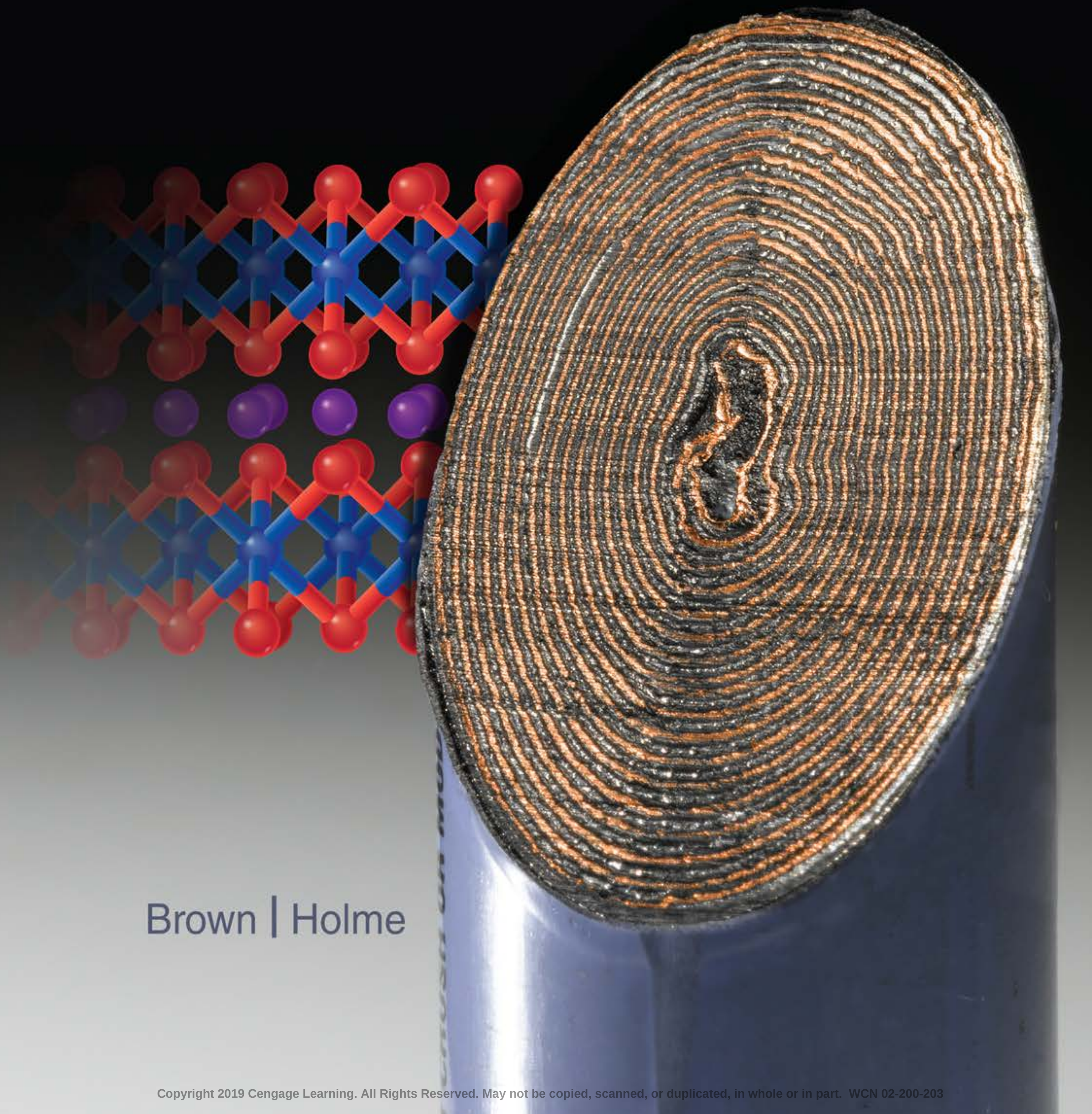
Chemistry

for Engineering Students

4th edition



Brown | Holme

SOME USEFUL CONSTANTS

(a more complete list appears in Appendix B)

Atomic mass unit	1 amu = $1.660539040 \times 10^{-24}$ g
Avogadro's number	$N = 6.022140857 \times 10^{23}$ particles/mol
Electronic charge	$e = 1.6021766208 \times 10^{-19}$ coulombs
Faraday constant	$F = 96{,}485.33289$ coulombs/mol e^-
Gas constant	$R = 0.082057338 \dfrac{\text{L atm}}{\text{mol K}} = 62.363577 \dfrac{\text{L torr}}{\text{mol K}}$
	$= 8.3144598 \dfrac{\text{J}}{\text{mol K}} = 8.3144598 \dfrac{\text{kPa dm}^3}{\text{mol K}}$
Pi	$\pi = 3.1415927$
Planck's constant	$h = 6.626070040 \times 10^{-34}$ J s
Speed of light (in vacuum)	$c = 2.99792458 \times 10^{8}$ m/s

SOME USEFUL RELATIONSHIPS

Mass and Weight

SI Base Unit: Kilogram (kg)

1 kilogram = 1000 grams = 2.205 pounds
1 gram = 1000 milligrams
1 pound = 453.59 grams
1 amu = 1.6605×10^{-24} grams
1 gram = 6.022×10^{23} amu
1 ton = 2000 pounds

Length

SI Base Unit: Meter (m)

1 inch = 2.54 centimeters (exactly)
1 meter = 100 centimeters = 39.37 inches
1 yard = 0.9144 meter
1 mile = 1.609 kilometers
1 kilometer = 1000 meters = 0.6215 mile
1 Ångstrom = 1.0×10^{-10} meters = 1.0×10^{-8} centimeters

Volume

SI Base Unit: Cubic Meter (m^3)

1 liter = 0.001 cubic meter
1 liter = 1000 cubic centimeters = 1000 mL
1 liter = 1.056 quarts
1 quart = 0.9463 liter
1 milliliter = 0.001 liter = 1 cubic centimeter
1 cubic foot = 7.475 gallons = 28.316 liters
1 gallon = 4 quarts

Energy

SI Base Unit: Joule (J)

1 calorie = 4.184 joules = 4.129×10^{-2} L atm
1 joule = $1 \dfrac{\text{kg m}^2}{\text{s}^2}$ = 0.23901 calorie
1 joule = 1×10^{7} ergs
1 electron volt = 1.6022×10^{-19} joule
1 electron volt = 96.485 kJ/mol
1 L atm = 24.217 calories = 101.325 joules

Pressure

SI Base Unit: Pascal (Pa)

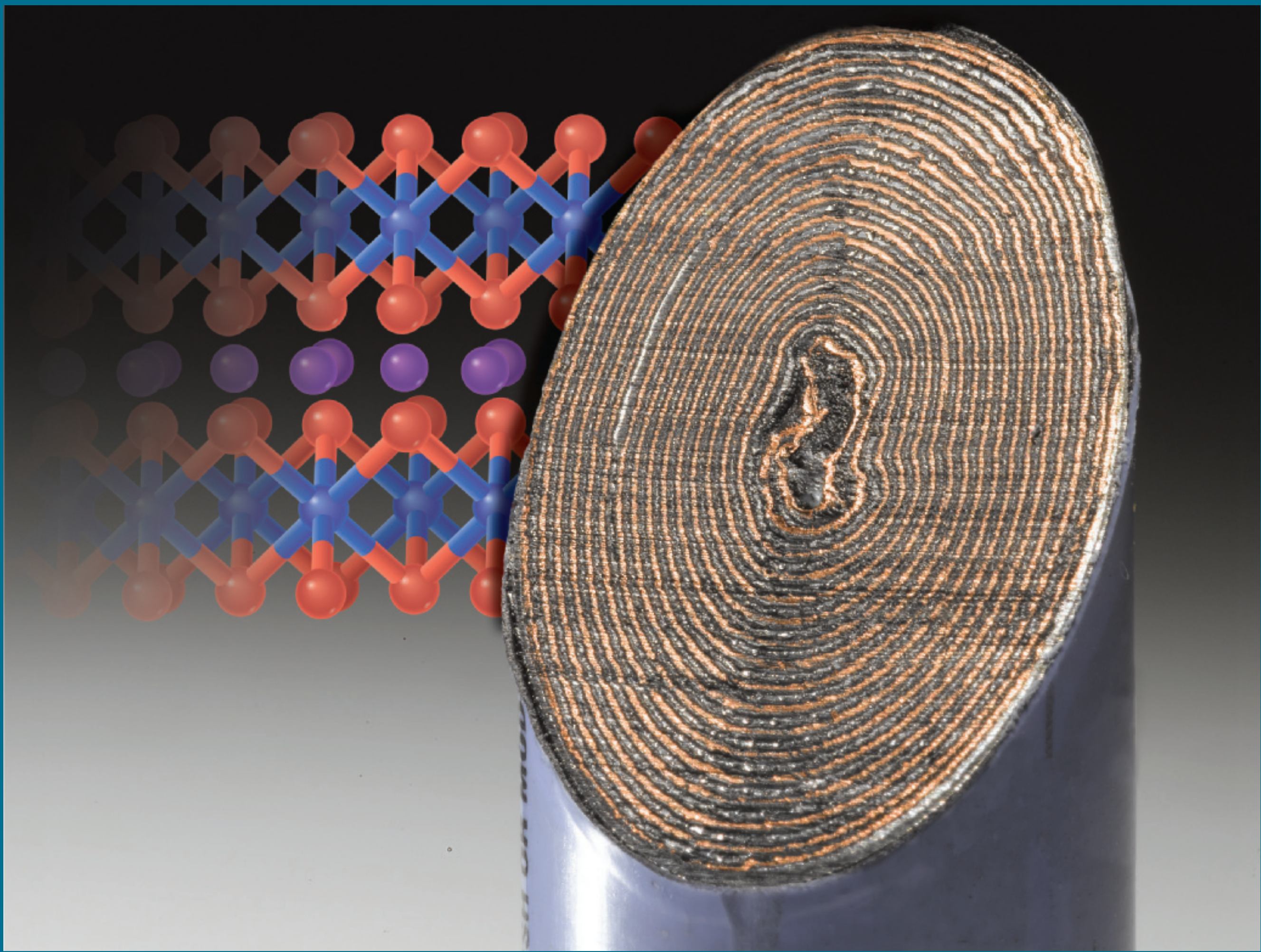
1 pascal = $\dfrac{\text{kg}}{\text{m s}^2}$ = 1 Newton/m^2
1 atmosphere = 760 torr
= 760 millimeters of mercury
= 1.01325×10^{5} pascals
= 1.01325 bar
= 14.70 pounds per square inch
1 torr = 1 millimeter of mercury

Temperature

SI Base Unit: Kelvin (K)

0 K = −273.15°C
K = °C + 273.15°
°F = 1.8(°C) + 32°
$°C = \dfrac{°F - 32°}{1.8°}$

Chemistry for Engineering Students



Mark Thiessen/Getty Images

Aspects of chemistry influence almost any product an engineer might design. In some cases this leads to the identity of a chemical substance appearing in the product's name. The cover image shows such a case: a lithium battery that has been cut open to reveal its internal design. The accompanying molecular scale drawing represents the structure of lithium cobalt oxide ($LiCoO_2$), a material that is frequently used in lithium ion batteries. Recent advances in battery design are one important example of the interface between chemistry and engineering in modern technology.

Chemistry for Engineering Students

FOURTH EDITION

Lawrence S. Brown
Texas A&M University

Thomas A. Holme
Iowa State University

CENGAGE

Australia • Brazil • Mexico • Singapore • United Kingdom • United States

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Lawrence S. Brown, Thomas A. Holme

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About the Authors

Courtesy of Lawrence Brown/photo by Sherry Yennello

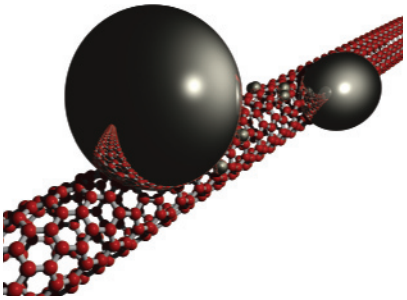
Larry Brown has been a faculty member at Texas A&M University since 1988, and in 2013 he was named Presidential Professor for Teaching Excellence. He received his B.S. in 1981 from Rensselaer Polytechnic Institute, and his M.A. in 1983 and Ph.D. in 1986 from Princeton University. During his graduate studies, Larry spent a year working in what was then West Germany. He was a Postdoctoral Fellow at the University of Chicago for two years before moving to Texas A&M. Over the years, he has taught more than 16,000 general chemistry students, most of them engineering majors. Larry's excellence in teaching has been recognized by awards from the Association of Former Students at Texas A&M at both the College of Science and University levels. A version of his class has been broadcast on KAMU-TV, College Station's PBS affiliate. From 2001 to 2004, Larry served as a Program Officer for Education and Interdisciplinary Research in the Physics Division of the National Science Foundation. He also helped establish the chemistry program at Texas A&M's campus in Doha, Qatar. When not teaching chemistry, he enjoys solving crossword puzzles with his daughter Stephanie and watching her run.

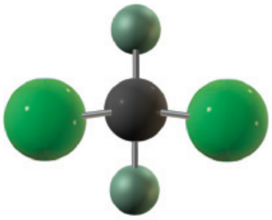
Courtesy of Thomas Holme/photo by Dennis Salisbury

Tom Holme is a Morrill Professor in the Department of Chemistry at Iowa State University and Past Director of the ACS Examinations Institute. He received his B.S. in 1983 from Loras College, and his Ph.D. in 1987 from Rice University. He began his teaching career as a Fulbright Scholar in Zambia, Africa and has also lived in Jerusalem, Israel, and Suwon, South Korea. He is a fellow of the American Chemical Society (ACS) and the American Association for the Advancement of Science. He was the recipient of the 2017 Pimentel Award for Chemical Education from the ACS. His research interests lie primarily in chemistry education research and human-computer interaction, where he studies how different technology interfaces influence student learning of chemistry. He has been involved with the general chemistry for engineers course at both Iowa State University and at the University of Wisconsin–Milwaukee where he was a member of the Chemistry and Biochemistry Department for 14 years. He has received several grants from the National Science Foundation for work in assessment methods for chemistry, and the "*Focus on Problem Solving*" feature in this textbook grew out of one of these projects. He has served as an editor or associate editor on several book projects, including the encyclopedia "*Chemistry Foundations and Applications*" and the lab manual for AP Chemistry. He has a long-standing interest in chemistry outreach and won the ACS's Helen Free Award for Public Outreach for his efforts doing chemical demonstrations on live television in the Milwaukee area.

Brief Contents

Contents





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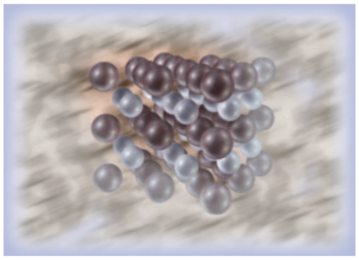


Original illustration courtesy of Raymond Schaak


Thomas A. Holme

Thomas A. Holme

National Park Service


Thomas A. Holme

Lawrence S. Brown

Appendixes

Preface

The Audience for This Text

As chemists, we see connections between our subject and virtually everything. So the idea that engineering students should learn chemistry strikes most chemists as self-evident. But chemistry is only one of many sciences with which a practicing engineer must be familiar, and the undergraduate curriculum must find room for many topics. Hence, engineering curricula at more and more universities are shifting from the traditional year-long general chemistry sequence to a single semester. And in most cases, these schools are offering a separate one-term course designed specifically for their engineering students. When schools—including our own—originally began offering these courses, there was no text on the market for them, so content from two-semester texts had to be heavily modified to fit the course. Although it is possible to do this, it is far from ideal. It became apparent that a book specifically geared for this shorter course was necessary. ***We have written this book to fill this need.***

Our goal is to instill an appreciation for the role of chemistry in many areas of engineering and technology and of the interplay between chemistry and engineering in a variety of modern technologies. For most engineering students, the chemistry course is primarily a prerequisite for courses involving materials properties. These courses usually take a phenomenological approach to materials rather than emphasizing the chemist's molecular perspective. Thus one aim of this text is to provide knowledge of and appreciation for the chemical principles of structure and bonding that underpin materials science. This does *not* mean that we have written the book as a materials science text, but rather that the text is intended to prepare students for subsequent study in that area.

The book also provides sufficient background in the science of chemistry for a technically educated professional. Engineering, after all, is the creative and practical application of a broad array of scientific principles, so its practitioners should have a broad base in the natural sciences.

Content and Organization

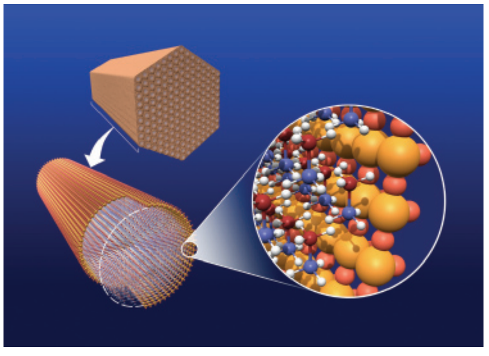
The full scope of the traditional general chemistry course cannot be taught meaningfully in one semester or one or two quarters, so we have had to decide what content to include. There are basically two models used to condense the general chemistry curriculum. The first is to take the approach of an "essentials" book and reduce the depth of coverage and the number of examples but retain nearly all of the traditional topics. The second is to make more difficult and fundamental decisions as to what chemistry topics are proper and relevant to the audience—in this case, future engineers. We chose the latter approach and built a 14-chapter book from the ground up to satisfy what we think are the goals of the course:

- Provide a concise but thorough introduction to the science of chemistry.
- Give students a firm foundation in the principles of structure and bonding as a foundation for further study of materials science.

- Show the connection between molecular behavior and observable physical properties.
- Show the connections between chemistry and the other subjects studied by engineering students, especially mathematics and physics.

Taken together, the 14 chapters in this book represent somewhat more material than can comfortably fit into a standard semester course. Thus departments or individual instructors will need to make some further choices as to the content that is most suitable for their own students. We suspect that many instructors will not choose to include all of the material on equilibrium in Chapter 12, for example. Similarly, we have included more topics in Chapter 8, on condensed phases, than we expect most faculty will include in their courses.

Topic Coverage



The coverage of topics in this text reflects the fact that chemists constantly use multiple concepts to understand their field, often using more than one model simultaneously. Thus the study of chemistry we present here can be viewed from multiple perspectives: macroscopic, microscopic, and symbolic. The latter two perspectives are emphasized in Chapters 2 and 3 on atoms, molecules, and reactions. In Chapters 4 and 5, we establish more of the connection between microscopic and macroscopic in our treatment of stoichiometry and gases. We return to the microscopic perspective to cover more details of atomic structure and chemical bonding in Chapters 6 through 8. The energetic aspects of chemistry, including important macroscopic consequences, are considered in Chapters 9 and 10, and kinetics and equilibrium are treated in Chapters 11 and 12, respectively. Chapter 13 deals with electrochemistry and corrosion, an important chemistry application for many engineering disciplines. Finally, we conclude with a discussion of nuclear chemistry.

Specific Content Coverage

We know that there are specific topics in general chemistry that are vital to future engineers. We've chosen to treat them in the following ways.

Organic Chemistry: Organic chemistry is important in many areas of engineering, particularly as related to the properties of polymers. Rather than using a single organic chapter, we integrate our organic chemistry coverage over the entire text, focusing on polymers. We introduce organic polymers in Section 2.1 and use polymers and their monomers in many examples in this chapter. Chapter 2 also contains a rich discussion of organic line structures and functional groups and ends with a section on the synthesis, structure, and properties of polyethylene. Chapter 4 opens and ends with discussions of fuels, a topic to which we return in Chapter 9. Chapter 8 contains more on carbon and polymers, and the recycling of polymers provides the context for consideration of the second law of thermodynamics in Chapter 10.

Acid–Base Chemistry: Acid–base reactions represent another important area of chemistry with applications in engineering, and again we have integrated our coverage into appropriate areas of the text. Initially, we define acids and bases in conjunction with the introduction to solutions in Chapter 3. Simple solution stoichiometry is presented in Chapter 4. Finally, a more detailed treatment of acid–base chemistry is presented in the context of equilibria in Chapter 12, and this section has been expanded significantly in this edition.

Nuclear Chemistry: A chapter dealing with nuclear chemistry is included for those wishing to teach that topic. Coverage in this chapter includes fundamentals of nuclear reactions, nuclear stability and radioactivity, decay kinetics, and the energetic consequences of nuclear processes.

Mathematics: The math skills of students entering engineering majors generally are stronger than those in the student body at large, and most of the students taking a course of the type for which this book is intended will be concurrently enrolled in an introductory calculus course. In light of this, we include references to the role of calculus where appropriate via our **MathConnections** boxes. These essays expand and review math concepts as they pertain to the particular topic being studied, and appear wherever the links between the topic at hand and mathematics seems especially strong. These boxes are intended to be unobtrusive, so those students taking a precalculus math course will not be adversely affected. The point of including calculus is not to raise the level of material being presented, but rather to show the natural connections between the various subjects students are studying.

MathConnections

INSIGHT

Connections Between Chemistry and Engineering

Because this book is intended for courses designed for engineering majors, we strive to present chemistry in contexts that we feel will appeal to the interests of such students. Links between chemistry and engineering are central to the structure of the text. Each chapter begins and ends with a section called **INSIGHT**, which introduces a template or theme showing the interplay between chemistry and engineering. These sections are only the beginning of the connections, and the theme introduced in the initial *Insight* appears regularly throughout that chapter.

We opt for currency in our engineering applications wherever possible, so throughout the book, we discuss recent key innovations in various fields. For example, Chapter 5 includes a discussion of hydraulic fracturing and natural gas recovery. In Chapter 7, we describe mesoporous silicon nanoparticles, a front-line research topic that may have important applications in biomedical engineering in the future. Chapter 8 closes with a discussion of the fabrication of micro-electrical-mechanical systems (MEMS).

Approach to Problem Solving

Problem solving is a key part of college chemistry courses and is especially important as a broadly transferable skill for engineering students. Accordingly, this text includes worked problems throughout. All of our Example Problems include a *Strategy* section immediately following the problem statement, in which we emphasize the concepts and relationships that must be considered to work the problem. After the solution, we often include a section called *Analyze Your Answer* that is designed to help students learn to estimate whether or not the answer they have obtained is reasonable. In many examples, we also include *Discussion* sections that help explain the importance of a problem solving concept or point out common pitfalls to be avoided. Finally, each example closes with a *Check Your Understanding* problem or question to help the student to generalize or extend what's been learned in the example problem.

EXAMPLE PROBLEM

Strategy
Analyze Your Answer
Discussion
Check Your Understanding

We believe that the general chemistry experience should help engineering students develop improved problem solving skills. Moreover, we feel that those skills should be transferable to other subjects in the engineering curriculum even though chemistry

Focus On Problem Solving

content may not be involved. Accordingly, we include a unique feature at the end of each chapter called *Focus on Problem Solving*. In these sections, the questions posed do not require a numerical answer, but rather ask the student to identify the strategy or reasoning to be used in the problem and often require them to identify missing information for the problem. In most cases, it is not possible to arrive at a final numerical answer using the information provided, so students are forced to focus on developing a solution rather than just identifying and executing an algorithm. The end-of-chapter exercises include additional problems of this nature so the *Focus on Problem Solving* can be fully incorporated into the course. This feature grew out of an NSF-funded project on assessing problem solving in chemistry classes.

Text Features

We employ a number of features, some of which we referred to earlier, to help students see the utility of chemistry and understand the connections to engineering.

INSIGHT Sections Each chapter is built around a template called an *Insight*. These themes, which both open and close each chapter, have been chosen to showcase connections between engineering and chemistry. In addition to the chapter opening and closing sections, the template themes are woven throughout the chapter, frequently providing the context for points of discussion or example problems. This special *Insight* icon is used throughout the book to identify places where ideas presented in the chapter opening section are revisited in the narrative.

FOCUS ON PROBLEM SOLVING Sections Engineering faculties unanimously say that freshman engineering students need practice in solving problems. However, it is important to make a distinction here between problems and exercises. Exercises provide a chance to practice a narrow skill, whereas problems require multiple steps and thinking outside the context of the information given. *Focus on Problem Solving* offers students the chance to develop and practice true problem solving skills. These sections, which appear at the end of every chapter, include a mix of quantitative and qualitative questions that focus on the *process* of finding a solution to a problem, not the solution itself. We support these by including additional similar problems in the end-of-chapter material.

MathConnections In our experience, one trait that distinguishes engineering students from other general chemistry students is a higher level of comfort with mathematics. Typically, most students who take a class of the sort for which this book has been written will also be taking a course in calculus. Thus it seems natural to us to point out the mathematical underpinnings of several of the chemistry concepts presented in the text because this should help students forge mental connections between their courses. At the same time, we recognize that a student taking a precalculus math course should not be precluded from taking chemistry. To balance these concerns, we have placed any advanced mathematics into special *MathConnections* sections, which are set off from the body of the text. Our hope is that those students familiar with the mathematics involved will benefit from seeing the origin of things such as integrated rate laws, whereas those students with a less extensive background in math will still be able to read the text and master the chemistry presented.

EXAMPLE PROBLEM Our examples are designed to illustrate good problem solving practices by first focusing on the reasoning behind the solution before moving into any needed calculations. We emphasize this “think first” approach by beginning with a *Strategy* section, which outlines a plan of attack for the problem. We find that many students are too quick to accept whatever answer their calculator might display. To combat this, we follow most solutions with an *Analyze Your Answer* section, which uses estimation and other strategies to walk students through a double check of their answers. Every example closes with a *Check Your Understanding* exercise to allow students to practice or extend the skill they have just learned. Answers to these additional exercises are included in Appendix J at the end of the book.

End-of-Chapter Features Each chapter concludes with a chapter summary, outlining the main points of the chapter, and a list of **key terms**, each of which includes the section number where the term first appeared. Definitions for all key terms appear in the Glossary.

Problem Sets Each chapter includes roughly 100 problems and exercises, spanning a wide range of difficulty. Most of these exercises are identified with specific sections to provide the practice that students need to master material from that section. Most chapters also include a number of *Additional Problems*, which are not tied to any particular section and which may incorporate ideas from multiple sections. *Focus on Problem Solving* exercises follow, as described earlier. The problems for most chapters conclude with *Cumulative Problems*, which ask students to synthesize information from the current chapter with what they've learned from previous chapters to form answers. For the fourth edition, we have added a new *Conceptual Problems* section, which emphasizes molecular scale visualization and other nonalgorithmic exercises. Answers for all odd-numbered problems appear at the end of the book in Appendix K.

Additional Problems
Focus on Problem Solving
Cumulative Problems

Conceptual Problems

Margin Notes Margin notes in the text point out additional facts, further emphasize points, or point to related discussion either earlier or later in the book. Margin Notes are denoted with an ▶ icon that is also placed in the narrative and links the margin note with the relevant passage in the text.

New in This Edition

There are several important changes in this fourth edition of the textbook. As we have done in each edition, we have replaced a number of the *Insight* sections to make them more current and to try to include topics that will appeal to a wider range of student interests. Thus, we have introduced three new topics for the chapter-opening insights: Critical Materials in Chapter 1, Natural Gas Production in Chapter 5, and Urban Air Pollution in Chapter 11. We have also reworked the Polymer insight theme for Chapter 2 to focus more specifically on the emerging area of conducting polymers. The closing insight sections for Chapters 1 and 11 have also been rewritten, and the closing section of Chapter 13 has been updated to highlight topics with more current relevance.

In this revision, we have also focused on the following areas:

- In the end-of-chapter problems for each chapter, we have added an additional section labeled as *Conceptual Problems*. These sections emphasize molecular level visualization and nonalgorithmic problem solving, in an effort to help foster conceptual understanding that goes beyond manipulating equations.
- In Chapter 1, we introduce the idea of systems thinking, and this concept is revisited throughout the text.
- We have revised a number of figures throughout in an effort to make them more useful to students.
- Wherever possible, references to date-specific information have been updated.
- We have updated all periodic tables to include the recently approved names for heavy elements and all atomic weight listings to use the IUPAC 2015 values.

Beyond these changes running throughout the book, a detailed list of specific changes in each chapter is given below.

Chapter	Summary of Changes

1	Major Change
	• Changed the opening Insight and chapter theme to focus on the concept of critical materials
	  ◦ Includes new opening Insight section
	  ◦ Includes changes in several example problems
	  ◦ Includes changes at several points in the text where references to context are made
	  ◦ Includes changes for several Figures (1.1, 1.2, 1.6, 1.10, 1.11, 1.12)
	  ◦ Includes changes to end-of-chapter problems related to the context theme
	Other Changes
	• Introduced the importance of systems and systems thinking, which is then used where appropriate in later chapters
	• Changed closing Insight theme to touchscreen technology

2	Major Change
	• Changed the opening Insight from the previous focus on polymers to a more directed focus on new conducting polymers
	  ◦ Includes changes in the opening Insight section
	  ◦ Includes changes in several example problems
	  ◦ Includes changes at several points in the text where references to context are made

3	• Added a simple introduction to the Brønsted-Lowry definition of acids and bases, which is also now addressed in more detail in Chapter 12 • Added an important note related to the proposed change in the IUPAC definition of the mole, which is likely to take place during the life of this edition
4	• Tightened description of how mole ratios can be defined using the balanced chemical equation • Replaced Example Problem 4.7 with an updated version

5	Major Change
	• Changed the opening Insight and chapter theme to natural gas production
	  ◦ Includes new opening Insight discussing hydraulic fracturing and other aspects of natural gas recovery and refining
	  ◦ Includes changes in several example problems
	  ◦ Includes changes at several points in the text where references to context are made
	  ◦ Includes new Figure 5.1
	  ◦ Includes changes to end-of-chapter problems related to the context theme

6	• Moved treatment of anion and cation sizes from Chapter 7 into this chapter to group this concept with trends in atomic sizes • Improved artwork for several figures, particularly those related to atomic orbitals
7	• Moved material on ionic size and trends in ionic sizes out of this chapter and into Chapter 6 • Revised artwork for several figures, particularly those related to orbitals
8	• Revised artwork for several figures • Added a brief discussion of dipole vectors and molecular polarity in the discussion of intermoleular forces
9	• Incorporated a discussion of systems thinking within the broader context of the world energy economy • Updated all data and figures containing dated information on the energy economy
10	• Incorporated a discussion of systems thinking in terms of resources and use and disposal of consumer products

Chapter	Summary of Changes

11	Major Change
	• Changed the opening Insight and chapter theme to urban air pollution and the role of kinetics in smog formation
	  ◦ Includes new opening Insight
	  ◦ Includes changes in several example problems
	  ◦ Includes changes at several points in the text where references to context are made
	  ◦ Includes changes for Figures 11.1, 11.2, and 11.3
	  ◦ Includes changes to end-of-chapter problems related to the context theme
	  ◦ Includes a new closing Insight on air quality monitoring

12	Major Change • Added extensive discussion of acid–base chemistry and equilibrium, including titrations and titration curves
13	• Updated closing Insight section to include discussion of more recent failures of lithium-ion batteries in consumer products
14	• Improved consistency of notation used to refer to specific isotopes, especially in end-of-chapter problems

Supporting Material

Please visit www.cengage.com/chemistry/brownholme/chemengineer4e for more information about student and instructor resources for this text.

Acknowledgments

We are very excited to see this book move forward in this fourth edition, and we are grateful for the help and support we have enjoyed from a large and talented team of professionals. There are many people without whom we never could have done this. But foremost among them are our families, to whom this book is again dedicated.

The origin of this text can be traced back many years, and as we move into this new edition, we would like once more to thank a few people who were instrumental in getting this project started. Jennifer Laugier first brought the two of us together to work on a book for engineering students. Jay Campbell's work as developmental editor for the first edition was tremendous, and without his efforts the book may never have been published. When Jay became involved, the project had been languishing for some time, and the subsequent gains in momentum were clearly not coincidental. The editorial leadership team at that time, consisting of Michelle Julet, David Harris, and Lisa Lockwood, was also crucial in seeing this project come to fruition. The decision to launch a book in a market segment that had not really existed was clearly not an easy one, and we appreciate the confidence that everyone at what was then Brooks/Cole placed in us.

In the development of the fourth edition, our Cengage team includes a mix of the familiar and the new. We would like to thank our product manager, Lisa Lockwood, whose continued support is always appreciated. Our Content Developer for this edition is Peter McGahey, and both Lisa and Peter contributed greatly to discussions on where to focus our efforts in this revision. Peter has worked with us through the entire revision process and provided a number of suggestions that have improved the finished edition. Stacey Lutkoski and Lynn Lustberg at MPS Limited have overseen the production process. Photo and text research was handled by a team at Lumina Datamatics. Anne Alexander (Milwaukee School of Engineering) and Dan Collins (Texas A&M University) helped us check the page proofs, providing valuable comments that have improved the accuracy of the text. The book in your hands truly reflects the best efforts of many hard-working professionals, and we are grateful to all of them for their roles in this project.

It has been 12 years since the first edition was published, and throughout that time, we have received useful feedback from numerous students and colleagues. Much of that feedback is informal, including e-mail from students or faculty members pointing out errors they have found or letting us know about sections they really liked. Although there is no way to list all of the people who have contributed in this way, we do sincerely thank you all.

Faculty members from a wide variety of institutions also provided more formal comments on the text at various stages of its development. We thank the following reviewers for their contributions to the current revision.

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Student Introduction

Chemistry and Engineering

As you begin this chemistry course, odds are that you may be wondering "Why do I have to take chemistry anyway? I'll never really need to know any of this to be an engineer." So we'd like to begin by offering just a few examples of the many links between our chosen field of chemistry and the various branches of engineering. The most obvious examples, of course, might come from chemical engineering. Many chemical engineers are involved with the design or optimization of processes in the chemical industry, so it is clear that they would be dealing with concepts from chemistry on a daily basis. Similarly, civil or environmental engineers working on environmental protection or remediation might spend a lot of time thinking about chemical reactions taking place in the water supply or the air. But what about other engineering fields?

Much of modern electrical engineering relies on solid-state devices whose properties can be tailored by carefully controlling their chemical compositions. And although most electrical engineers do not regularly make their own chips, an understanding of how those chips operate on an atomic scale is certainly helpful. As the push for ever smaller circuit components continues, the ties between chemistry and electrical engineering will grow tighter. From organic light-emitting diodes (OLEDs) to single molecule transistors, new developments will continue to move out of the chemistry lab and into working devices at an impressive pace.

Some applications of chemistry in engineering are much less obvious. At 1483 feet, the Petronas Towers in Kuala Lumpur, Malaysia, were the tallest buildings in the world when they were completed in 1998. Steel was in short supply in Malaysia, so the towers' architects decided to build the structures out of something the country had an abundance of and local engineers were familiar with: concrete. But the impressive height of the towers required exceptionally strong concrete. The engineers eventually settled on a material that has come to be known as high-strength concrete, in which chemical reactions between silica fume and Portland cement produce a stronger material, more resistant to compression. This example illustrates the relevance of chemistry even to very traditional fields of engineering, and we will discuss some aspects of the chemistry of concrete in Chapter 12, including the development of novel bendable concrete.

About This Text

Both of us have taught general chemistry for many years, and we are familiar with the difficulties that students may encounter with the subject. Perhaps more importantly, for the past several years, we've each been teaching engineering students in the type of one-semester course for which this text is designed. The approach to subjects presented in this text draws from both levels of experience.

We've worked hard to make this text as readable and student friendly as possible. One feature that makes this book different from any other text you could have used for this course is that we incorporate connections between chemistry and engineering as a fundamental component of each chapter. You will notice that each chapter begins and ends with a section called an **INSIGHT**. These sections are only the beginning of the connections, and the theme introduced in the initial insight appears regularly throughout that chapter. This special icon identifies material that is closely related to the theme of the chapter opening *Insight* section. We've heard many students complain that they don't see what chemistry has to do with their chosen fields, and we hope that this approach might help you to see some of the connections.

Engineering students tend to take a fairly standard set of courses during their first year of college, so it's likely that you might be taking calculus and physics courses along with chemistry. We've tried to point out places where strong connections between these subjects exist, and at the same time to do this in a way that does not disadvantage a student who might be taking a precalculus math class. Thus we may refer to similarities between equations you see here and those you might find in a physics text, but we do not presume that you are already familiar with those equations. In the case of math, we use special sections called **MathConnections** to discuss the use of math, and especially calculus, in chemistry. If you are familiar with calculus or are taking it concurrently with this class, these sections will help you to see how some of the equations used in chemistry emerge from calculus. But if you are not yet taking calculus, you can simply skip over these sections and still be able to work with the needed equations.

MathConnections

Although our primary intent is to help you learn chemistry, we also believe that this text and the course for which you are using it can help you to develop a broad set of skills that you will use throughout your studies and your career. Foremost among them is problem solving. Much of the work done by practicing engineers can be characterized as solving problems. The problems you will confront in your chemistry class clearly will be different from those you will see in engineering, physics, or math. But taken together, all of these subjects will help you formulate a consistent approach that can be used to attack virtually any problem. Many of our students tend to "jump right in" and start writing equations when facing a problem. But it is usually a better idea to think about a plan of attack before doing that, especially if the problem is difficult or unfamiliar. Thus all of our worked examples include a *Strategy* section in which we outline the path to a solution before starting to calculate anything. The *Solution* section then puts that strategy into action. For most numerical examples, we follow the solution with a section we call *Analyze Your Answer*, in which we use estimation or comparison to known values to confirm that our result makes sense. We've seen many students who believe that whatever their calculator shows must be the right answer, even when it should be easy to see that a mistake has been made. Many examples also include a *Discussion* section in which we might talk about common pitfalls that you should avoid or how the problem we've just done relates to other ideas we've already explored. Finally, each example problem closes with a *Check Your Understanding* question or problem, which gives you a chance to practice the skills illustrated in the example or to extend them slightly. Answers to these *Check Your Understanding* questions appear in Appendix J.

Strategy
Solution
Analyze Your Answer
Discussion
Check Your Understanding

While we are thinking about the example problems, a few words about rounding and significant figures are in order. In solving the example problems, we have used atomic weights with the full number of significant figures shown in the periodic table inside the back cover. We have also used as many significant figures as available for constants such as the speed of light or the universal gas constant. Where intermediate results are shown in the text, we have tried to write them with the appropriate number of significant figures. But when those same intermediate results are used in a subsequent calculation, we have *not* rounded the values. Instead, we retain the full calculator result. Only the final answer has actually been rounded. If you follow this same procedure, you should be able to duplicate our answers. (The same process has been used to generate the answers to numerical problems appearing in Appendix K.) For problems that involve finding the slope or intercept of a line, the values shown have been obtained by linear regression using the algorithms built into either a spreadsheet or a graphing calculator.

Focus On Problem Solving

A unique feature of this text is the inclusion of a *Focus on Problem Solving* question at the end of each chapter. These questions are designed to force you to think about the *process* of solving the problem rather than just getting an answer. In many cases, these problems do not include sufficient information to allow you to reach a final solution. Although we know from experience that many beginning engineering students might find this frustrating, we feel it is a good approximation to the kind of problems that a working engineer might confront. Seldom would a client sit down and provide every piece of information that you need to solve the problem at hand.

One of the most common questions we hear from students is "How should I study for chemistry?" Sadly, that question is most often asked after the student has done poorly on one or more exams. Because different people learn best in different ways, there isn't a single magic formula to ensure that everyone does well in chemistry. But there are some common strategies and practices that we can recommend. First and foremost, we suggest that you avoid getting behind in *any* of your classes. Learning takes time, and very few people can master three chapters of chemistry (or physics, or math, or engineering) the night before a big exam. Getting behind in one class inevitably leads to letting things slide in others, so you should strive to keep up from the outset. Most professors urge students to read the relevant textbook material before it is presented in class. We agree that this is the best approach because even a general familiarity with the ideas being presented will help you to get a lot more out of your class time.

In studying for exams, you should try to make a realistic assessment of what you do and don't understand. Although it can be discomforting to focus on the problems that you don't seem to be able to get right, spending more time studying things that you have already mastered will probably have less impact on your grade. Engineering students tend to focus much of their attention on numerical problems. Although such calculations are likely to be very important in your chemistry class, we also encourage you to try to master the chemical concepts behind them. Odds are that your professor will test you on qualitative or conceptual material, too.

Finally, we note that this textbook is information rich. It includes many of the topics that normally appear in a full year college chemistry course, but it is designed for a course that takes only one semester. To manage the task of paring down the volume of materials, we've left out some topics and shortened the discussion of others. Having the Internet available means that you can always find more information if what you have read sparks your interest.

We are excited that this book has made it into your hands. We hope you enjoy your semester of learning chemistry and that this book is a positive part of your experience.

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Introduction to Chemistry

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A ferrofluid, which is essentially a magnetic liquid, can be induced to take on a structure by the presence of a strong magnetic field. In this photo, the shape is created by a powerful neodymium magnet, and the colors are reflections of colored lights.

CHAPTER OUTLINE

In the not too distant future, engineers may design and assemble miniature mechanical or electronic devices, gears, and other parts fabricated on an atomic scale. Their decisions will be guided by knowledge of the sizes and properties of the atoms of different elements. Such devices might be built up atom by atom: Each atom would be specified based on relevant design criteria and maneuvered into position

Nanoscience deals with objects whose sizes are similar to those of atoms and molecules. Try a web search for "nanoscience" or "molecular machines" to learn more.

using nanoscience techniques. These nanomachines will be held together not by screws or rivets but by the forces of attraction between the different atoms—by chemical bonds. Clearly, these futuristic engineers will need to understand atoms and the forces that bind them together. In other words, they will need to understand chemistry.

At least for now, though, this atomic-level engineering remains in the future. But what about today's practicing engineers? How do their decisions depend on knowledge of chemistry? And from your own perspective as an engineering student, why are you required to take chemistry?

The Accreditation Board for Engineering and Technology, or ABET, is a professional organization that oversees engineering education. According to ABET's definition, "Engineering is the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind." So as one of the sciences, chemistry is clearly included in the realm of knowledge at the disposal of an engineer. Yet engineering students do not always recognize the role of chemistry in their chosen profession. One of the main goals of this textbook is to instill an appreciation of the role of chemistry in many areas of engineering and technology and in the interplay between chemistry and engineering in a variety of modern technologies.

The study of chemistry involves a vast number of concepts and skills. The philosophy of this book is to present those basic ideas and also to apply them to aspects of engineering where chemistry is important. Each chapter will begin with an example of chemistry related to engineering. Some of these examples, such as the burning of fuels, will involve fairly clear applications of chemical principles and reactions. In other cases, the role of chemistry may be less immediately apparent. In Chapter 10, we will consider the recycling of plastics and examine some factors that limit both the feasibility and the profitability of recycling. Other themes will involve the design and selection of materials for various uses and the ways that even very small changes in composition can influence the properties of alloys that are often used in engineering designs. All of these chapter-opening sections are marked with an **INSIGHT** icon because they provide some insight into applications of chemistry. The questions that are raised in these "Insight" sections will guide our exploration of the relevant fundamentals of chemistry presented throughout that chapter. Our first case considers potential supply and demand issues affecting a number of chemical elements that play important roles in modern technology.

CHAPTER OBJECTIVES

After mastering this chapter, you should be able to

- explain what is meant by the term *critical materials*.
- explain the usefulness of the macroscopic, microscopic, and symbolic perspectives in understanding chemical systems.
- draw pictures to illustrate simple chemical phenomena (like the differences among solids, liquids, and gases) on the molecular scale.
- explain the difference between inductive and deductive reasoning in your own words.
- use appropriate techniques to convert measurements from one unit to another.
- express the results of calculations using the correct number of significant figures.

INSIGHT

1.1 Critical Materials

Even a writer of science fiction would probably say that we are living in an astounding era for new technology. If you wanted to define differences among eras, looking at the size of the technology that emerges might be a good place to start. The icons of the industrial revolution were large and powerful objects, including steam locomotives and giant ocean liners. Today, advances are much more likely to be made at the opposite extreme as we now value the ability to miniaturize our tools. What might be less apparent, however, is how these different directions affect the sorts of materials that we need to extract from the earth in order to make the things we build.

Iron and steel, copper, nickel, lead, and zinc were materials that were vitally important to the advances of the early industrial revolution, and they remain important economic commodities today. At the same time, new technologies like smartphones are made from components that contain more than half of the naturally occurring elements in the periodic table. ▶ With so many elements needed to build the devices we use daily, it is not surprising that some of these materials are found in relatively few places on the planet.

The periodic table is discussed briefly in Chapter 2 and in more detail in Chapter 6.

Concerns about the availability of needed materials are not new or unique to modern technologies. For decades, governments have identified certain materials as vitally important, and collectively, these substances are often referred to as **critical materials.** Critical materials possess unique chemical and physical properties that allow them to play vital roles in technology, but at the same time, they may be vulnerable to disruptions in their availability for some reason.

Among the government agencies concerned with the criticality of materials is the U.S. Department of Energy (DOE). Emerging technologies employed in such applications as wind energy or electric cars rely on some of the elements noted in **Figure 1.1**, which categorizes various elements in terms of their importance and the extent to which their supply is considered to be at risk for disruption. Some of the elements in this figure sound more familiar than others, but the applications in which they are used are probably quite familiar.

For example, lithium appears as "near critical" in this assessment largely because of its use in lithium batteries, which power many of the devices we use. Even though it's not part of the name, cobalt is also required for a lithium battery, and it too is

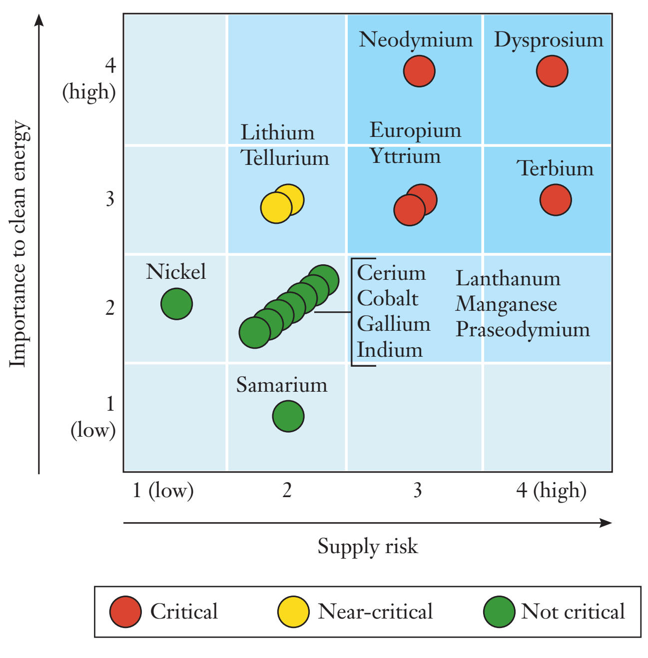

FIGURE 1.1 The U.S. Department of Energy regularly determines the criticality of various elements important in energy-related technologies. The assessment shown in the figure is for the period 2015–2025.