chemistry" because they are organized, but also under "biochemistry" (because lignin and cellulose are made by living organisms) and under "art prints" (because high-quality prints must be printed on "acid-free" paper, which uses special chemistry to remove the lignin).

When an engineer tries to solve a problem, she works at both the conscious and subconscious level (Figure 1.7). The subconscious seeks information that solves a qualitative model of the problem. As long as it finds no solution, the subconscious mind keeps searching the information data banks. Here, we see the advantage of the creative thinker. With information stored in multiple places and connected in useful ways, there is a greater probability that a solution to the qualitative model will be found. When the subconscious finds a solution, it emerges into consciousness. You have certainly experienced this. Perhaps you went to bed with a problem on your mind, and when you woke up, the solution seemingly "popped" into your head. In actuality, the subconscious worked on the problem while you were sleeping, and the solution emerged into your consciousness when you awoke. For engineers, generally what emerges from the subconscious is a potential solution. The actual solution won't be known until the potential solution is analyzed using a quantitative model. If analysis proves the solution, then the engineer has cause for celebration; she has solved the problem.

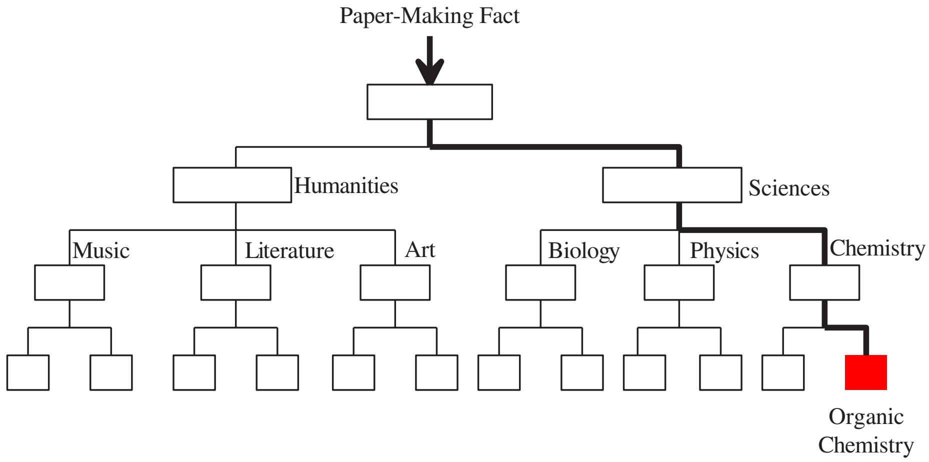


FIGURE 1.4
Papermaking fact stored by an organized thinker.

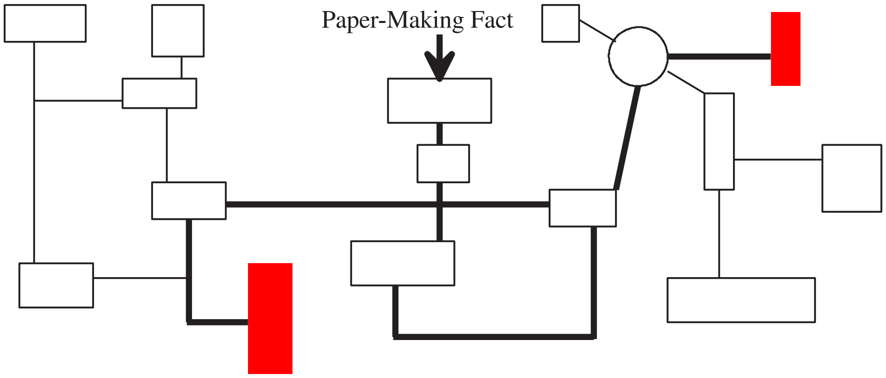


FIGURE 1.5
Papermaking fact stored by a disorganized thinker.

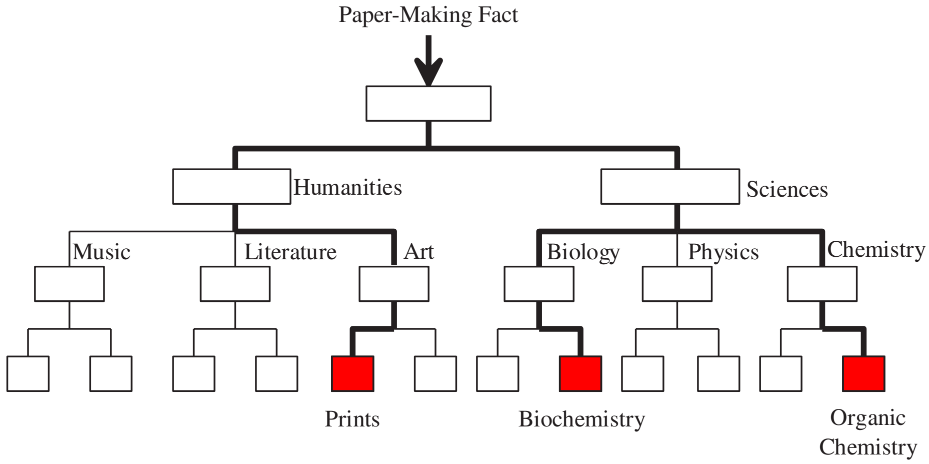


FIGURE 1.6
Papermaking fact stored by a creative thinker.

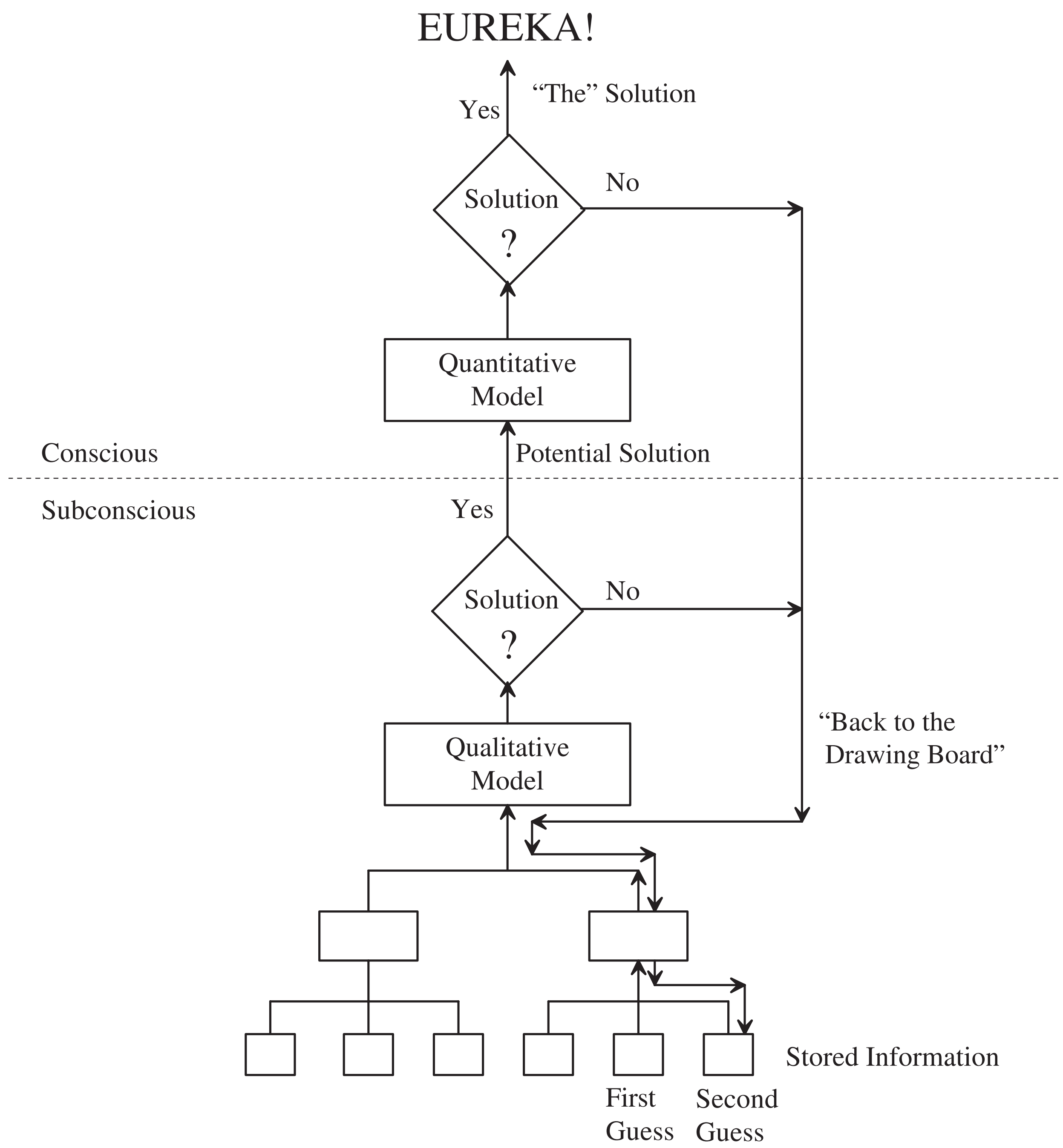


FIGURE 1.7
The problem-solving process.