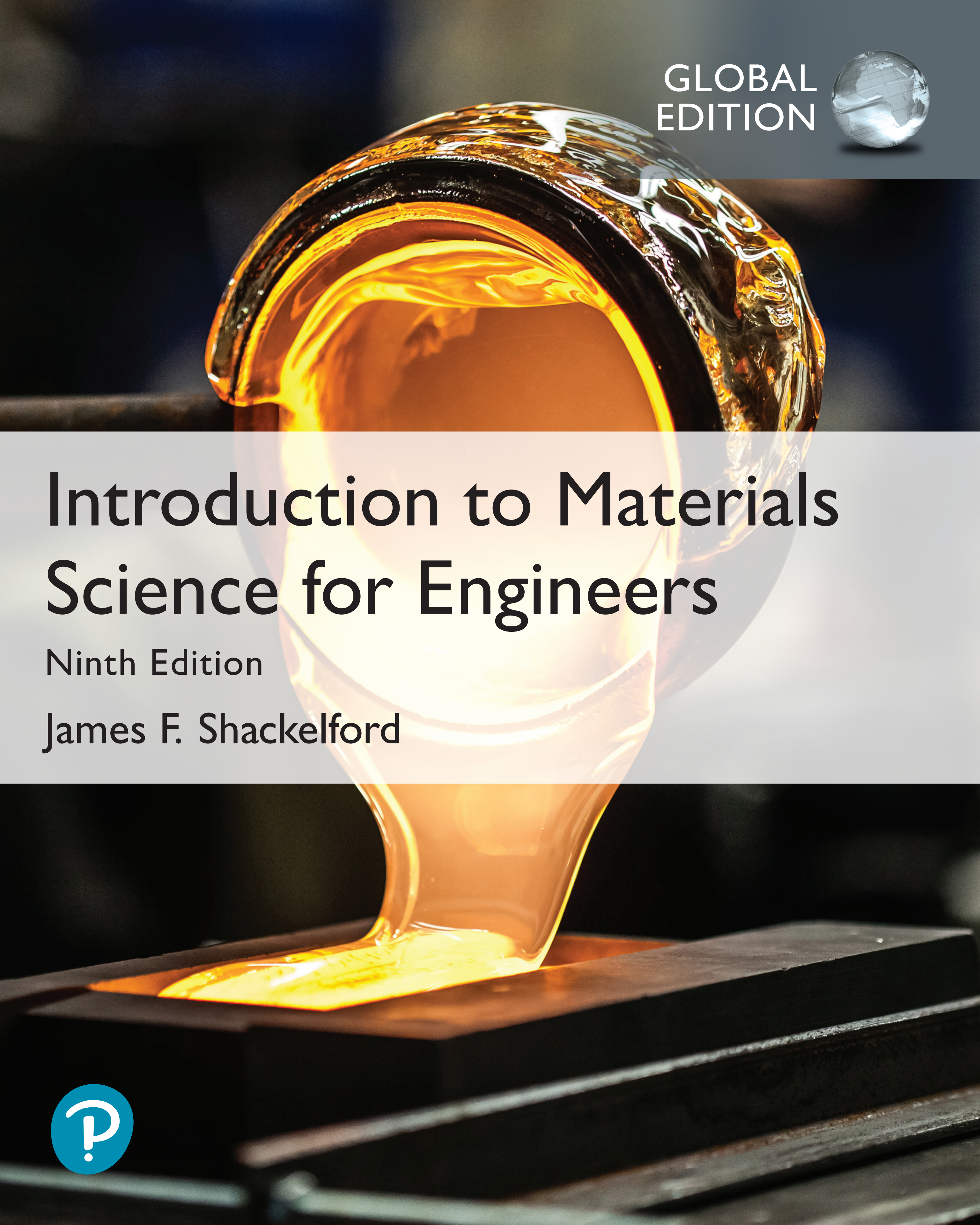

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Introduction to Materials Science for Engineers

Ninth Edition

James F. Shackelford

NINTH EDITION
GLOBAL EDITION

Introduction to MATERIALS SCIENCE FOR ENGINEERS

James F. Shackelford
University of California, Davis

Pearson

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ISBN 10 (Print): 1-292-44099-6
ISBN 13 (Print): 978-1-292-44099-6
ISBN 13 (uPDF eBook): 978-1-292-44102-3

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

eBook formatted by B2R Technologies Pvt. Ltd.

Dedicated to Penelope, Scott, Megumi, Mia, and Toki

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Preface

This book is designed for a first course in engineering materials. The field that covers this area of the engineering profession has come to be known as "materials science and engineering." To me, this label serves two important functions. First, it is an accurate description of the balance between scientific principles and practical engineering that is required in selecting the proper materials for modern technology. Second, it gives us a guide to organizing this book. After a short introductory chapter, "science" serves as a label for Part I on "The Fundamentals." Chapters 2 through 10 cover various topics in applied physics and chemistry. These are the foundation for understanding the principles of "materials science." I assume that some students take this course at the freshman or sophomore level and may not yet have taken their required coursework in chemistry and physics. As a result, Part I is intended to be self-contained. A previous course in chemistry or physics is certainly helpful, but should not be necessary. If an entire class has finished freshman chemistry, Chapter 2 (atomic bonding) could be left as optional reading, but it is important not to overlook the role of bonding in defining the fundamental types of engineering materials. The remaining chapters in Part I are less optional, as they describe the key topics of materials science. Chapter 3 outlines the ideal, crystalline structures of important materials. Chapter 4 introduces the structural imperfections found in real, engineering materials. These structural defects are the bases of solid-state diffusion (Chapter 5) and plastic deformation in metals (Chapter 6). Chapter 6 also includes a broad range of mechanical behavior for various engineering materials. Similarly, Chapter 7 covers the thermal behavior of these materials. Subjecting materials to various mechanical and thermal processes can lead to their failure, the subject of Chapter 8. In addition, the systematic analysis of material failures can lead to the prevention of future catastrophes. Chapters 9 and 10 are especially important in providing a bridge between "materials science" and "materials engineering." Phase diagrams (Chapter 9) are an effective tool for describing the equilibrium microstructures of practical engineering materials. Instructors will note that this topic is introduced in a descriptive and empirical way. Since some students in this course may not have taken a course in thermodynamics, I avoid the use of the free-energy property. Kinetics (Chapter 10) is the foundation of the heat treatment of engineering materials.

The words "materials engineering" give us a label for Part II of the book that deals with "Materials and Their Applications." First, we discuss the five categories of *structural materials*: metals, ceramics, and glasses (Chapter 11) and polymers and composites (Chapter 12). In both chapters, we give examples of each type of structural material and describe their processing, the techniques used to produce the materials. In Chapter 13, we discuss *electronic materials* and discover a sixth category of materials, semiconductors, based on an electrical rather than bonding classification system. Metals are generally good electrical conductors, while ceramics, glasses, and polymers are generally good insulators, and semiconductors are intermediate. The exceptional discovery of superconductivity in certain ceramic materials at relatively high temperatures augments the long-standing use of superconductivity in certain metals at very low temperatures. Chapter 14 covers optical behavior that determines the application of many materials, from traditional glass windows to some of the latest advances in telecommunications. A wide variety of *materials* is also discussed in Chapter 14. Traditional metallic and ceramic magnets are being supplemented by superconducting metals and ceramics, which can provide some intriguing design applications based on their magnetic behavior. Finally, in Chapter 15 (Materials in Engineering Design), we see that our previous discussions of properties have left us with "design parameters." Herein lies a final bridge between the principles of materials science and the use of those materials in modern engineering designs. We also must note that chemical degradation, radiation damage, wear, recycling, and reuse must be considered in making a final judgment on a materials application.

I hope that students and instructors alike will find what I have attempted to produce: a clear and readable textbook organized around the title of this important branch of engineering. It is also worth noting that materials play a central role across the broad spectrum of contemporary science and technology. In the report *Science: The End of the Frontier?* from the American Association for the Advancement of Science, 10 of the 26 technologies identified at the forefront of economic growth are various types of advanced materials.

In the presentation of this book, I have attempted to be generous with examples and practice problems within each chapter, and I have tried to be even more generous with the end-of-chapter homework problems (with the level of difficulty for the homework problems clearly noted). Problems dealing with the role of materials in the engineering design process are noted with the use of a design icon **D**. One of the most enjoyable parts of writing the book was the preparation of biographical footnotes for those cases in which a person's name has become intimately associated with a basic concept in materials science and engineering. I suspect that most readers will share my fascination with these great contributors to science and engineering from the distant and not-so-distant past. In addition to a substantial set of useful data, the Appendices provide convenient location of materials properties and key term definitions.

The various editions of this book have been produced during a period of fundamental change in the field of materials science and engineering. This change was exemplified by the change of name in the Fall of 1986 for the "American Society for Metals" to "ASM International"—a society for *materials*, as opposed to metals only. An adequate introduction to materials science can no longer be a traditional treatment of physical metallurgy with supplementary introductions to nonmetallic materials. The first edition was based on a balanced treatment of the full spectrum of engineering materials.

Subsequent editions have reinforced that balanced approach with the timely addition of new materials that are playing key roles in the economy of the twenty-first century: lightweight metal alloys, "high tech" ceramics for advanced structural applications, engineering polymers for metal substitution, advanced composites for aerospace applications, increasingly miniaturized semiconductor devices, high-temperature ceramic superconductors, fullerene carbons, graphene, engineered biomaterials, and biological materials. Since the debut of the first edition, we have also seen breakthroughs in materials characterization, such as the evolution of the high-resolution transmission electron microscope (HRTEM), and in materials processing, such as additive manufacturing (AM). "Feature boxes" have been introduced in recent editions. These one- or two-page case studies labeled "The Material World" are located in each chapter to provide a focus on some fascinating topics in the world of both engineered and natural materials. Another feature from recent editions is to emphasize the concept of "Powers of Ten." In Chapter 1, we point out that an underlying principle of materials science is that understanding the behavior of materials in engineering designs (on the human scale) is obtained by looking at mechanisms that occur at various fine scales, such as the atomic-scale diffusion of carbon atoms involved in the heat treatment of steel. There is a full ten orders of magnitude difference between the size of typical engineered products and the size of typical atoms. Much of modern engineering practice has depended on engineering designs based on micrometer-scale structures, such as the transistors in an integrated circuit. Increasingly, engineers are designing systems involving the nanometer-scale. At various times throughout the text, a Powers of Ten icon will be used to highlight discussions that demonstrate this structure-property relationship.

New to This Edition

As with previous editions, an effort has been made to add the most important advances in engineering materials, as well as respond to recommendations of previous users for additional content coverage. The results are:

- The addition of Learning Objectives to each chapter to give students clearer goals for the knowledge to be acquired.
- The inclusion of end-of-chapter conceptual problems throughout the text.
- The inclusion of *all* end-of-chapter problems in the Mastering^{TM} platform.
- The upgrade of images to full color where appropriate to provide a more vibrant presentation of visual information throughout the book.
- Updated discussions of the role of engineering materials in smartphones and tablets, increasingly ubiquitous parts of our everyday lives.
- Enhanced discussion of the nature of optical fibers in telecommunication.
- The refreshing and updating of all discussions of contemporary materials in modern engineering design, including an emphasis on the role of sustainability.

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Related Massively Open Online Course (MOOC)

A MOOC based on this book and entitled "MATERIALS SCIENCE: Ten Things Every Engineer Should Know" is available as open access on coursera.org. In the course, the author delivers ten short lectures on topics of practical significance to both students of engineering and practicing professionals.

Acknowledgments

Finally, I want to acknowledge a number of people who have been immensely helpful in making this book possible. My family has been more than the usual "patient and understanding." They are a constant reminder of the rich life beyond the material plane. Peter Gordon (first edition), David Johnstone (second and third editions), Bill Stenquist (fourth and fifth editions), Dorothy Marrero (sixth edition), and Holly Stark (seventh, eighth, and ninth editions) are much appreciated in their roles as editors. Erin Ault, Manager of Content Strategy, has been indispensible in shepherding this edition to completion. Lilian Davila at the University of California, Merced skillfully produced the computer-generated crystal structure images. A special appreciation is due to my colleagues at the University of California, Davis and to the many reviewers of all editions, especially D. J. Montgomery, John M. Roberts, D. R. Rossington, R. D. Daniels, R. A. Johnson, D. H. Morris, J. P. Mathers, Richard Fleming, Ralph Graff, Ian W. Hall, John J. Kramer, Enayat Mahajerin, Carolyn W. Meyers, Ernest F. Nippes, Richard L. Porter, Eric C. Skaar, E. G. Schwartz, William N. Weins, M. Robert

Baren, John Botsis, D. L. Douglass, Robert W. Hendricks, J. J. Hren, Sam Hruska, I. W. Hull, David B. Knoor, Harold Koelling, John McLaughlin, Alvin H. Meyer, M. Natarajan, Jay Samuel, John R. Schlup, Theodore D. Taylor, Ronald Kander, Alan Lawley, Joanna McKittrick, Kathleen R. Rohr, James F. Fitz-Gerald. Valery Bliznyuk, David Bahr, K. Srinagesh, Stacy Gleixner, Raj Vaidyanathan. Jeffrey Fergus, Christoph Steinbruchel, Wayne Elban, Giovanni Zangari, Guanshui Xu, Atin Sinha, Yu-Lin Shen, Qiuming Wei, Blair London, and James Chelikowsky.

JAMES F. SHACKELFORD
Davis, California

Acknowledgments for the Global Edition

Pearson would like to acknowledge and thank the following for their work on the Global Edition:

Contributor
K. S. Vijay Sekar, Sri Sivasubramaniya Nadar College of Engineering

Reviewers
Durul Huda, Swinburne University of Technology
Tanay Karademir, Istanbul Bilgi Üniversitesi
Murat Saribay, Istanbul Bilgi Üniversitesi

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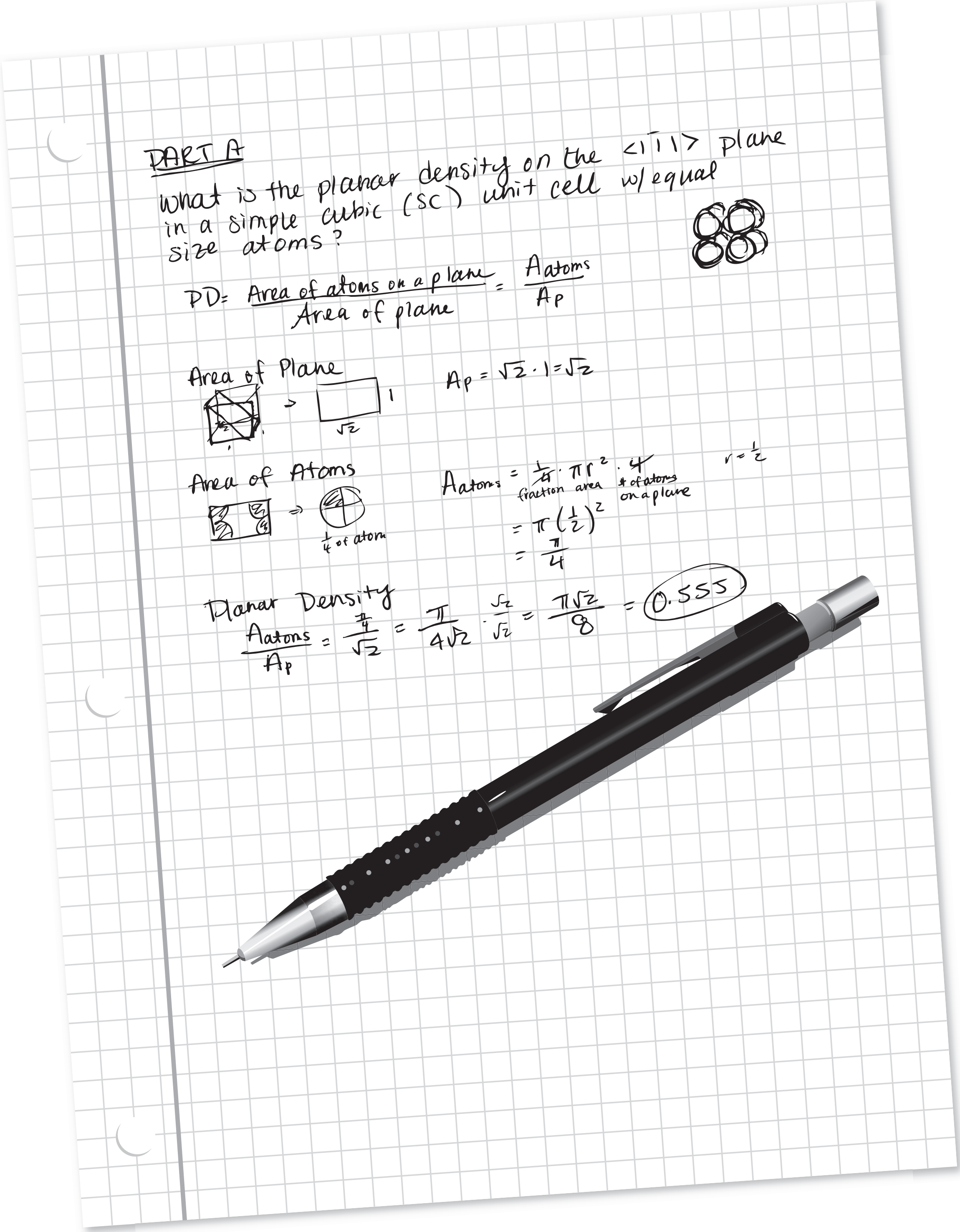

PART A

What is the planar density on the $\langle 1\bar{1}1 \rangle$ plane in a simple cubic (SC) unit cell w/ equal size atoms?

$$PD = \frac{\text{Area of atoms on a plane}}{\text{Area of plane}} = \frac{A_{atoms}}{A_p}$$

Area of Plane

$$A_p = \sqrt{2} \cdot 1 = \sqrt{2}$$

Area of Atoms

$$A_{atoms} = \underbrace{\cancel{\tfrac{1}{4}}}_{\text{fraction}} \cdot \underbrace{\pi r^2}_{\text{area}} \cdot \underbrace{\cancel{4}}_{\text{\# of atoms on a plane}}$$

$r = \frac{1}{2}$

$$= \pi \left(\tfrac{1}{2}\right)^2$$

$$= \frac{\pi}{4}$$

Planar Density

$$\frac{A_{atoms}}{A_p} = \frac{\frac{\pi}{4}}{\sqrt{2}} = \frac{\pi}{4\sqrt{2}} \cdot \frac{\sqrt{2}}{\sqrt{2}} = \frac{\pi\sqrt{2}}{8} = \boxed{0.555}$$

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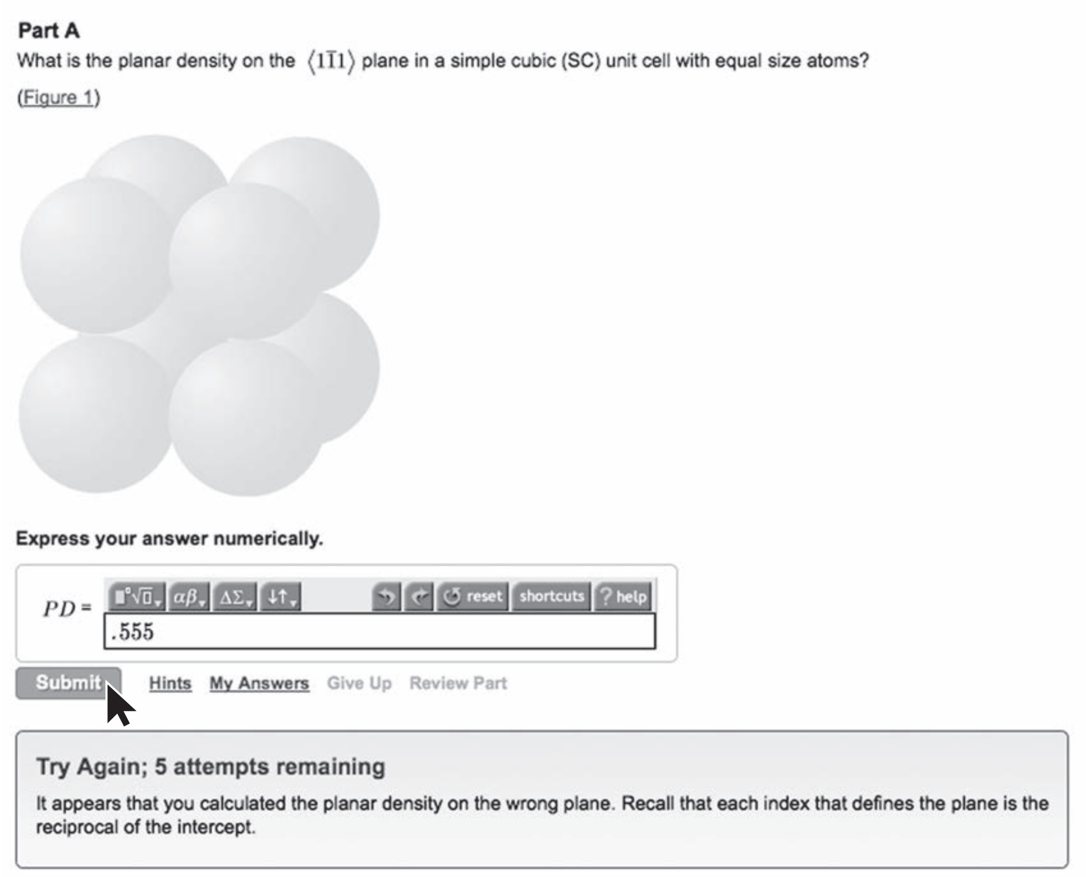

Part A

What is the planar density on the $\langle 1\bar{1}1 \rangle$ plane in a simple cubic (SC) unit cell with equal size atoms?

(Figure 1)

Express your answer numerically.

$PD =$ .555

Try Again; 5 attempts remaining

It appears that you calculated the planar density on the wrong plane. Recall that each index that defines the plane is the reciprocal of the intercept.

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About the Author

James F. Shackelford has BS and MS degrees in Ceramic Engineering from the University of Washington and a Ph.D. in Materials Science and Engineering from the University of California, Berkeley. Following a postdoctoral fellowship at McMaster University in Canada, he joined the University of California, Davis, where he is currently Distinguished Professor Emeritus in the Department of Materials Science and Engineering. For many years, he served as the Associate Dean for Undergraduate Studies in the College of Engineering and later as the Director of the University Honors Program that serves students from a wide spectrum of majors. Dr. Shackelford also served as Associate Director for Education for the National Science Foundation (NSF)-funded Center for Biophotonics Science and Technology (CBST) and as Faculty Assistant to the Director of the McClellan Nuclear Research Center (MNRC) of UC Davis. He teaches and conducts research in the structural characterization and processing of materials, focusing on glasses and biomaterials. His current focus in teaching is doing so through online technologies. A member of the American Ceramic Society and ASM International, he was named a Fellow of the American Ceramic Society in 1992, was named a Fellow of ASM International in 2011, and received the Outstanding Educator Award of the American Ceramic Society in 1996 and the Albert Easton White Distinguished Teacher Award from ASM International in 2019. In 2003, he received a Distinguished Teaching Award from the Academic Senate of the University of California, Davis. In 2012, he received the Outstanding Teaching Award of the College of Engineering at UC Davis, and, in 2014, received an Outstanding Service Award from UC Davis Extension. In 2016, Professor Shackelford received the Inaugural Award for Outstanding Contributions to Materials Education at the North American Materials Education Symposium (NAMES) held at the University of California, Berkeley. He has published over 150 archived papers and books including *Introduction to Materials Science for Engineers* now in its 9th Edition and which has been translated into Chinese, German, Italian, Japanese, Korean, Portuguese, and Spanish.

CHAPTER 1

Materials for Engineering

The future of transportation will include new advances in materials such as this glass road sign allowing instantaneous route changes and updates. (Courtesy of Corning Glass Works.)

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

1. Explain how materials have played a central role in the development of human cultures throughout history.
2. Distinguish between the terms materials science and materials engineering.
3. Identify six categories of engineering materials, five types of structural materials, and semiconductors as one example of electronic materials.
4. (a) Describe how the atomic- and microscopic-scale structure of materials help us understand the properties of those materials that are used in engineering applications.
   (b) Recall the materials tetrahedron that includes the terms structure and properties as well as their relationship with the processing of materials and their ultimate performance in an engineering design.
5. List the wide range of dimensional scales involved in materials science and engineering:
   (a) The atomic scale: 1×10^{-10} meter
   (b) The nanoscale: 1×10^{-9} meter
   (c) The microscale: 1×10^{-6} meter
   (d) The milliscale: 1×10^{-3} meter
   (e) The human scale: 1 meter

1.1 The Material World

We live in a world of material possessions that largely define our social relationships and economic quality of life. The material possessions of our earliest ancestors were probably their tools and weapons. In fact, the most popular way of naming the era of early human civilization is in terms of the materials from which these tools and weapons were made. The **Stone Age** has been traced as far back as 2.5 million years ago when human ancestors, or hominids, chipped stones to form weapons for hunting (Figure 1.1). The **Bronze Age** roughly spanned the period from 2000 B.C. to 1000 B.C. and represents the foundation of metallurgy, in which **alloys** of copper and tin were discovered to produce superior tools and weapons. (An *alloy* is a metal composed of more than one element.)

Contemporary archaeologists note that an earlier but less well known "Copper Age" existed between roughly 4000 B.C. and 3000 B.C. in Europe, in which relatively pure copper was used before tin became available. The limited utility of those copper products provided an early lesson in the importance of proper alloy additions. The **Iron Age** defines the period from 1000 B.C. to 1 B.C. By 500 B.C., iron alloys had largely replaced bronze for tool and weapon making in Europe.

Although archaeologists do not refer to a "pottery age," the presence of domestic vessels made from baked clay has provided some of the best descriptions of human cultures for thousands of years. Similarly, glass artifacts have been traced back to 4000 B.C. in Mesopotamia.

Modern culture in the second half of the 20th century is sometimes referred to as "plastic," a not entirely complimentary reference to the lightweight and economical polymeric materials from which so many products are made. Some observers have suggested instead that this same time frame should be labeled the "silicon age," given the pervasive impact of modern electronics largely based on silicon technology.

FIGURE 1.1 *Stone age tools. (Georg Hergenhan / 123RF.)*

1.2 Materials Science and Engineering

Since the 1960s, the term that has come to label the general branch of engineering concerned with materials is *materials science and engineering*. This label is accurate in that this field is a true blend of fundamental scientific studies and practical engineering. It has grown to include contributions from many traditional fields, including metallurgy, ceramic engineering, polymer chemistry, condensed matter physics, and physical chemistry.

The term “materials science and engineering” will serve a special function in this introductory textbook; it will provide the basis for the text’s organization. First, the word *science* describes the topics covered in Chapters 2 through 10, which deal with the fundamentals of structure, classification, and properties. Second, the word *materials* describes Chapters 11 through 13, which deal with the five types of *structural materials* (Chapters 11 and 12) and various electronic materials, especially *semiconductors* (Chapter 13), along with optical and magnetic materials (Chapter 14). Finally, the word *engineering* describes Chapter 15, which puts the materials to work with discussions of key aspects of the selection of the right materials for the right job, along with some caution about the issue of environmental degradation in those real-world applications.

1.3 Six Materials That Changed Your World

The most obvious question to be addressed by the engineering student entering an introductory course on materials is, “What materials are available to me?” Various classification systems are possible for the wide-ranging answer to this question. In this book, we distinguish six categories that encompass the materials available to practicing engineers: metals, ceramics, glasses, polymers, composites, and semiconductors. We will introduce each of these categories with a single example.

STEEL BRIDGES—INTRODUCING METALS

If there is a “typical” material associated in the public’s mind with modern engineering practice, it is structural *steel*. This versatile construction material has several properties that we consider **metallic**: First, it is strong and can be readily formed into practical shapes. Second, its extensive, permanent deformability, or **ductility**, is an important asset in permitting small amounts of yielding to sudden and severe loads. For example, many Californians have been able to observe moderate earthquake activity that leaves windows of glass, which is relatively **brittle** (i.e., lacking in ductility), cracked, while steel-support framing still functions normally. Third, a freshly cut steel surface has a characteristic metallic luster; and fourth, a steel bar shares a fundamental characteristic with other metals: It is a good conductor of electrical current.

Among the most familiar uses of structural steel are bridges, and one of the most famous and beautiful examples is the Golden Gate Bridge connecting San Francisco, California with Marin County to the north (Figure 1.2). The opening on May 27, 1937, allowed 200,000 local residents to stroll across the impressive

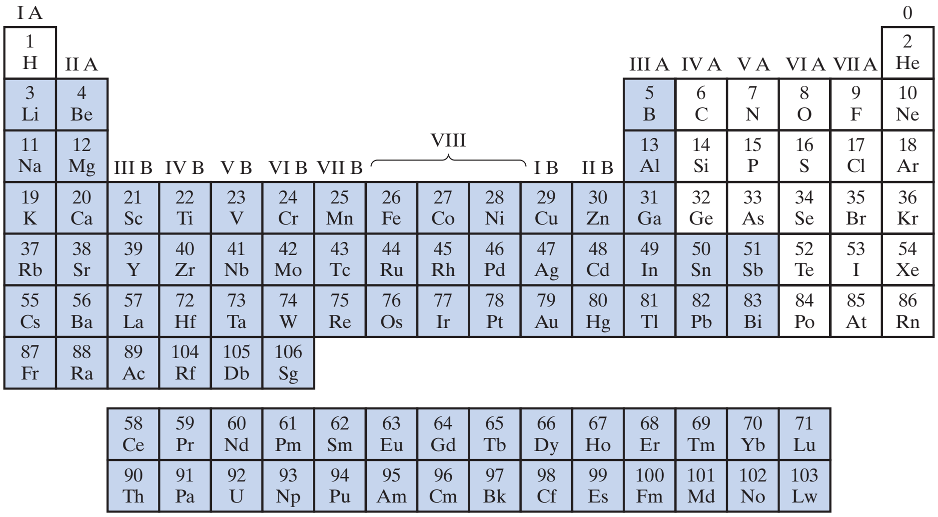
FIGURE 1.2 *The Golden Gate Bridge north of San Francisco, California, is one of the most famous and most beautiful examples of a steel bridge. (© LOOK Die Bildagentur der Fotografen GmbH / Alamy.)*

new structure. The following day, a ribbon cutting ceremony inaugurated automobile traffic that has continued to be an important part of the fabric of life in the San Francisco Bay area for more than 80 years. For many years, the Golden Gate held the title of "longest suspension bridge" in the world (2,737 meters). Although new bridge technologies have provided newer holders of that title, the Golden Gate is still, in the words of a local historian, a "symphony in steel."

Steel bridges continue to provide a combination of function and beauty with the Sundial Bridge in Redding, California being a stunning example (Figure 1.3). The Redding Bridge is a 66-meter pedestrian walkway designed by the famous Spanish architect Santiago Calatrava. It connects a walking trail system with the Turtle Bay Exploration Park. New bridges like this one are not merely serving as sculptural art projects. The aging infrastructure, including many bridges built as long as a century ago, also provides a challenge to engineers and the requirement for both maintenance and replacement of these important structures.

In Chapter 2, the nature of metals will be defined and placed in perspective relative to the other categories. It is useful to consider the extent of metallic behavior in the currently known range of chemical elements. Figure 1.4 highlights the chemical elements in the periodic table that are inherently metallic. This is a large family indeed. The shaded elements are the bases of the various engineering alloys, including the irons and steels (from Fe), aluminum alloys (Al), magnesium alloys (Mg), titanium alloys (Ti), nickel alloys (Ni), zinc alloys (Zn), and copper alloys (Cu) [including the brasses (Cu, Zn)].

FIGURE 1.3 *The Sundial Bridge in Redding, California is a modern masterpiece of bridge design.*



I A	II A	III B	IV B	V B	VI B	VII B	VIII			I B	II B	III A	IV A	V A	VI A	VII A	0
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg												

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

FIGURE 1.4 *Periodic table of the elements. Those elements that are inherently metallic in nature are shown in color.*

TRANSPARENT OXIDES—INTRODUCING CERAMICS

Aluminum (Al) is a common metal, but aluminum *oxide*, a compound of aluminum and oxygen such as Al_2O_3, is typical of a fundamentally different family of engineering materials, **ceramics**. Aluminum oxide has two principal advantages

FIGURE 1.5 *A variety of alumina ceramic products are available for high-temperature (refractory) applications. (Courtesy of AdValue Technology.)*

over metallic aluminum. First, Al_2O_3 is chemically stable in a wide variety of severe environments, whereas metallic aluminum would be oxidized (a term discussed further in Chapter 15). In fact, a common reaction product in the chemical degradation of aluminum is the more chemically stable oxide. Second, the ceramic Al_2O_3 has a significantly higher melting point (2020°C) than does the metallic Al (660°C), which makes Al_2O_3 a popular **refractory** (i.e., a high-temperature-resistant material of wide use in industrial furnace construction). A variety of engineered alumina products are shown in Figure 1.5.

With its superior chemical and temperature-resistant properties, why isn't Al_2O_3 used for applications such as automotive engines in place of metallic aluminum? The answer to this question lies in the most limiting property of ceramics—brittleness. Aluminum and other metals have high ductility, a desirable property that permits them to undergo relatively severe impact loading without fracture, whereas aluminum oxide and other ceramics lack this property. Thus, ceramics are eliminated from many structural applications because they are brittle.

A significant achievement in materials technology is the development of transparent ceramics, which has made possible new products and substantial improvements in others (e.g., commercial lighting). To make traditionally opaque ceramics, such as aluminum oxide (Al_2O_3), into optically transparent materials required a fundamental change in manufacturing technology. Commercial ceramics are frequently produced by heating crystalline powders to high temperatures until a relatively strong and dense product results. Traditional ceramics made in this way contained a substantial amount of residual porosity (see also the Feature Box, "Structure Leads to Properties"), corresponding to the open space between the original powder particles prior to high-temperature processing. A significant reduction in porosity resulted from a relatively simple invention* that involved

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*R. L. Coble, U.S. Patent 3,026,210, March 20, 1962.

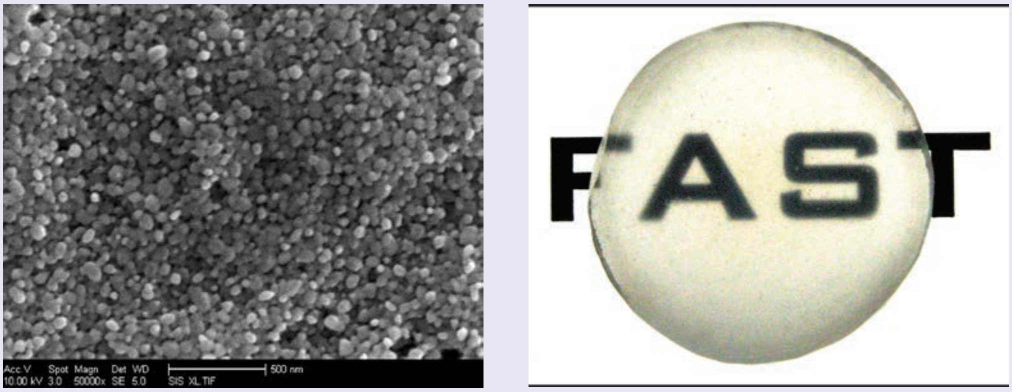
THE MATERIAL WORLD

Structure Leads to Properties

To understand the properties or observable characteristics of engineering materials, it is necessary to understand their structure. Virtually every major property of the six materials' categories outlined in this chapter will be shown to result directly from mechanisms occurring on a small scale (usually either the atomic or the microscopic level).

The dramatic effect that fine-scale structure has on large-scale properties is well illustrated by the development of transparent ceramics, just discussed in the introduction to ceramic materials. The microscopic-scale residual porosity in a traditional aluminum oxide leads to loss of visible light transmission (i.e., a loss in transparency) by providing a light-scattering mechanism. Each Al_2O_3—air interface at a pore surface is a source of light refraction (change of direction). Only about 0.3% porosity can cause Al_2O_3 to be translucent (capable of transmitting a diffuse image), and 3% porosity can cause the material to be completely opaque. The elimination of porosity provided by the Lucalox patent (adding 0.1 wt % MgO) produced a pore-free microstructure and a nearly transparent material with an important additional property—excellent resistance to chemical attack by high-temperature sodium vapor.

The example of translucent ceramics shows a typical and important demonstration of how properties of engineering materials follow directly from structure. Throughout this book, we shall be alert to the continuous demonstration of this interrelationship for all the materials of importance to engineers. A contemporary example is given in the images below, a microstructure and the resulting translucent disc of hydroxyapatite ceramic developed for biomedical applications. By using the Field-Assisted Sintering Technique (FAST) as highlighted in the Feature Box in Chapter 10, researchers were able to produce a material with minimal porosity (note the densely packed nano-scale grain structure in part a) and the resulting ability to transmit a visual image (part b). The effect of porosity on light transmission is discussed further in Chapter 14 (e.g., Figures 14.8 and 14.9), and the importance of hydroxyapatite in orthopedic prostheses is discussed further in Chapter 15.



(a) (b)

(Courtesy of T. B. Tran and J. R. Groza, University of California, Davis.)

adding a small amount of impurity (0.1 wt % MgO), which caused the high-temperature densification process for the Al_2O_3 powder to go to completion. Cylinders of translucent Al_2O_3 became the heart of the design of high-temperature (1000°C) sodium vapor lamps, which provide substantially higher illumination than do conventional lightbulbs (100 lumens/W compared to 15 lumens/W).

FIGURE 1.6 *An yttrium-aluminum-oxide ($Y_3Al_5O_{12}$ or YAG) crystal grown over a period of 21 days for use in laser rods. (James L. Amos / Science Source.)*

After the invention of transparent aluminum oxide and the resulting advancement in lighting technology, ceramic scientists and engineers have applied a similar approach to a wide range of compositions, including the development of ceramics for laser technology, a topic covered more fully in Chapter 14. A prime example is yttrium-aluminum-oxide ($Y_3Al_5O_{12}$ or YAG), typically with a small amount of neodymium (Nd) in a solution to provide the lasing property. These Nd:YAG lasers are used in a wide range of medical and engineering applications, including manufacturing technologies. It is also important to note that these transparent laser materials are also made by a more traditional technique, viz. growing large single crystals from a melt as shown in Figure 1.6.

Aluminum oxide is typical of the traditional ceramics, with magnesium oxide (MgO) and **silica** (SiO_2) being other good examples. In addition, SiO_2 is the basis of a large and complex family of **silicates**, which includes clays and claylike minerals. Silicon nitride (Si_3N_4) is an important nonoxide ceramic used in a variety of structural applications. The vast majority of commercially important ceramics are chemical compounds made up of at least one metallic element (see Figure 1.4) and one of five **nonmetallic** elements (C, N, O, P, or S). Figure 1.7 illustrates the various metals (in light color) and the five key nonmetals (in dark color) that can be combined to form an enormous range of ceramic materials. Bear in mind that many commercial ceramics include compounds and solutions of many more than two elements, just as commercial metal alloys are composed of many elements.

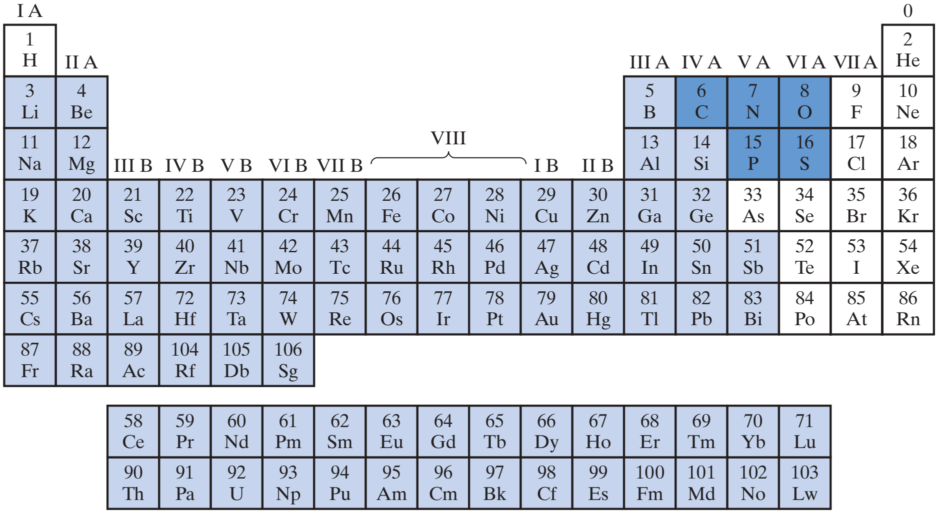


FIGURE 1.7 *Periodic table with ceramic compounds indicated by a combination of one or more metallic elements (in light color) with one or more nonmetallic elements (in dark color). Note that elements silicon* (Si) *and germanium* (Ge) *are included with the metals in this figure but were not included in the periodic table shown in Figure 1.4. They are included here because, in elemental form,* Si *and* Ge *behave as semiconductors (Figure 1.16). Elemental tin* (Sn) *can be either a metal or a semiconductor, depending on its crystalline structure.*

SMARTPHONES AND TABLETS—INTRODUCING GLASSES

The metals and ceramics just introduced have a similar structural feature on the atomic scale: They are **crystalline**, which means that their constituent atoms are stacked together in a regular, repeating pattern. A distinction between metallic- and ceramic-type materials is that, by fairly simple processing techniques, many ceramics can be made in a **noncrystalline** form (i.e., their atoms are stacked in irregular, random patterns), which is illustrated in Figure 1.8. The general term for noncrystalline solids with compositions comparable to those of crystalline ceramics is **glass** (Figure 1.9). Most common glasses are silicates; ordinary

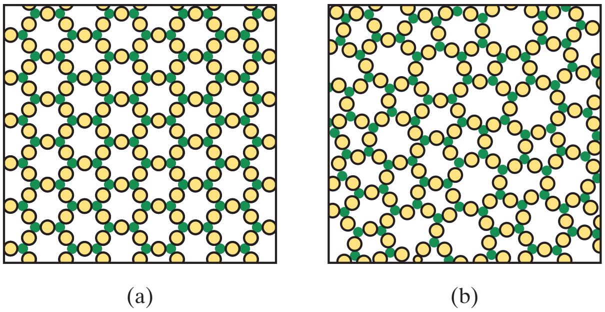


FIGURE 1.8 *Schematic comparison of the atomic-scale structure of (a) a ceramic (crystalline) and (b) a glass (noncrystalline). The yellow circles represent a nonmetallic atom, and the green circles represent a metal atom.*

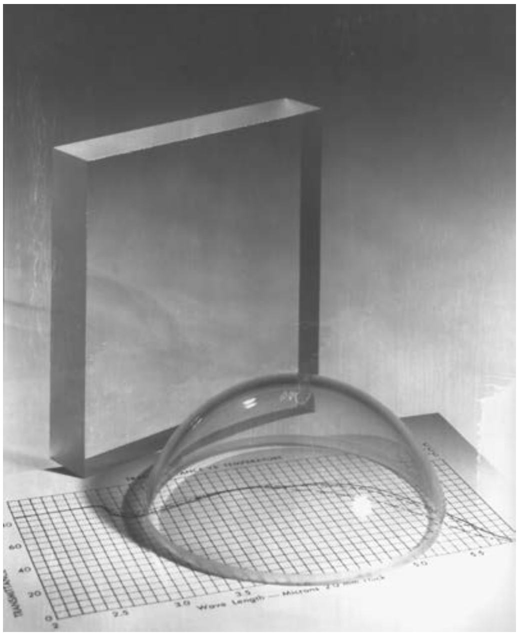


FIGURE 1.9 *Some common silicate glasses for engineering applications. These materials combine the important qualities of transmitting clear visual images and resisting chemically aggressive environments. (Courtesy of Corning Glass Works.)*

window glass is approximately 72% silica (SiO_2) by weight, with the balance of the material being primarily sodium oxide (Na_2O) and calcium oxide (CaO). Glasses share the property of brittleness with crystalline ceramics. Glasses are important engineering materials because of other properties, such as their ability to transmit visible light (as well as ultraviolet and infrared radiation) and chemical inertness.

In the decade following the introduction of the Apple iPhone in 2007, the annual sales of smartphones increased from 122 million to 1.5 billion in 2017. By 2025, there will be an estimated 6 billion mobile subscribers, roughly 70% of the earth's population. The introduction of the Apple iPad in 2010 led to the similarly expanding role of tablet devices in our daily lives. The cover glass in these increasingly ubiquitous devices is one of the most common state-of-the-art glass materials used by the general public. As such device users are painfully aware, a major criterion for the cover glass, beyond the obvious optical transparency, is resistance to mechanical damage (scratching and breakage). A practical technique to provide improved mechanical performance is "chemical strengthening," as discussed in Section 6.6 in which the chemical substitution of some relatively large potassium ions for the smaller sodium ions in the silicate glass creates a compressive surface state that effectively resists such damage. Figure 1.10 shows some contemporary examples.

NYLON PARACHUTES—INTRODUCING POLYMERS

A major impact of modern engineering technology on everyday life has been made by the class of materials known as **polymers**. An alternative name for this


(a)

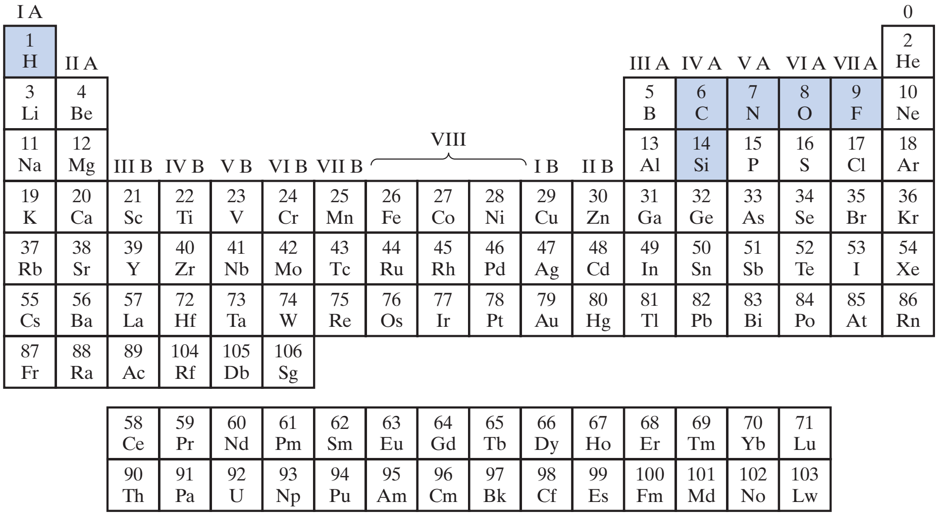
(b)

FIGURE 1.10 *(a) The smartphone and tablet have joined the laptop computer as integral parts of our personal and business lives. (© wavebreakmedia / Shutterstock) (b) Damage-resistant cover glass is a central component of the design of iPhone 11. (Courtesy of Apple Inc.)*

category is **plastics**, which describes the extensive formability of many polymers during fabrication. These synthetic, or human-made, materials represent a special branch of organic chemistry. Examples of inexpensive, functional polymer products are readily available to each of us (Figure 1.11). The "mer" in a polymer is a single hydrocarbon molecule such as ethylene (C_2H_4). Polymers are long-chain molecules composed of many mers bonded together. The most common commercial polymer is **polyethylene** $\left(C_2H_4\right)_n$ where n can range from approximately 100 to 1,000. Figure 1.12 shows the relatively limited portion of the periodic table that is associated with commercial polymers. Many important polymers, including polyethylene, are simply compounds of hydrogen and carbon. Others contain oxygen (e.g., acrylics), nitrogen (nylons), fluorine (fluoroplastics), and silicon (silicones).

Nylon is an especially familiar example. Polyhexamethylene adipamide, or nylon, is a member of the family of synthetic polymers known as polyamides invented in 1935 at the DuPont Company. Nylon was the first commercially successful polymer and was initially used as bristles in toothbrushes (1938) followed by the highly popular use as an alternative to silk stockings (1940). Developed as a synthetic alternative to silk, nylon became the focus of an intensive effort during the early stages of World War II to replace the diminishing supply of Asian silk for parachutes and other military supplies. At the beginning of World War II, the fiber industry was dominated by the natural materials cotton and wool. By the end, synthetic fibers accounted for 25% of the market share. A contemporary example of a nylon parachute is shown in Figure 1.13. Today, nylon remains a

FIGURE 1.11 *Polymers are the basis of a wide range of common consumer products, often available for recycling. (PBWPIX / Alamy.)*



I A	II A	III B	IV B	V B	VI B	VII B	VIII			I B	II B	III A	IV A	V A	VI A	VII A	0
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg												

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

FIGURE 1.12 *Periodic table with the elements associated with commercial polymers in color.*

FIGURE 1.13 *Since its development during World War II, nylon fabric remains the most popular material of choice for parachute designs. (Courtesy of Stringer/Agence France Presse/Getty Images.)*

popular fiber material, but it is also widely used in solid form for applications such as gears and bearings.

As the descriptive title implies, *plastics* commonly share with metals the desirable mechanical property of ductility. Unlike brittle ceramics, polymers are frequently lightweight, low-cost alternatives to metals in structural design applications. The nature of chemical bonding in polymeric materials will be explored in Chapter 2. Important bonding-related properties include lower strength compared with metals and lower melting point and higher chemical reactivity compared with ceramics and glasses. In spite of their limitations, polymers are highly versatile and useful materials. Substantial progress has been made in recent decades in the development of engineering polymers with sufficiently high strength and stiffness to permit substitution for traditional structural metals.

KEVLAR®-REINFORCED TIRES—INTRODUCING COMPOSITES

The structural engineering materials we have discussed so far—metals, ceramics/glasses, and polymers—contain various elements and compounds that can be classified by their chemical bonding. Metals are associated with metallic bonding, ceramics/glasses with ionic bonding, and polymers with covalent bonding. Such classifications are described further in Chapter 2. Another important set of materials is made up of some combinations of individual materials from the previous categories. This fourth group is **composites**, and an excellent example is **fiberglass**. This composite of glass fibers embedded in a polymer matrix is commonplace (Figure 1.14). Characteristic of good composites, fiberglass has the best

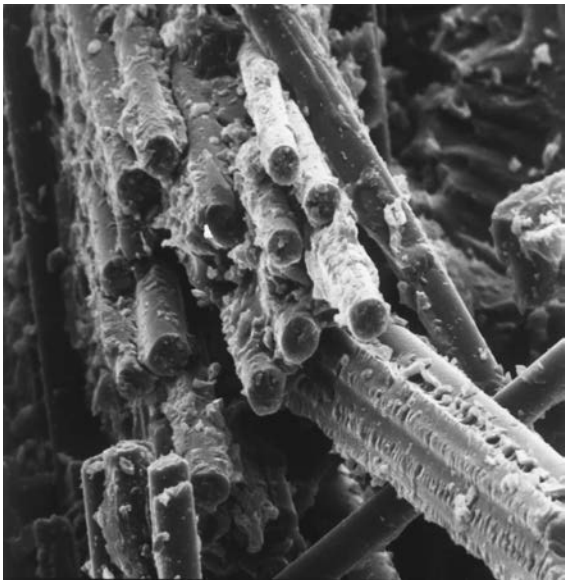


FIGURE 1.14 *Example of a fiberglass composite composed of microscopic-scale reinforcing glass fibers in a polymer matrix. (Courtesy of Owens-Corning Fiberglas Corporation.)*

FIGURE 1.15 *Kevlar reinforcement is a popular application in modern high-performance tires. In this case, an automobile is subjected to aquaplaning at a test track. (© Culture-images GmbH / Alamy.)*

properties of each component, producing a product that is superior to either of the components separately. The high strength of the small-diameter glass fibers is combined with the ductility of the polymer matrix to produce a strong material capable of withstanding the normal loading required of a structural material. There is no need to illustrate a region of the periodic table as characteristic of composites, since they involve virtually the entire table except for the noble gases (column 0), equivalent to an overlay of the periodic table coverage for metals, ceramics, and polymers combined.

Kevlar fiber reinforcements provide significant advances over traditional glass fibers for **polymer–matrix composites**. Kevlar is a DuPont trade name for poly *p*-phenyleneterephthalamide (PPD-T), a para-aramid. Substantial progress has been made in developing new polymer matrices, such as polyetheretherketone (PEEK) and polyphenylene sulfide (PPS). These materials have the advantages of increased toughness and recyclability. Kevlar-reinforced polymers are used in pressure vessels, and Kevlar reinforcement is widely used in tires (Figure 1.15). Kevlar was developed in 1965 and has been used commercially since the early 1970s. It is especially popular for demanding applications given that its strength-to-weight ratio is five times that of structural steel. The modern automobile tire is an especially good example.

SILICON CHIPS—INTRODUCING SEMICONDUCTORS

Although polymers are highly visible engineering materials that have had a major impact on contemporary society, semiconductors are relatively invisible but have