Cengage SI EDITION

THE SCIENCE AND ENGINEERING OF MATERIALS

ENHANCED SEVENTH EDITION

DONALD R. ASKELAND
WENDELIN J. WRIGHT

CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Acceleration (linear)					
foot per second squared	ft/s^2	0.3048*	0.305	meter per second squared	m/s^2
inch per second squared	$in./s^2$	0.0254*	0.0254	meter per second squared	m/s^2
Area					
square foot	ft^2	0.09290304*	0.0929	square meter	m^2
square inch	$in.^2$	645.16*	645	square millimeter	mm^2
Density (mass)					
slug per cubic foot	$slug/ft^3$	515.379	515	kilogram per cubic meter	kg/m^3
Density (weight)					
pound per cubic foot	lb/ft^3	157.087	157	newton per cubic meter	N/m^3
pound per cubic inch	$lb/in.^3$	271.447	271	kilonewton per cubic meter	kN/m^3
Energy; work					
foot-pound	ft-lb	1.35582	1.36	joule (N·m)	J
inch-pound	in.-lb	0.112985	0.113	joule	J
kilowatt-hour	kWh	3.6*	3.6	megajoule	MJ
British thermal unit	Btu	1055.06	1055	joule	J
Force					
pound	lb	4.44822	4.45	newton ($kg·m/s^2$)	N
kip (1000 pounds)	k	4.44822	4.45	kilonewton	kN
Force per unit length					
pound per foot	lb/ft	14.5939	14.6	newton per meter	N/m
pound per inch	lb/in.	175.127	175	newton per meter	N/m
kip per foot	k/ft	14.5939	14.6	kilonewton per meter	kN/m
kip per inch	k/in.	175.127	175	kilonewton per meter	kN/m
Length					
foot	ft	0.3048*	0.305	meter	m
inch	in.	25.4*	25.4	millimeter	mm
mile	mi	1.609344*	1.61	kilometer	km
Mass					
slug	$lb\text{-}s^2/ft$	14.5939	14.6	kilogram	kg
Moment of a force; torque					
pound-foot	lb-ft	1.35582	1.36	newton meter	N·m
pound-inch	lb-in.	0.112985	0.113	newton meter	N·m
kip-foot	k-ft	1.35582	1.36	kilonewton meter	kN·m
kip-inch	k-in.	0.112985	0.113	kilonewton meter	kN·m

CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS (Continued)

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Moment of inertia (area)					
inch to fourth power	$in.^4$	416,231	416,000	millimeter to fourth power	mm^4
inch to fourth power	$in.^4$	0.416231×10^{-6}	0.416×10^{-6}	meter to fourth power	m^4
Moment of inertia (mass)					
slug foot squared	slug-ft^2	1.35582	1.36	kilogram meter squared	kg·m^2
Power					
foot-pound per second	ft-lb/s	1.35582	1.36	watt (J/s or N·m/s)	W
foot-pound per minute	ft-lb/min	0.0225970	0.0226	watt	W
horsepower (550 ft-lb/s)	hp	745.701	746	watt	W
Pressure; stress					
pound per square foot	psf	47.8803	47.9	pascal (N/m^2)	Pa
pound per square inch	psi	6894.76	6890	pascal	Pa
kip per square foot	ksf	47.8803	47.9	kilopascal	kPa
kip per square inch	ksi	6.89476	6.89	megapascal	MPa
Section modulus					
inch to third power	$in.^3$	16,387.1	16,400	millimeter to third power	mm^3
inch to third power	$in.^3$	16.3871×10^{-6}	16.4×10^{-6}	meter to third power	m^3
Velocity (linear)					
foot per second	ft/s	0.3048*	0.305	meter per second	m/s
inch per second	in./s	0.0254*	0.0254	meter per second	m/s
mile per hour	mph	0.44704*	0.447	meter per second	m/s
mile per hour	mph	1.609344*	1.61	kilometer per hour	km/h
Volume					
cubic foot	ft^3	0.0283168	0.0283	cubic meter	m^3
cubic inch	$in.^3$	16.3871×10^{-6}	16.4×10^{-6}	cubic meter	m^3
cubic inch	$in.^3$	16.3871	16.4	cubic centimeter (cc)	cm^3
gallon (231 $in.^3$)	gal.	3.78541	3.79	liter	L
gallon (231 $in.^3$)	gal.	0.00378541	0.00379	cubic meter	m^3

*An asterisk denotes an *exact* conversion factor

Note: **To convert from SI units to USCS units, *divide* by the conversion factor**

Temperature Conversion Formulas

$$T(°C) = \frac{5}{9}[T(°F) - 32] = T(K) - 273.15$$

$$T(K) = \frac{5}{9}[T(°F) - 32] + 273.15 = T(°C) + 273.15$$

$$T(°F) = \frac{9}{5}T(°C) + 32 = \frac{9}{5}T(K) - 459.67$$

The Science and Engineering of Materials

Enhanced Seventh Edition, SI Edition

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University of Missouri—Rolla, Emeritus

Wendelin J. Wright
Bucknell University

SI Edition Prepared By:

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The Science and Engineering of Materials,
Enhanced Seventh Edition, SI Edition

Donald R. Askeland and
Wendelin J. Wright

SI Edition Prepared by D.K. Bhattacharya and Raj P. Chhabra

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Compositor: MPS Limited

Designer: Nadine Ballard

Manufacturing Planner: Ron Montgomery

Cover Designer: Nadine Ballard

Cover Image: Courtesy of the Materials Research Society Science-as-Art Competition and Minyung Song, North Carolina State University

Library of Congress Control Number: 2020937870

ISBN: 978-0-357-44788-8

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200 Pier 4 Boulevard
Boston, MA 02210
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Printed in the United States of America
Print Number: 01 Print Year: 2020

To Mary Sue and Tyler
–Donald R. Askeland

To my mom, Patricia Wright,
my first writing teacher
–Wendelin J. Wright

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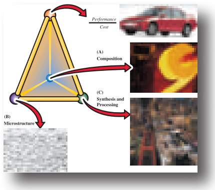

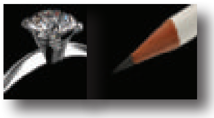

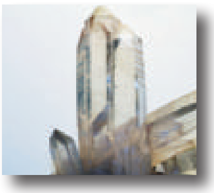

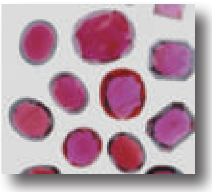

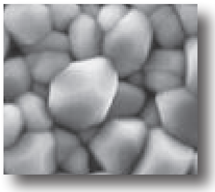

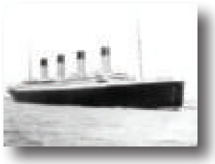

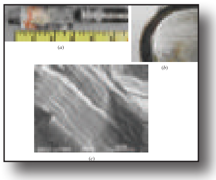

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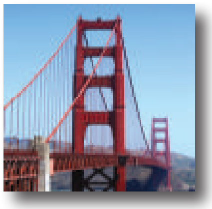

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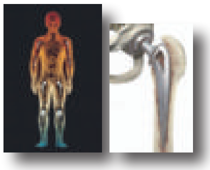

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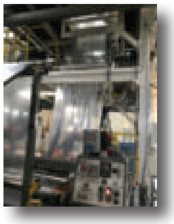

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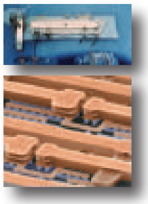

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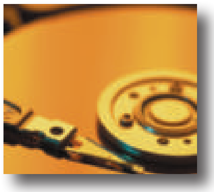

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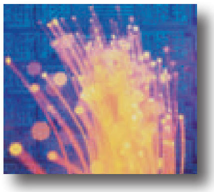

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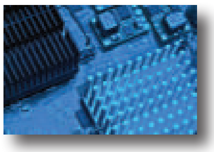

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PREFACE

The copper age, the iron age, the silicon age . . . eras defined by the materials found in nature, but manipulated by the engineers of their day. The fundamental principles of structure, defects, kinetics, and processing are generally applicable to all materials, while over time our understanding has advanced and incorporated new ideas. As a result, the observable and macroscopic behavior of materials, spanning such varied characteristics as mechanical strength and toughness, electrical conductivity, refractive index, and corrosion resistance, is both understood more deeply and related more directly to underlying atomic-level phenomena.

Our tools for characterizing and manipulating materials have also grown vastly more sophisticated, allowing for deeper insights into materials structures and phenomena. At the edge of innovation we find the discovery—or even the creation—of entirely new materials, often made possible by new processing techniques, by circumventing equilibrium to cause materials to exist in metastable states, and by developing the tools to assemble, form, and study materials at the nanoscale. It is now routine, for instance, to examine materials at the near-atomic level for both structure and composition, using techniques such as high resolution transmission electron microscopy, grazing incidence x-ray diffraction, and electron energy loss spectroscopy. At the same time, materials processing has advanced to the point where thin films just a few atomic layers thick can in many instances be grown or deposited, while three-dimensional structures with dimensions of only a few tens of nanometers or less can also be manufactured. The entire electronics industry, for instance, is based on these types of advances. Flat screen televisions, high-speed wireless data systems, portable computation and telecommunication devices, automobiles and other transportation systems . . . these and countless other technologies are all dependent on our contemporary understanding of materials.

While not all students who study materials science will be practicing materials engineers, most engineers will in fact work with a diverse materials set, comprising metals, ceramics, plastics, composites, and semiconductors, and across lengths scales from the nanoscale to the macroscale, all within a context of myriad and diverse applications. Materials are an enabling component of what engineers imagine, design, and build. The ability to *innovate* and to incorporate materials *safely* in a design is rooted in an understanding of how to manipulate materials properties and functionality through the control of materials structure and processing techniques. The objective of this textbook, then, is to describe the foundations and applications of materials science for college-level engineering students as predicated upon the structure-processing-properties paradigm.

The challenge of any textbook is to provide the proper balance of breadth and depth for the subject at hand, to provide rigor at the appropriate level, to provide meaningful examples and up to date content, and to stimulate the intellectual excitement of the reader. Our goal here is to provide enough *science* so that the reader may understand basic materials phenomena, and enough *engineering* to prepare a wide range of students for competent professional practice.

Cover Art

The cover art for the enhanced seventh edition of the text is a photograph showing a metal droplet with the eutectic composition of a gallium indium alloy (EGaIn). The eutectic of gallium and indium, which is a liquid at room temperature, will spontaneously form a spherical droplet when in the presence of certain liquids, owing to its high surface tension. This is true especially when the alloy is placed in a strongly alkaline electrolyte. When a positive electric potential is applied to the eutectic, however, surface oxidation commences and produces a skin of material that effectively lowers the surface tension. The balance of interfacial forces is thereby altered, which allows the sphere to relax into other shapes, in this case, a shape like a flower. In the photo, the red wire applies the positive potential. The image is titled "EGaIn Flower" by Minyung Song of North Carolina State University.

Audience and Prerequisites

This text is intended for an introductory science of materials class taught at the sophomore or junior level. A first course in college level chemistry is assumed, as is some coverage of first-year college physics. A calculus course is helpful, but certainly not required. The text does not presume that students have taken other introductory engineering courses such as statics, dynamics, or mechanics of materials.

New in the Seventh Edition

The beginning of each chapter includes learning objectives to guide students in their studies. New problems have been added to the end of each chapter to increase the number of problems by 15%. The breadth of Chapter 15 on ceramic materials has been extended to include crystalline ceramics, silica and silicate compounds, and other topics of interest to provide a more comprehensive view of this important class of engineering materials. Other portions of the chapter have been revised for clarity. The cost of common engineering materials in Chapter 14 has been updated. As always, we have taken great care to provide the most error-free text possible.

The enhanced seventh edition includes new digital resources and solutions for end of chapter problems. Select problems have also been updated.

Knovel™ Problems

At the conclusion of the end of chapter problems, you will find a special section with problems that require the use of Knovel **(app.knovel.com/web/)**. Knovel is an online aggregator of engineering references including handbooks, encyclopedias, dictionaries, textbooks, and databases from leading technical publishers and engineering societies such as the American Society of Mechanical Engineers (ASME) and the American Institute of Chemical Engineers (AIChE).

The Knovel problems build on material found in the textbook and require familiarity with online information retrieval. The problems are also available online at **login.cengage.com.** In addition, the solutions are accessible by registered instructors. If your institution does not have a subscription to Knovel or if you have any questions about Knovel, please visit **www.elsevier.com/solutions/knovel-engineering-information**.

The Knovel problems were created by a team of engineers led by Sasha Gurke, senior vice president and cofounder of Knovel.

Supplements for the Instructor

Supplements to the text include a Solution and Answer Guide that provides complete solutions to all problems, annotated Lecture Note PowerPoint™ slides, and an image library of all figures in the book. These can be found on the password-protected Instructor's Resources website for the book at login.cengage.com.

Acknowledgments

We thank all those who have contributed to the success of past editions and also the reviewers who provided detailed and constructive feedback on the sixth edition:

Cynthia W. Barnicki, Milwaukee School of Engineering

Deborah Chung, University of Buffalo, SUNY

Margaret Pinnell, University of Dayton

Stephen W. Stafford, University of Texas, El Paso

We also thank Jeffrey Florando of Lawrence Livermore National Laboratory for comments on the revisions to Chapter 15.

We are grateful to the team at Cengage Learning that has carefully guided this enhanced seventh edition through all stages of the publishing process. In particular, we wish to thank Timothy Anderson, Senior Product Manager; MariCarmen Constable, Learning Designer; Alexander Sham, Associate Content Manager; and Anna Goulart, Senior Product Assistant.

Wendelin Wright thanks Xiaojun Gu for his careful review of the proofs of the text as well as Briana King and Joanne Mowen for their assistance during the revision process. Elyssa Penson of Bucknell University wrote activities and answers that are available online for the "Have You Ever Wondered" questions at the beginning of each chapter. Professor Wright is grateful to John Bravman of Bucknell University for his feedback, contributed illustrations, patience, and constant support.

Donald R. Askeland
University of Missouri — Rolla, Emeritus

Wendelin J. Wright
Bucknell University

PREFACE TO THE SI EDITION

This edition of *The Science and Engineering of Materials* has been adapted to incorporate the International System of Units (*Le Système International d'Unités* or SI) throughout the book.

Le Système International d'Unités

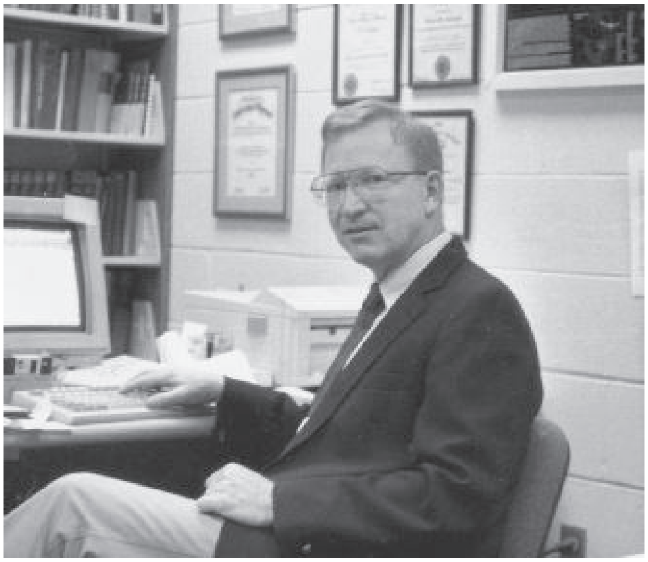
SI units are primarily the units of the MKS (meter–kilogram–second) system. However, CGS (centimeter–gram–second) units are often accepted as SI units, especially in textbooks.

Using SI Units in this Book

In this book, we have used both MKS and CGS units. USCS (United States Customary Units) or FPS (foot-pound-second) units used in the US Edition of the book have been converted to SI units throughout the text and problems. However, in case of data sourced from handbooks, government standards, and product manuals, it is not only extremely difficult to convert all values to SI, it also encroaches upon the intellectual property of the source. Some data in figures, tables, and references, therefore, remains in FPS units. For readers unfamiliar with the relationship between the FPS and the SI systems, a conversion table has been provided inside the front cover.

To solve problems that require the use of sourced data, the sourced values can be converted from FPS units to SI units just before they are to be used in a calculation. To obtain standardized quantities and manufacturers' data in SI units, the readers may contact the appropriate government agencies or authorities in their countries/regions.

ABOUT THE AUTHORS



Donald R. Askeland is a Distinguished Teaching Professor Emeritus of Missouri University of Science and Technology. He received his degrees from the Thayer School of Engineering at Dartmouth College and the University of Michigan prior to joining the faculty at the University of Missouri–Rolla in 1970. Dr. Askeland taught a number of courses in materials and manufacturing engineering to students in a variety of engineering and science curricula. He received a number of awards for excellence in teaching and advising at UMR. He served as a Key Professor for the Foundry Educational Foundation and received several awards for his service to that organization. His teaching and research were directed primarily to metals casting and joining, in particular lost foam casting, and resulted in over 50 publications and a number of awards for service and best papers from the American Foundry Society.

Emily Paine/Bucknell University

Wendelin J. Wright is Professor at Bucknell University with a joint appointment in the departments of Mechanical Engineering and Chemical Engineering. She received her B.S., M.S., and Ph.D. in Materials Science and Engineering from Stanford University. Prior to assuming her position at Bucknell, Professor Wright was a faculty member at Santa Clara University.

Professor Wright's research interests focus on the mechanical behavior of materials, particularly of metallic glasses. She is the recipient of the 2003 Walter J. Gores Award for Excellence in Teaching, which is Stanford University's highest teaching honor, a 2005 Presidential Early Career Award for Scientists and Engineers, and a 2010 National Science Foundation CAREER Award. Professor Wright is a licensed professional engineer in metallurgy in California. She is married to John Bravman and is the mother of two young sons, Cole and Cooper.

DIGITAL RESOURCES

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In addition to common question types such as multiple choice, fill-in-the-blank, essay, and numerical, you can also incorporate robust answer entry palettes (mathPad, chemPad, calcPad, physPad, Graphing Tool) to input and grade symbolic expressions, equations, matrices, and chemical structures using powerful computer algebra systems.

WebAssign Offers Engineering Instructors the Following

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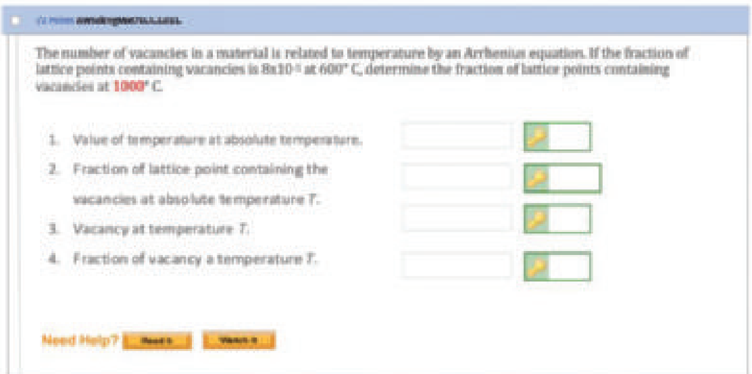
  Within WebAssign, a "Read It" button at the bottom of each question links students to corresponding sections of the textbook, enabling access to the MindTap Reader at the precise moment of learning. A "Watch It" button allows a short video to play. These videos help students understand and review the problem they need to complete, enabling support at the precise moment of learning.



- **My Class Insights**
  WebAssign's built-in study feature shows performance across course topics so that students can quickly identify which concepts they have mastered and which areas they may need to spend more time on.
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MindTap Reader

Available via WebAssign, **MindTap Reader** is Cengage's next-generation eBook for engineering students.

The MindTap Reader provides more than just text learning for the student. It offers a variety of tools to help our future engineers learn chapter concepts in a way that resonates with their workflow and learning styles.

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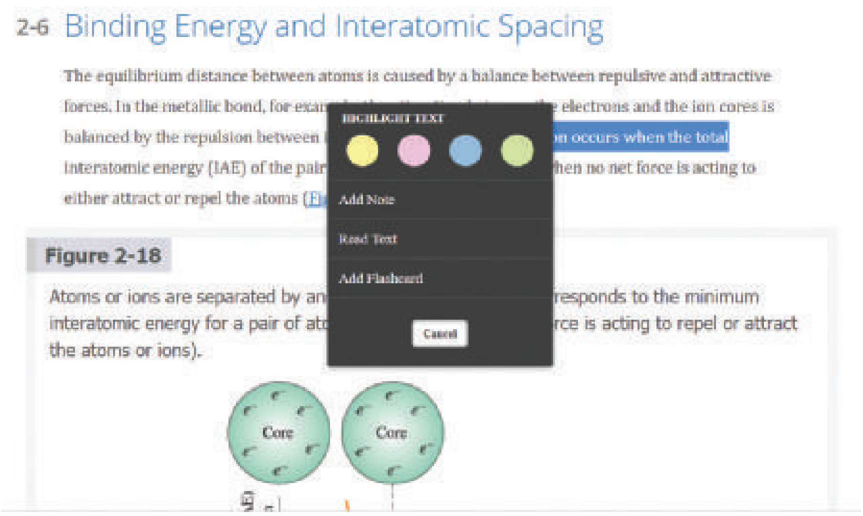

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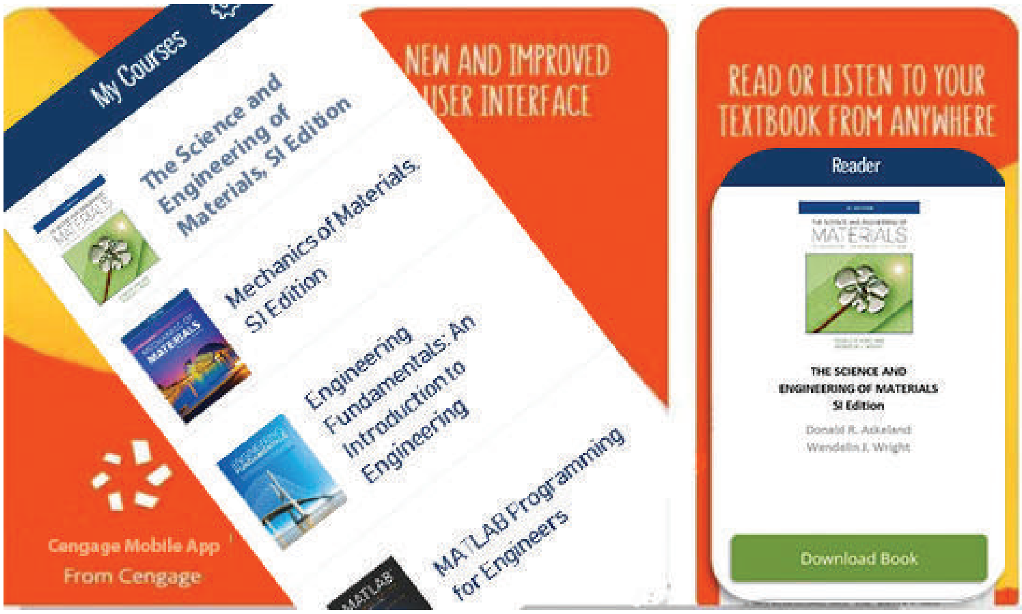
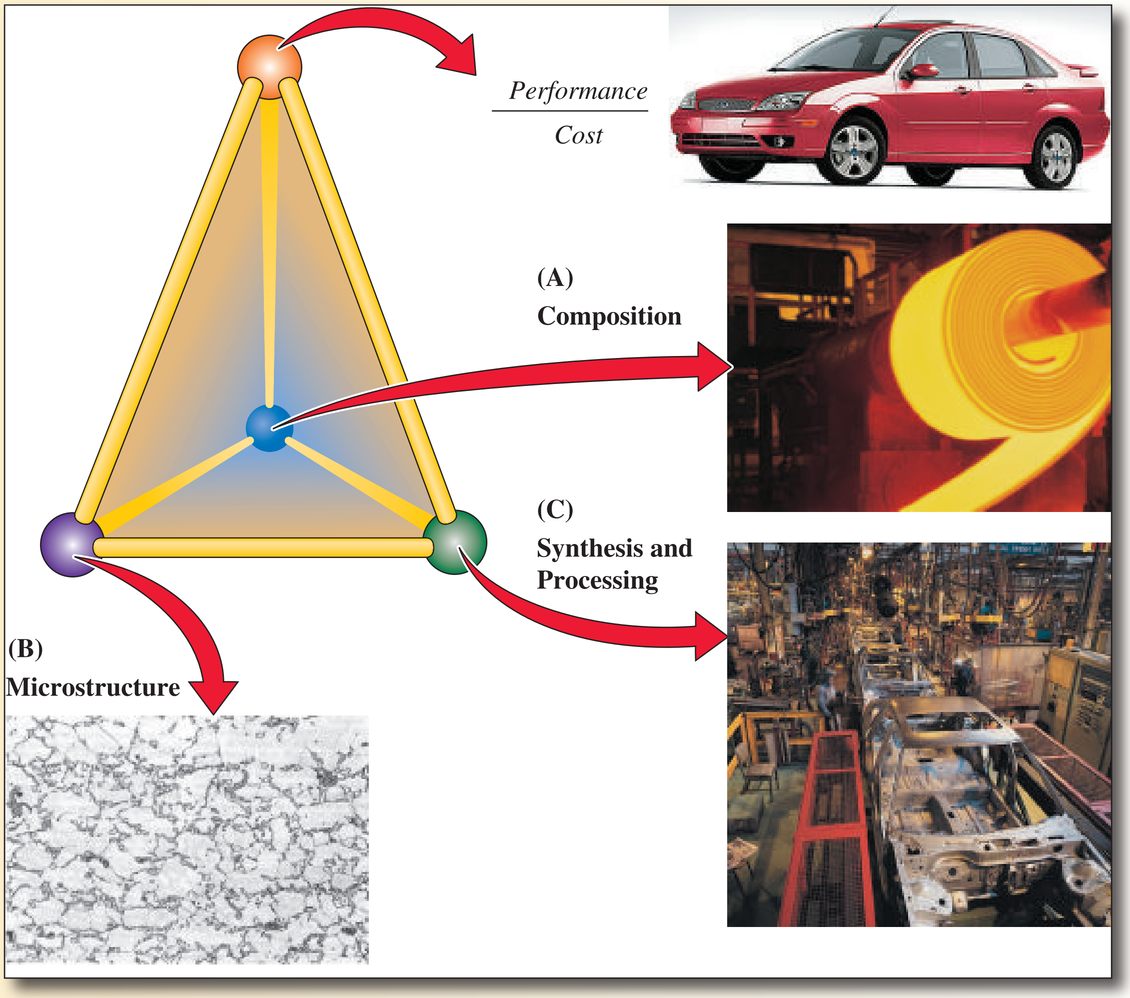
Available on iOS and Android smartphones, the Cengage Mobile App provides convenience. Students can access their entire textbook anyplace and anytime. They can take notes, highlight important passages, and have their text read aloud whether they are online or off. To learn more and download the mobile app, visit **www.cengage.com/mobile-app/.**



The Science and Engineering of Materials

Enhanced Seventh Edition, SI Edition



The principal goals of a materials scientist and engineer are to (1) make existing materials better and (2) invent or discover new phenomena, materials, devices, and applications. Breakthroughs in the materials science and engineering field are applied to many other fields of study such as biomedical engineering, physics, chemistry, environmental engineering, and information technology. The materials science and engineering tetrahedron shown here represents the heart and soul of this field, and its use is illustrated for the production of steel for an automotive chassis. As shown in this diagram, a materials scientist and engineer's main objective is to develop materials or devices that have the best performance for a particular application. In most cases, the performance-to-cost ratio, as opposed to the performance alone, is of utmost importance. This concept is shown as the apex of the tetrahedron and the three corners are representative of *A*—the composition, *B*—the microstructure, and *C*—the synthesis and processing of materials. These are all interconnected and ultimately affect the performance-to-cost ratio of a material or a device. The accompanying micrograph shows the microstructure of a dual phase steel. The microstructure of dual phase steels is engineered to absorb energy during automotive collisions. Hard particles of a phase called martensite (dark) are dispersed in a matrix of relatively soft, ductile ferite (light).

For materials scientists and engineers, materials are like a palette of colors to an artist. Just as an artist can create different paintings using different colors, materials scientists create and improve upon different materials using different elements of the periodic table, and different synthesis and processing routes. (*Michael Shake/Shutterstock.com / Digital Vision/Getty Images / Digital Vision/Getty Images /* Metals Handbook, *Desk Edition (1998), ASM International, Materials Park, OH 44073-0002. Reprinted with permission of ASM International. All rights reserved. www.asminternational.org.*)

CHAPTER

1

Introduction to Materials Science and Engineering

Have You Ever Wondered?

- *What do materials scientists and engineers study?*
- *From a materials stand point, how do you significantly improve the fuel efficiency of a commercial jet airliner?*
- *Can we make flexible and lightweight electronic circuits using plastics?*
- *Why do jewelers add copper to gold?*
- *What is a "smart material?"*

Chapter Learning Objectives

The key objectives of this chapter are to

- Describe the primary concepts that define materials science and engineering.
- Explain the role of materials science in the design process.
- Classify materials by properties.
- Classify materials by function.

In this chapter, we will first introduce you to the field of materials science and engineering using different real-world examples. We will then provide an introduction to the classification of materials. Although most engineering programs require students to take a materials science course, you should approach your study of materials science as more than a mere requirement. A thorough knowledge of materials science and engineering will make you a better engineer and designer. Materials science underlies all technological advances, and an understanding of the basics of materials and their applications will not only make you a better engineer, but will help you during the design process. In order to be a good designer, you must learn what materials will be appropriate to use in different applications. You need to be capable of choosing the right material for your application based on its properties, and you must recognize how and why these properties might change over time and due to processing. Any engineer can look up materials properties in a book or search databases for a material that meets design specifications, but the *ability to innovate* and to *incorporate materials safely* in a design is rooted in an understanding of how to manipulate materials properties and functionality through the control of the material's structure and processing techniques.

The most important aspect of materials is that they are enabling; materials make things happen. For example, in the history of civilization, materials such as stone, iron, and bronze played a key role in mankind's development. In today's fast-paced world, the discovery of silicon single crystals and an understanding of their properties have enabled the information age.

In this book, we provide compelling examples of real-world applications of engineered materials. The diversity of applications and the unique uses of materials illustrate why a good engineer needs to understand and know how to apply the principles of materials science and engineering.

1-1 What is Materials Science and Engineering?

Materials science and engineering (MSE) is an interdisciplinary field that studies and manipulates the composition and structure of materials across length scales to control materials properties through synthesis and processing. The term **composition** means the chemical make-up of a material. The term **structure** means the arrangement of atoms, as seen at different levels of detail. Materials scientists and engineers not only deal with the development of materials, but also with the **synthesis** and **processing** of materials and manufacturing processes related to the production of components. The term "synthesis" refers to how materials are made from naturally occurring or man-made chemicals. The term "processing" means how materials are shaped into useful components to cause changes in the properties of different materials. One of the most important functions of materials scientists and engineers is to establish the relationships between a material or a device's properties and performance and the microstructure of that material, its composition, and the way the material or the device was synthesized and processed. In **materials science**, the emphasis is on the underlying relationships between the synthesis and processing, structure, and properties of materials. In **materials engineering**, the focus is on how to translate or transform materials into useful devices or structures.

One of the most fascinating aspects of materials science involves the investigation of a material's structure. The structure of materials has a profound influence on many properties of materials, even if the overall composition does not change! For example, if you take a pure copper wire and bend it repeatedly, the wire not only becomes harder but also becomes increasingly brittle! Eventually, the pure copper wire becomes so hard and brittle that it will break! The electrical resistivity of the wire will also increase as we bend it repeatedly. In this simple example, take note that we did not change the material's composition (i.e., its chemical make-up). The changes in the material's properties are due to a change in its internal structure. If you look at the wire after bending, it will look the same as before; however, its structure has been changed at the microscopic scale. The structure at the microscopic scale is known as the **microstructure**. If we can understand what has changed microscopically, we can begin to discover ways to control the material's properties.

Let's consider one example using the **materials science and engineering tetrahedron** shown in Figure 1-1. (Another example is shown on the chapter opening page.) For most of the history of commercial air travel, the fuselages of airplanes have been made using aluminum alloys. The fuselage material must possess sufficiently high strength, but must also be lightweight and formable into aerodynamic contours. Aluminum is one material that meets these requirements. In 2011, passengers began traveling on Boeing's 787 Dreamliner aircraft. One of the primary innovations of the Boeing 787 is the extensive use of **composites**; composite materials are formed by incorporating multiple components in a material in such a way that the properties of the resultant material are unique and not otherwise attainable. Composite materials comprise half of the Dreamliner's total weight, and in fact, the fuselage of the Boeing 787 is made from carbon fiber-reinforced plastic. Carbon fiber-reinforced plastic is a composite of carbon fiber in a polymer epoxy resin matrix.

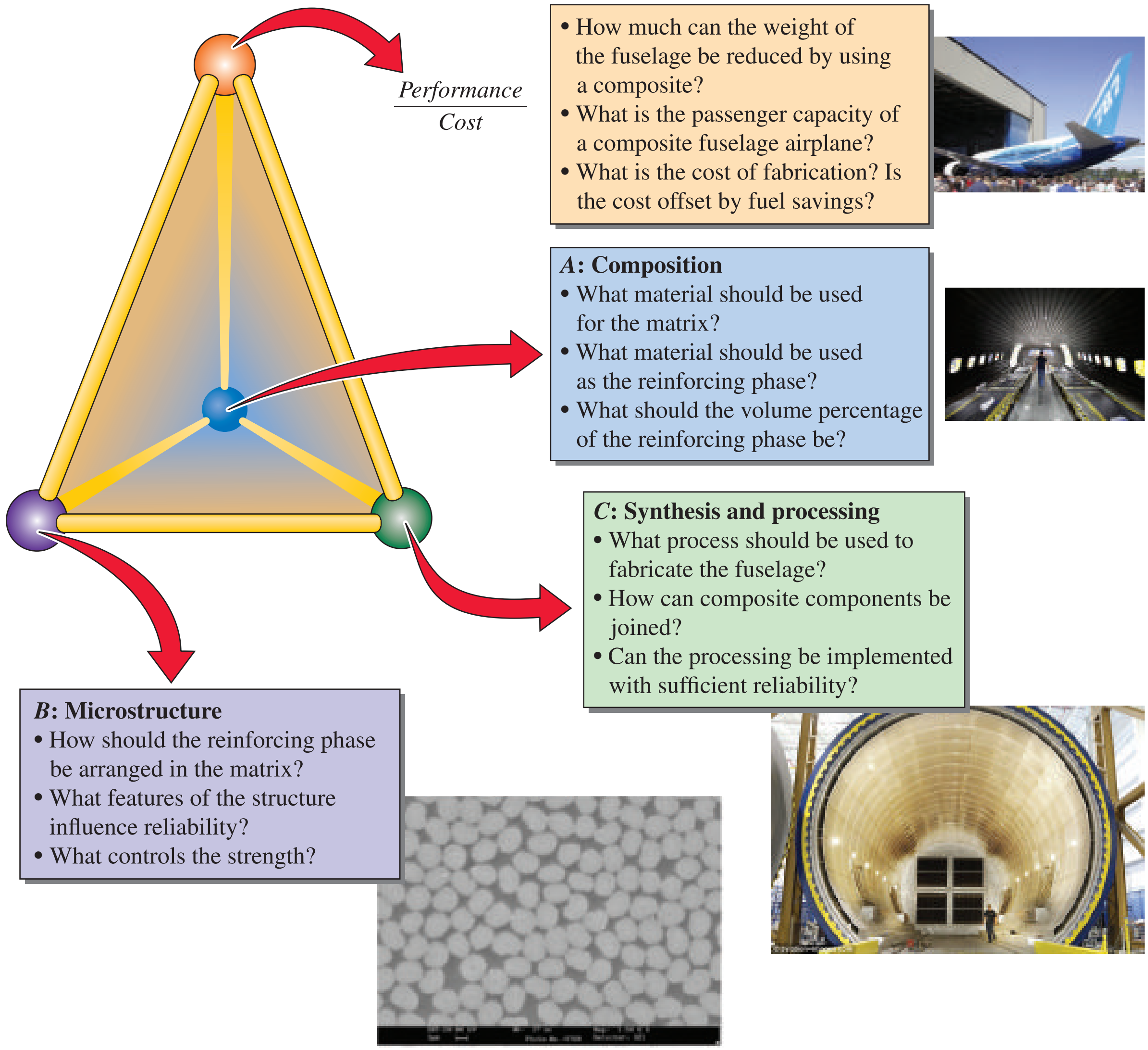


Figure 1-1 Application of the materials science and engineering tetrahedron to carbon fiber-reinforced plastic for the fabrication of aircraft fuselages. The composition, microstructure, and synthesis/processing are all interconnected and affect the performance-to-cost ratio. Clockwise from upper right: the Boeing 787; the interior of an empty Boeing 787 fuselage; a giant autoclave used to bake carbon fiber-reinforced plastic sections; carbon fiber in an epoxy matrix. (*Bloomberg via Getty Images / Srinivasa, Vinod, Shivakumar, Vinay, Nayaka, Vinay, Jagadeeshaiaih, Sunil, Seethram, Murali, Shenoy, Raghavendra, & Nafidi, Abdelhakim. (2010). Fracture morphology of carbon fiber reinforced plastic composite laminates.* Materials Research, *13(3), 417-424. Retrieved January 6, 2014, from www.scielo.br/scielo.php?script=sci_arttext&pid=S1516-14392010000300022&lng=en&tlng=en. 10.1590/S1516-14392010000300022./ AFP/Getty Images / Aviation Images*)

After decades of success with their various models of aircraft, Boeing invested billions of dollars to develop a commercial airplane based on a new class of materials. Why would Boeing do this? The driving force behind the move to carbon fiber-reinforced plastic was to reduce the weight of the fuselage, thereby increasing fuel efficiency. This significantly increases the performance to cost ratio of the aircraft.

The switch to a composite material involved numerous technical challenges. What would the composite material be? How would the composite fuselage be formed? Decades of data are available for the growth of cracks in aluminum under the cyclic loading of take-offs and landings. Would the composite fuselage be reliable? Would a carbon fiber-reinforced plastic also have the corrosion-resistance that aluminum has or would delamination between the fibers and plastic occur? Aluminum jets have structural panels that are riveted together. How can various structural components made from composites be joined? From this discussion, you can see that many issues need to be considered during the design and materials selection for any product and that the ratio of performance to cost, composition, microstructure, and synthesis and process are all critical factors.

Let's look at one more example of the application of the materials science and engineering tetrahedron by considering the use in microelectronic devices of a class of materials known as semiconducting polymers (Figure 1-2). Many types of displays such as those found in alarm clocks and watches utilize light emitting diodes (LEDs) made from inorganic compounds based on gallium arsenide (GaAs) and other materials; however, semiconducting polymers also have been used more recently. The advantages of using plastics for microelectronics include their flexibility and ease of processing. The questions materials scientists and engineers must answer with applications of semiconducting polymers are

- What are the relationships between the structure of polymers and their electrical properties?
- How can devices be made using these plastics?
- Will these devices be compatible with existing silicon chip technology?
- How robust are these devices?
- How will the performance and cost of these devices compare with traditional devices?

These are just a few of the factors that engineers and scientists must consider during the development, design, and manufacturing of semiconducting polymer devices.

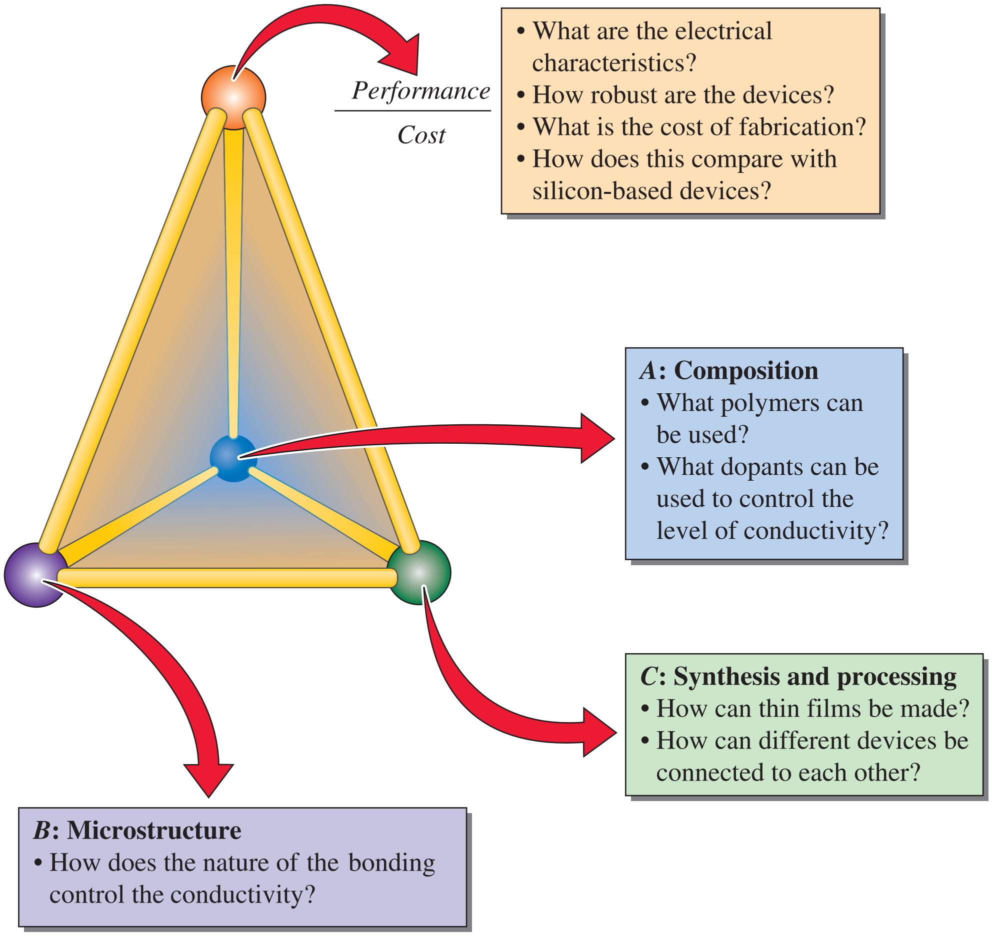


Figure 1-2 Application of the tetrahedron of materials science and engineering to semiconducting polymers for microelectronics.

1-2 Classification of Materials

There are different ways of classifying materials. One way is to describe five groups (Table 1-1):

1. **metals** and **alloys**;
2. **ceramics**, **glasses**, and **glass-ceramics**;
3. **polymers** (plastics);
4. **semiconductors**; and
5. **composite** materials.

Table 1-1 Representative examples, applications, and properties for each category of materials

	Examples of Applications	Properties
Metals and Alloys		
Copper	Electrical conductor wire	High electrical conductivity, good formability
Gray cast iron	Automobile engine blocks	Castable, machinable, vibration-damping
Alloy steels	Wrenches, automobile chassis	Significantly strengthened by heat treatment
Ceramics and Glasses		
SiO_2-Na_2O-CaO	Window glass	Optically transparent, thermally insulating
Al_2O_3, MgO, SiO_2	Refractories (i.e., heat-resistant lining of furnaces) for containing molten metal	Thermally insulating, withstand high temperatures, relatively inert to molten metal
Barium titanate	Capacitors for microelectronics	High ability to store charge
Silica	Optical fibers for information technology	Low optical losses
Polymers		
Polyethylene	Food packaging	Easily formed into thin, flexible, airtight film
Epoxy	Encapsulation of integrated circuits	Electrically insulating and moisture resistant
Phenolics	Adhesives for joining plies in plywood	Strong, moisture resistant
Semiconductors		
Silicon	Transistors and integrated circuits	Unique electrical behavior
GaAs	Optoelectronic systems	Converts electrical signals to light, used in lasers, laser diodes, etc.
Composites		
Graphite-epoxy	Aircraft components	High strength-to-weight ratio
Tungsten carbide-cobalt (WC-Co)	Carbide cutting tools for machining	High hardness, yet good shock resistance
Titanium-clad steel	Reactor vessels	Low cost and high strength of steel with the corrosion resistance of titanium

Materials in each of these groups possess different structures and properties. The differences in strength, which are compared in Figure 1-3, illustrate the wide range of properties from which engineers can select. Since metallic materials are extensively used for load-bearing applications, their mechanical properties are of great practical interest. We briefly introduce these properties here. The term “stress” refers to load or force per unit area. “Strain” refers to elongation or change in dimension divided by the original dimension. Application of “stress” causes “strain.” If the strain goes away after the load or applied stress is removed, the strain is said to be “elastic.” If the strain remains after the stress is removed, the strain is said to be “plastic.” When the deformation is elastic, stress and strain are linearly related; the slope of the stress strain diagram is known as the elastic or Young’s modulus. The level of stress needed to initiate plastic deformation is known as the “yield strength.” The maximum percent deformation that can be achieved is a measure of the ductility of a metallic material. These concepts are discussed further in Chapters 6 and 7.

Metals and Alloys

Metals include aluminum, magnesium, zinc, iron, titanium, copper, and nickel. An alloy is a metal that contains additions of one or more metals or non-metals, e.g., steel is an alloy of iron with carbon additions. In general, metals have good electrical and thermal conductivities. Metals and alloys have relatively high strength, high stiffness, ductility or formability, and shock resistance. They are particularly useful for structural or load-bearing applications. Although pure metals are occasionally used, alloys provide improvement in a particular desirable property or permit better combinations of properties. For example, pure gold is a soft metal; thus, jewelers add copper to gold to improve strength so that gold jewelry is not easily damaged.

Ceramics

Ceramics can be defined as inorganic nonmetallic materials. Beach sand and rocks are examples of naturally occurring ceramics. Advanced ceramics are materials made by refining naturally occurring ceramics and other special processes. Advanced ceramics are used in substrates that house computer chips, sensors and

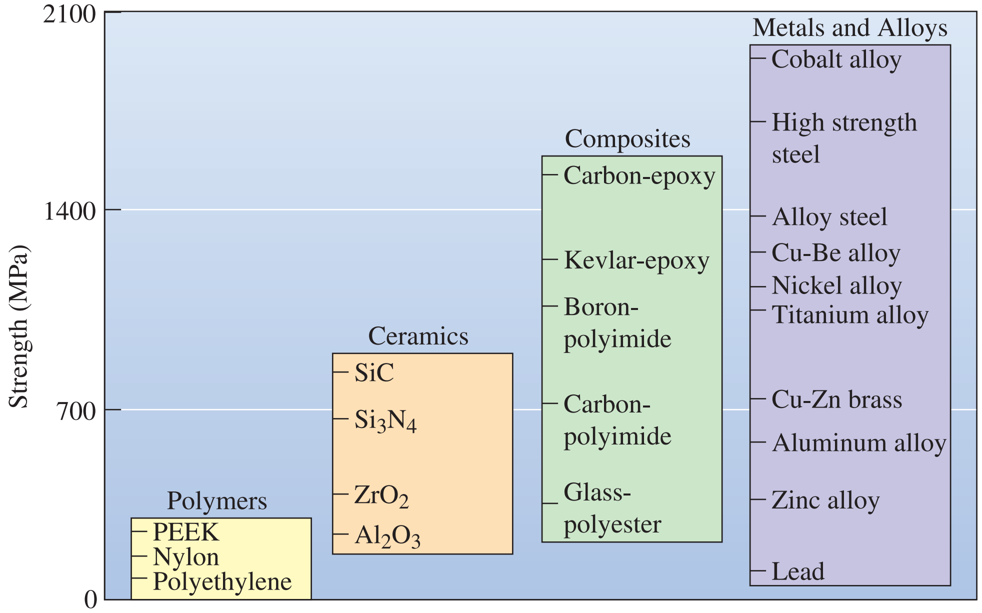


Figure 1-3 Representative strengths of various categories of materials. Compressive strengths are shown for ceramics.

actuators, capacitors, wireless communications, spark plugs, inductors, and electrical insulation. Some ceramics are used as barrier coatings to protect metallic substrates in turbine engines. Ceramics are also used in such consumer products as paints, plastics, and tires, and for industrial applications such as the oxygen sensors used in cars. Traditional ceramics are used to make bricks, tableware, bathroom fixtures, refractories (heat-resistant materials), and abrasives. In general, ceramics do not conduct heat well; they must be heated to very high temperatures before melting. Ceramics are strong and hard, but also very brittle. We normally prepare fine powders of ceramics and mold into different shapes. New processing techniques make ceramics sufficiently resistant to fracture that they can be used in load-bearing applications, such as impellers in turbine engines. Ceramics have exceptional strength under compression. Can you believe that an entire fire truck can be supported using four ceramic coffee cups?

Glasses and Glass-Ceramics Glass is an amorphous material, often, but not always, derived from a molten liquid. The term "amorphous" refers to materials that do not have a regular, periodic arrangement of atoms. Amorphous materials will be discussed in Chapter 3. The fiber optics industry is founded on optical fibers based on high-purity silica glass. Glasses are also used in houses, cars, screens for computers, televisions, and smart phones, and hundreds of other applications. Glasses can be thermally treated (tempered) to make them stronger. Forming glasses and then nucleating (forming) small crystals within them by a special thermal process creates materials that are known as glass-ceramics. Zerodur™ is an example of a glass-ceramic material that is used to make the mirror substrates for large telescopes (e.g., the Chandra and Hubble telescopes). Glasses and glass-ceramics are usually processed by melting and casting.

Polymers Polymers are typically organic materials. They are produced using a process known as **polymerization**. Polymeric materials include rubber (elastomers) and many types of adhesives. Polymers typically are good electrical and thermal insulators although there are exceptions. Although they have lower strengths than metals or ceramics, polymers have very good **strength-to-weight ratios**. They are typically not suitable for use at high temperatures. Many polymers have very good resistance to corrosive chemicals. Polymers have thousands of applications ranging from bulletproof vests, compact discs (CDs), ropes, and liquid crystal displays (LCDs) to clothes and coffee cups. **Thermoplastic** polymers, in which the long molecular chains are not rigidly connected, have good ductility and formability; **thermosetting** polymers are stronger but more brittle because the molecular chains are tightly linked (Figure 1-4). Polymers are

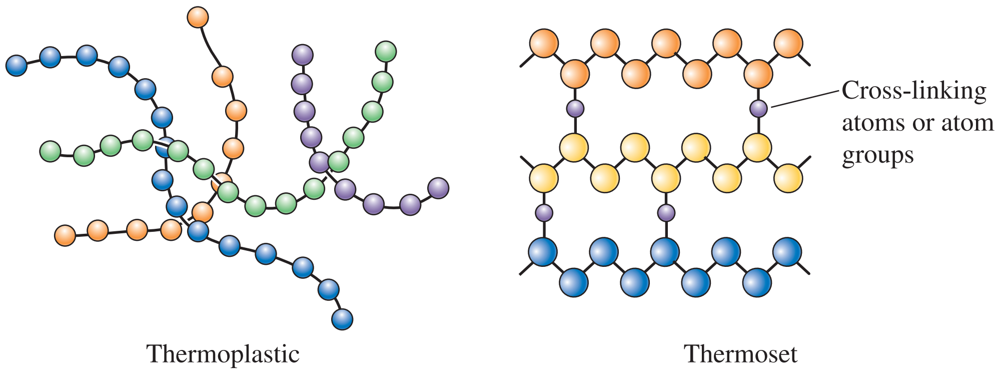


Figure 1-4 Polymerization occurs when small molecules, represented by the circles, combine to produce larger molecules, or polymers. The polymer molecules can have a structure that consists of many chains that are entangled but not connected (thermoplastics) or can form three-dimensional networks in which chains are cross-linked (thermosets).

used in many applications, including electronic devices. Thermoplastics are made by shaping their molten form. Thermosets are typically cast into molds. **Plastics** contain additives that enhance the properties of polymers.

Semiconductors

Silicon, germanium, and gallium arsenide-based semiconductors such as those used in computers and electronics are part of a broader class of materials known as electronic materials. The electrical conductivity of semiconducting materials is between that of ceramic insulators and metallic conductors. Semiconductors have enabled the information age. In some semiconductors, the level of conductivity can be controlled to produce electronic devices such as transistors and diodes that are used to build integrated circuits. In many applications, we need large single crystals of semiconductors. These are grown from molten materials. Often, thin films of semiconducting materials are also made using specialized processes.

Composite Materials

The main idea in developing composites is to blend the properties of different materials. These are formed from two or more materials, producing properties not found in any single material. Concrete, plywood, and fiberglass are examples of composite materials. Fiberglass is made by dispersing glass fibers in a polymer matrix. The glass fibers make the polymer stiffer, without significantly increasing its density. With composites, we can produce lightweight, strong, ductile, temperature-resistant materials or we can produce hard, yet shock-resistant, cutting tools that would otherwise shatter. Advanced aircraft and aerospace vehicles rely heavily on composites. As discussed earlier in this chapter, the Boeing 787 uses carbon fiber-reinforced plastic in many structural components instead of aluminum, leading to high fuel efficiency. Sports equipment such as bicycles, golf clubs, tennis rackets, and the like also make use of different kinds of composite materials that are light and stiff.

1-3 Functional Classification of Materials

We can classify materials based on whether the most important function they perform is mechanical (structural), biological, electrical, magnetic, or optical. This classification of materials is shown in Figure 1-5. Some examples of each category are shown. These categories can be broken down further into subcategories.

Aerospace

Light materials such as wood and an aluminum alloy (that accidentally strengthened the engine even more by picking up copper from the mold used for casting) were used in the Wright brothers' historic flight. NASA's space shuttle made use of aluminum powder for booster rockets and silica for the space shuttle tiles. The fuselage and wings of Boeing's 787 aircraft are largely composed of carbon-fiber-reinforced plastic.

Biomedical

Our bones and teeth are made, in part, from a naturally formed ceramic known as hydroxyapatite. A number of artificial organs, bone replacement parts, cardiovascular stents, orthodontic braces, and other components are made using different plastics, titanium alloys, and nonmagnetic stainless steels. Ultrasonic imaging systems make use of ceramics known as lead zirconium titanate (PZT).

Electronic Materials

As mentioned before, semiconductors, such as those made from silicon, are essential to making integrated circuits for computer chips. Barium titanate ($BaTiO_3$), tantalum oxide (Ta_2O_5), and other dielectric materials are used to make ceramic capacitors and other devices. Copper, aluminum, and other metals are used as conductors in power transmission and in microelectronics.

Figure 1-5 Functional classification of materials. Notice that metals, plastics, and ceramics occur in different categories. A limited number of examples in each category are provided.

Energy Technology and Environmental Technology The nuclear industry uses materials such as uranium dioxide and plutonium as fuel. Numerous other materials, such as glasses and stainless steels, are used in handling nuclear materials and managing radioactive waste. Technologies related to batteries and fuel cells make use of many ceramic materials such as zirconia (ZrO_2) and polymers. Battery technology has gained significant importance owing to the need for many electronic devices that require longer lasting and portable power. Fuel cells are used in some electric cars. The oil and petroleum industry widely uses zeolites, alumina, and other materials as catalyst substrates. They use Pt, Pt/Rh, and many other metals as catalysts. Many membrane technologies for purification of liquids and gases make use of ceramics and plastics. Solar power is generated using materials such as amorphous silicon (a:Si:H).

Magnetic Materials Computer hard disks make use of many ceramic, metallic, and polymeric materials. Computer hard disks are made using cobalt-platinum-tantalum-chromium (Co-Pt-Ta-Cr) alloys. Many magnetic ferrites are used to make inductors and components for wireless communications. Steels based on iron and silicon are used to make transformer cores.

Photonic or Optical Materials Silica is used widely for making optical fibers. More than ten million kilometers of optical fiber have been installed around the world. Optical materials are used for making semiconductor detectors and lasers used in fiber optic communications systems and other applications. Similarly, alumina (Al_2O_3) and yttrium aluminum garnets (YAG) are used for making lasers. Amorphous silicon is used to make solar cells and photovoltaic modules. Polymers are used to make liquid crystal displays (LCDs).

Smart Materials A **smart material** can sense and respond to an external stimulus such as a change in temperature, the application of a stress, or a change in humidity or chemical environment. Usually a smart material-based system consists of sensors and actuators that read changes and initiate an action. An example of a passively smart material is lead zirconium titanate (PZT) and shape-memory alloys. When properly processed, PZT can be subjected to a stress, and a voltage is generated. This effect is used to make such devices as spark generators for gas grills and sensors that can detect underwater objects such as fish and submarines. Other examples of smart materials include magnetorheological or MR fluids. These are magnetic paints that respond to magnetic fields. These materials are being used in suspension systems of automobiles, including models by General Motors, Ferrari, and Audi. Still other examples of smart materials and systems are photochromic glasses and automatic dimming mirrors.

Structural Materials These materials are designed for carrying some type of stress. Steels, concrete, and composites are used to make buildings and bridges. Steels, glasses, plastics, and composites also are used widely to make automotives. Often in these applications, combinations of strength, stiffness, and toughness are needed under different conditions of temperature and loading.

1-4 Classification of Materials Based on Structure

As mentioned before, the term "structure" means the arrangement of a material's atoms; the structure at a microscopic scale is known as "microstructure." We can view these arrangements at different scales, ranging from a few angstrom units to a millimeter. We will learn in Chapter 3 that some materials may be **crystalline** (the material's atoms are arranged in a periodic fashion) or they may be amorphous (the arrangement of the material's atoms does not have long-range order). Some crystalline materials may be in the form of one crystal and are known as **single crystals**. Others consist of many crystals or **grains** and are known as **polycrystalline**. The characteristics of crystals or grains (size, shape, etc.) and that of the regions between them, known as the **grain boundaries**, also affect the properties of materials. We will further discuss these concepts in later chapters. The microstructure of a dual phase steel is shown on the chapter opening page.

1-5 Environmental and Other Effects

The structure-property relationships in materials fabricated into components are often influenced by the surroundings to which the material is subjected during use. This can include exposure to high or low temperatures, cyclical stresses, sudden impact, corrosion, or oxidation. These effects must be accounted for in design to ensure that components do not fail unexpectedly.

Temperature Changes in temperature dramatically alter the properties of materials (Figure 1-6). Metals and alloys that have been strengthened by certain heat treatments or forming techniques may suddenly lose their strength when heated. A tragic reminder of this is the collapse of the World Trade Center towers on September 11, 2001. Although the towers sustained the initial impact of the collisions, their steel structures were weakened by elevated temperatures caused by fire, ultimately leading to the collapse.

High temperatures change the structure of ceramics and cause polymers to melt or char. Very low temperatures, at the other extreme, may cause a metal or polymer to fail in a brittle manner, even though the applied loads are low. This low-temperature embrittlement was a factor that caused the *Titanic* to fracture and sink. Similarly, the 1986 *Challenger* accident, in part, was due to embrittlement of rubber O-rings. The reasons why some polymers and metallic materials become brittle are different. We will discuss these concepts in later chapters.

Corrosion Most metals and polymers react with oxygen or other gases, particularly at elevated temperatures. Metals and ceramics may disintegrate, and polymers and non-oxide ceramics may oxidize. Materials also are attacked by corrosive liquids, leading to premature failure. The engineer faces the challenge of selecting materials or coatings that prevent these reactions and permit operation in extreme environments. In space applications, we may have to consider the effect of radiation.

Fatigue For many applications, components must be designed such that the load on the material is not enough to cause permanent deformation. When we load and unload the material thousands of times, even at low loads, small cracks may begin to develop, and materials fail as these cracks grow. This is known as **fatigue failure**. In designing load-bearing components, the possibility of fatigue must be accounted for.

Strain Rate Many of you are aware of the fact that Silly Putty®, a silicone-based (not silicon) plastic, can be stretched significantly if we pull it slowly (small rate of strain). If you pull it fast (higher rate of strain), it snaps. A similar behavior can occur with many metallic materials. Thus, in many applications, the level and rate of strain have to be considered.

In many cases, the effects of temperature, fatigue, stress, and corrosion may be interrelated, and other outside effects can affect the material's performance.

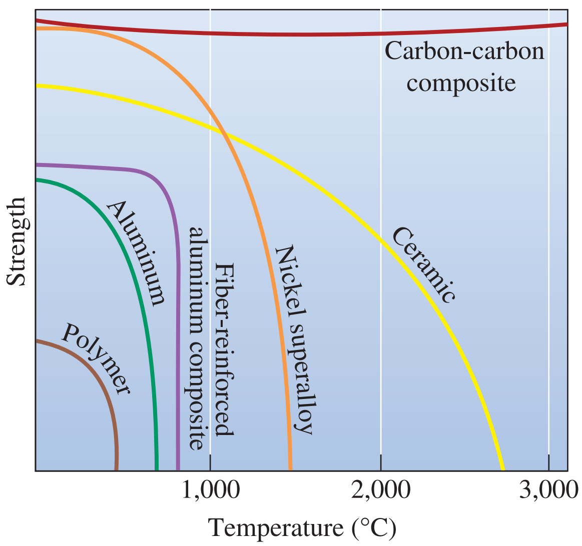


Figure 1-6 Increasing temperature normally reduces the strength of a material. Polymers are suitable only at low temperatures. Some composites, such as carbon-carbon composites, special alloys, and ceramics, have excellent properties at high temperatures.

1-6 Materials Design and Selection

When a material is designed for a given application, a number of factors must be considered. The material must acquire the desired **physical** and **mechanical properties**, must be capable of being processed or manufactured into the desired shape, and must provide an economical solution to the design problem. Satisfying these requirements in a manner that protects the environment—perhaps by encouraging recycling of the materials—is also essential. In meeting these design requirements, the engineer may have to make a number of trade-offs in order to produce a serviceable, yet marketable, product.

As an example, material cost is normally calculated on a cost-per-kilogram basis. We must consider the **density** of the material, or its weight-per-unit volume, in our design and selection (Table 1-2). Aluminum may cost more than steel on a weight basis, but it has only one-third the density of steel. Although parts made from aluminum may have to be thicker, the aluminum part may be less expensive than the one made from steel because of the weight difference.

In some instances, particularly in aerospace applications, weight is critical, since additional vehicle weight increases fuel consumption. By using materials that are lightweight but very strong, aerospace vehicles or automobiles can be designed to improve fuel utilization. Many advanced aerospace vehicles use composite materials instead of aluminum. These composites, such as carbon-epoxy, are more expensive than the traditional aluminum alloys; however, the fuel savings yielded by the higher strength-to-weight ratio of the composite (Table 1-2) may offset the higher initial cost of the aircraft as is also true for the Boeing 787. There are literally thousands of applications in which similar considerations apply. Usually the selection of materials involves trade-offs between many properties.

By this point of our discussion, we hope that you can appreciate that the properties of materials depend not only on composition, but also how the materials are made (synthesis and processing) and, most importantly, their internal structure. This is why it is not a good idea for an engineer to refer to a handbook and select a material for a given application. The handbooks may be a good starting point. A good engineer will consider: the effects of how the material was made, the exact composition of the candidate material for the application being considered, any processing that may have to be done for shaping the material or fabricating a component, the structure of the material after processing into a component or device, the environment in which the material will be used, and the cost-to-performance ratio.

Earlier in this chapter, we discussed the need for you to know the principles of materials science and engineering. If you are an engineer and you need to decide which materials you will choose to fabricate a component, the knowledge of principles of materials science and engineering will empower you with the fundamental concepts. These will allow you to make technically sound decisions in designing with engineered materials.

Table 1-2 Strength-to-weight ratios of various materials

Material	Strength (kg/m^2)	Density (g/cm^3)	Strength-to-Weight Ratio (cm)
Polyethylene	70×10^4	0.83	8.43×10^4
Pure aluminum	455×10^4	2.17	16.79×10^4
Al_2O_3	21×10^6	3.16	0.66×10^6
Epoxy	105×10^5	1.38	7.61×10^5
Heat-treated alloy steel	17×10^7	7.75	0.22×10^7
Heat-treated aluminum alloy	60×10^6	2.71	2.21×10^6
Carbon-carbon composite	42×10^6	1.80	2.33×10^6
Heat-treated titanium alloy	12×10^7	4.43	0.27×10^7
Kevlar-epoxy composite	46×10^6	1.47	3.13×10^6
Carbon-epoxy composite	56×10^6	1.38	4.06×10^6

Summary

- Materials science and engineering (MSE) is an interdisciplinary field concerned with inventing new materials and devices and improving existing materials by developing a deeper understanding of the microstructure-composition-synthesis-processing relationships.
- Engineered materials are materials designed and fabricated considering MSE principles.
- The properties of engineered materials depend upon their composition, structure, synthesis, and processing. An important performance index for materials or devices is their performance-to-cost ratio.
- The structure of a material refers to the arrangement of atoms or ions in the material.
- The structure at a microscopic level is known as the microstructure.
- Many properties of materials depend strongly on the structure, even if the composition of the material remains the same. This is why the structure-property or microstructure-property relationships in materials are extremely important.
- Materials are classified as metals and alloys, ceramics, glasses and glass-ceramics, composites, polymers, and semiconductors.
- Metals and alloys have good strength, good ductility, and good formability. Metals have good electrical and thermal conductivities. Metals and alloys play an indispensable role in many applications such as automotives, buildings, bridges, aerospace, and the like.
- Ceramics are inorganic crystalline materials. They are strong, serve as good electrical and thermal insulators, are often resistant to damage by high temperatures and corrosive environments, but are mechanically brittle. Modern ceramics form the underpinnings of many microelectronic and photonic technologies.
- Glasses are amorphous, inorganic solids that are typically derived from a molten liquid. Glasses can be tempered to increase strength. Glass-ceramics are formed by annealing glasses to nucleate small crystals that improve resistance to fracture and thermal shock.
- Polymers have relatively low strength; however, the strength-to-weight ratio is very favorable. Polymers are not suitable for use at high temperatures. They have very good corrosion resistance, and—like ceramics—provide good electrical and thermal insulation. Polymers may be either ductile or brittle, depending on structure, temperature, and strain rate.
- Semiconductors possess unique electrical and optical properties that make them essential for manufacturing components in electronic and communications devices.
- Composites are made from two or more different types of materials. They provide unique combinations of mechanical and physical properties that cannot be found in any single material.
- Functional classification of materials includes aerospace, biomedical, electronic, energy and environmental, magnetic, optical (photonic), and structural materials.
- Materials can also be classified as crystalline or amorphous. Crystalline materials may be single crystal or polycrystalline.
- Properties of materials can depend upon the temperature, level and type of stress applied, strain rate, oxidation and corrosion, and other environmental factors.
- Selection of a material having the needed properties and the potential to be manufactured economically and safely into a useful product is a complicated process requiring the knowledge of the structure-property-processing-composition relationships.

Glossary

Alloy A metallic material that is obtained by chemical combinations of different elements (e.g., steel is made from iron and carbon).

Ceramics A group of crystalline inorganic materials characterized by good strength, especially in compression, and high melting temperatures.

Composites A group of materials formed from mixtures of metals, ceramics, or polymers in such a manner that unusual combinations of properties are obtained (e.g., fiberglass).

Composition The chemical make-up of a material.

Crystalline material A material composed of one or many crystals. In each crystal, atoms or ions show a long-range periodic arrangement.

Density Mass per unit volume of a material, usually expressed in units of g/cm^3.

Fatigue failure Failure of a material due to repeated loading and unloading.

Glass An amorphous material derived from the molten state, typically, but not always, based on silica.

Glass-ceramics A special class of materials obtained by forming a glass and then heat treating it to form small crystals.

Grain boundaries Regions between grains of a polycrystalline material.

Grains Crystals in a polycrystalline material.

Materials engineering An engineering-oriented field that focuses on how to transform materials into useful devices or structures.

Materials science A field of science that emphasizes studies of relationships between the microstructure, synthesis and processing, and properties of materials.

Materials science and engineering An interdisciplinary field concerned with inventing new materials and improving existing materials by developing a deeper understanding of the structure-property-processing-composition relationships between different materials.

Materials science and engineering tetrahedron A tetrahedron diagram showing how the performance-to-cost ratio of materials depends upon their composition, microstructure, synthesis, and processing.

Mechanical properties Properties of a material, such as strength, that describe how well a material withstands applied forces, including tensile or compressive forces, impact forces, cyclical or fatigue forces, or forces at high temperatures.

Metal An element that has metallic bonding and generally good ductility, strength, and electrical conductivity.

Microstructure The structure of a material at the microscopic length scale.

Physical properties Characteristics such as color, elasticity, electrical conductivity, thermal conductivity, magnetism, and optical behavior that generally are not significantly influenced by forces acting on a material.

Plastics Polymers containing other additives.

Polycrystalline material A material composed of many crystals (as opposed to a single-crystal material that has only one crystal).

Polymerization The process by which organic molecules are joined into giant molecules, or polymers.

Polymers A group of materials normally obtained by joining organic molecules into giant molecular chains or networks.

Processing Different ways for shaping materials into useful components or changing their properties.

Semiconductors A group of materials (e.g., Si, GaAs) having electrical conductivity between metals and typical ceramics.

Single crystal A crystalline material that comprises only one crystal (there are no grain boundaries).

Smart material A material that can sense and respond to an external stimulus such as change in temperature, application of a stress, or change in humidity or chemical environment.

Strength-to-weight ratio The strength of a material divided by its density; materials with a high strength-to-weight ratio are strong but lightweight.

Structure The arrangements of atoms or ions in a material. The structure of materials has a profound influence on many properties of materials, even if the overall composition does not change.

Synthesis The process by which materials are made from naturally occurring or other chemicals.

Thermoplastics A special group of polymers in which molecular chains are entangled but not interconnected. They can be easily melted and formed into useful shapes. Normally, these polymers have a chainlike structure (e.g., polyethylene).

Thermosets A special group of polymers that decompose rather than melt upon heating. They are normally quite brittle due to a relatively rigid, three-dimensional network structure (e.g., polyurethane).

Problems

Section 1-1 What is Materials Science and Engineering?

1-1 Define materials science and engineering (MSE).

1-2 What is the importance of the engineering tetrahedron for materials engineers?

1-3 Define the following terms:
(a) composition;
(b) structure;
(c) synthesis;
(d) processing; and
(e) microstructure.

1-4 Explain the difference between the terms materials science and materials engineering.

Section 1-2 Classification of Materials

1-5 The myriad materials in the world primarily fall into four basic categories; what are they? What are materials called that have one or more different types of material fabricated into one component? Give one example.

1-6 What are some of the materials and mechanical properties of metals and alloys?

1-7 What is a ceramic, and what are some of the properties that you expect from a ceramic?

1-8 Make comparisons between thermoplastics and thermosetting polymers (a) on the basis of mechanical characteristics upon heating, and (b) according to possible molecular structures.

1-9 Give three examples of composites that can be fabricated.

1-10 For each of the following classes of materials, give two *specific* examples that are a regular part of your life:
(a) metals;
(b) ceramics;
(c) polymers; and
(d) semiconductors.
Specify the object that each material is found in and explain why the material is used in each specific application. *Hint:* One example answer for part (a) would be that aluminum is a metal used in the base of some pots and pans for even heat distribution. It is also a lightweight metal that makes it useful in kitchen cookware. Note that in this partial answer to part (a), a specific metal is described for a specific application.

1-11 Describe the enabling materials property of each of the following and why it is so:
(a) steel for I-beams in skyscrapers;
(b) a cobalt chrome molybdenum alloy for hip implants;
(c) polycarbonate for eyeglass lenses; and
(d) bronze for artistic castings.

1-12 Describe the enabling materials property of each of the following and why it is so:
(a) aluminum for airplane bodies;
(b) polyurethane for teeth aligners (invisible braces);
(c) steel for the ball bearings in a bicycle's wheel hub;
(d) polyethylene terephthalate for water bottles; and
(e) glass for wine bottles.

1-13 What properties should an engineer consider for a total knee replacement of a deteriorated knee joint with an artificial prosthesis when selecting the materials for this application?

1-14 Write one paragraph about why single-crystal silicon is currently the material of choice for microelectronics applications.

Write a second paragraph about potential alternatives to single-crystal silicon for solar cell applications. Provide a list of the references or websites that you used. You must use at least three references.

1-15 Coiled springs should be very strong and stiff. Silicon nitride (Si_3N_4) is a strong, stiff material. Would you select this material for a spring? Explain.

1-16 Temperature indicators are sometimes produced from a coiled metal strip that uncoils a specific amount when the temperature increases. How does this work; from what kind of material would the indicator be made; and what are the important properties that the material in the indicator must possess?

Section 1-3 Functional Classification of Materials

Section 1-4 Classification of Materials Based on Structure

Section 1-5 Environmental and Other Effects

1-17 What is the purpose of the classification for functional materials?

1-18 Explain the difference between crystalline and amorphous materials. Give an example of each that you use in your daily life.

1-19 If you were given a material and were asked to determine whether it is crystalline or amorphous, how would you determine it?

1-20 List six materials performance problems that may lead to failure of components.

1-21 Steel is often coated with a thin layer of zinc if it is to be used outside. What characteristics do you think the zinc provides to this coated, or galvanized, steel? What precautions should be considered in producing this product? How will the recyclability of the product be affected?

1-22 The relationship between structure and materials properties can be influenced by the service conditions (environmental conditions). Name two engineering disasters that have had tragic results and why they happened.

Section 1-6 Materials Design and Selection

1-23 What is the difference between physical and mechanical properties? List three examples for each one.

1-24 The type of jet engine used on most large commercial aircraft is called a turbofan jet engine because it has a large wheel at the front of the engine that propels air rearward. Most of this air bypasses the engine, but bypass air significantly increases thrust and efficiency of these engines. Some engine manufacturers are now using carbon fiber-epoxy composites rather than traditional aluminum blades.

(a) What materials properties do you think an engineer must consider when selecting a material for this application? Be as specific as possible.

(b) What benefits do you think carbon fiber epoxy composites have compared to aluminum alloys? What limitations or possible downsides could there be to using a carbon fiber epoxy composite?

1-25 You are an engineer working for a manufacturer of land-based gas turbines. These turbines are similar to jet engines, but they are used on land to provide power for electricity generation and gas compression pipeline applications. Suppose that you would like to apply a ceramic-based thermal barrier coating to the turbine blades in the first-stage turbine to increase the operating temperature and efficiency of the engine.

(a) What difficulties might engineers experience in trying to design a ceramic coating that will be applied to a super alloy metal blade?

(b) What properties should be taken into consideration when choosing a suitable ceramic material for a coating? Be as thorough as possible.

1-26 We would like to produce a transparent canopy for an aircraft. If we were to use a traditional window glass canopy, rocks or birds might cause it to shatter. Design a material that would minimize damage or at least keep the canopy from breaking into pieces.

1-27 You would like to design an aircraft that can be flown by human power nonstop for a distance of 30 km. What types of material properties would you recommend? What materials might be appropriate?

1-28 You would like to place a one-meter diameter microsatellite into orbit. The satellite will contain delicate electronic equipment that will send and receive radio signals from earth. Design the outer shell within which the electronic equipment is contained. What properties will be required, and what kind of materials might be considered?

1-29 What properties should the head of a carpenter's hammer possess? How would you manufacture a hammer head?

1-30 You would like to select a material for the electrical contacts in an electrical switching device that opens and closes frequently and forcefully. What properties should the contact material possess? What type of material might you recommend? Would Al_2O_3 be a good choice? Explain.

1-31 Aluminum has a density of 2.7 g/cm^3. Suppose you would like to produce a composite material based on aluminum having a density of 1.5 g/cm^3. Design a material that would have this density. Would introducing beads of polyethylene, with a density of 0.95 g/cm^3, into the aluminum be a likely possibility? Explain.

1-32 You would like to be able to identify different materials without resorting to chemical analysis or lengthy testing procedures. Describe some possible testing and sorting techniques you might be able to use based on the physical properties of materials.

1-33 You would like to be able to physically separate different materials in a scrap recycling plant. Describe some possible methods that might be used to separate materials such as polymers, aluminum alloys, and steels from one another.

1-34 Some pistons for automobile engines might be produced from a composite material containing small, hard silicon carbide particles in an aluminum alloy matrix. Explain what benefits each material in the composite may provide to the overall part. What problems might the different properties of the two materials cause in producing the part?

1-35 Investigate the origins and applications for a material that has been invented or discovered since you were born *or* investigate the development of a product or technology that has been invented since you were born that was made possible by the use of a novel material. Write one paragraph about this material or product. Provide a list of the references or websites that you used. You must use at least three references.

Knovel® Problems

All problems in the final section of each chapter require the use of the Knovel website (app.knovel.com/web). These three problems are designed to provide an introduction to Knovel, its website, and the interactive tools available on it.

K1-1
- Convert 7750 kg/m^3 to g/l using the Unit Converter.
- Using the Periodic Table, determine the atomic weight of magnesium.
- What is the name of Section 4 in *Perry's Chemical Engineers' Handbook (Seventh Edition)*?
- Find a book title that encompasses the fundamentals of chemistry as well as contains interactive tables of chemical data.

K1-2
- Using the basic search option in Knovel, find as much physical and thermodynamic data associated with ammonium nitrate as possible. What applications does this chemical have?
- Using the Basic Search, find the formula for the volume of both a sphere and a cylinder.
- Using the Data Search, produce a list of five chemicals with a boiling point between 300 and 400 K.

K1-3
- Using the Equation Plotter, determine the enthalpy of vaporization of pure acetic acid at 360 K.
- What is the pressure (in atm) of air with a temperature of 200°F and a water content of 10^{-2} kg water/(kg air)?
- Find three grades of polymers with a melting point greater than 325°C.

Diamond and graphite both comprise pure carbon, but their materials properties vary considerably. These differences arise from differences in the arrangements of the atoms in the solids and differences in the bonding between atoms. Covalent bonding in diamond leads to high strength and stiffness, excellent thermal conductivity, and poor electrical conductivity. (*Özer Öner/Shutterstock.com*) The atoms in graphite are arranged in sheets. Within the sheets, the bonding between atoms is covalent, but between the sheets, the bonds are less strong. Thus graphite can easily be sheared off in sheets as occurs when writing with a pencil. (*Ronald van der Beek/Shutterstock.com*) Graphite's thermal conductivity is much lower than that of diamond, and its electrical conductivity is much higher.

CHAPTER

2

Atomic Structure

Have You Ever Wondered?

- *What is nanotechnology?*
- *Why is carbon, in the form of diamond, one of the hardest materials known, but as graphite is very soft and can be used as a solid lubricant?*
- *How is silica, which forms the main chemical in beach sand, used in an ultrapure form to make optical fibers?*

Chapter Learning Objectives

The key objectives of this chapter are to

- Define four quantum numbers for electrons and explain the significance of each.
- Explain the arrangement of the elements in the periodic table.
- State the electronic structure of the elements.
- Explain the role of electronegativity in bonding.
- Define four different mechanisms of bonding in materials.
- Describe how interactions between atoms or between ions influence materials properties.
- Explain how allotropes can display dramatically different materials properties based on their structure even though they are composed of the same element.

Materials scientists and engineers have developed a set of instruments in order to characterize the **structure** of materials at various length scales. We can examine and describe the structure of materials at five different levels:

1. atomic structure;
2. short- and long-range atomic arrangements;
3. nanostructure;
4. microstructure; and
5. macrostructure.

The features of the structure at each of these levels may have distinct and profound influences on a material's properties and behavior.

The goal of this chapter is to examine **atomic structure** (the nucleus consisting of protons and neutrons and the electrons surrounding the nucleus) in order to lay a foundation for understanding how atomic structure affects the properties, behavior, and resulting applications of engineering materials. We will see that the structure of atoms affects the types of bonds that hold materials together. These different types of bonds directly affect the suitability of materials for real-world engineering applications. The diameter of atoms typically is measured using the angstrom unit (Å or 10^{-10} m).

It also is important to understand how atomic structure and bonding lead to different atomic or ionic arrangements in materials. A close examination of atomic arrangements allows us to distinguish between materials that are **amorphous** (those that lack a long-range ordering of atoms or ions) or **crystalline** (those that exhibit periodic geometrical arrangements of atoms or ions). Amorphous materials have only **short-range atomic arrangements**, while crystalline materials have short- and **long-range atomic arrangements**. In short-range atomic arrangements, the atoms or ions show a particular order only over relatively short distances (1 to 10 Å). For crystalline materials, the long-range atomic order is in the form of atoms or ions arranged in a three-dimensional pattern that repeats over much larger distances (from ~10 nm to cm).

Materials science and engineering is at the forefront of **nanoscience** and **nanotechnology**. Nanoscience is the study of materials at the nanometer length scale, and nanotechnology is the manipulation and development of devices at the nanometer length scale. The **nanostructure** is the structure of a material at a **length scale** of 1 to 100 nm. Controlling nanostructure is becoming increasingly important for advanced materials engineering applications.

The **microstructure** is the structure of materials at a **length scale** of 100 to 100,000 nm or 0.1 to 100 micrometers (often written as μm and pronounced as "microns"). The microstructure typically refers to features such as the grain size of a crystalline material and others related to defects in materials. (A *grain* is a single crystal in a material composed of many crystals.)

Macrostructure is the structure of a material at a macroscopic level where the length scale is >100 μm. Features that constitute macrostructure include porosity, surface coatings, and internal and external microcracks.

We will conclude the chapter by considering some of the **allotropes** of carbon. We will see that, although both diamond and graphite are made from pure carbon, they have different materials properties. The key to understanding these differences is to understand how the atoms are arranged in each allotrope.

2-1 The Structure of Materials: Technological Relevance

In today's world, information technology (IT), biotechnology, energy technology, environmental technology, and many other areas require smaller, lighter, faster, portable, more efficient, reliable, durable, and inexpensive devices. We want batteries that are smaller, lighter, and last longer. We need cars that are relatively affordable, lightweight, safe, highly fuel efficient, and "loaded" with many advanced features, ranging from global positioning systems (GPS) to sophisticated sensors for airbag deployment.

Some of these needs have generated considerable interest in nanotechnology and **micro-electro-mechanical systems** (MEMS). As a real-world example of MEMS technology, consider a small accelerometer sensor obtained by the micro-machining of silicon. This sensor is used to measure acceleration in automobiles. The information is processed by a computer and then used for controlling airbag deployment. Properties and behavior of materials at these "micro" levels can vary greatly when compared to those in their "macro" or bulk state. As a result, understanding the nanostructure and microstructure are areas that are receiving considerable attention.

The applications shown in Table 2-1 and the accompanying figures (Figures 2-1 through 2-6) illustrate how important the different levels of structure are to materials behavior. The applications are broken out by their levels of structure and their length scales (the approximate characteristic length that is important for a given application).

We now turn our attention to the details concerning the structure of atoms, the bonding between atoms, and how these form a foundation for the properties of materials. Atomic structure influences how atoms are bonded together. An understanding of this helps categorize materials as metals, semiconductors, ceramics, or polymers. It also permits us to draw some general conclusions concerning the mechanical properties and physical behaviors of these four classes of materials.

Table 2-1 Levels of structure

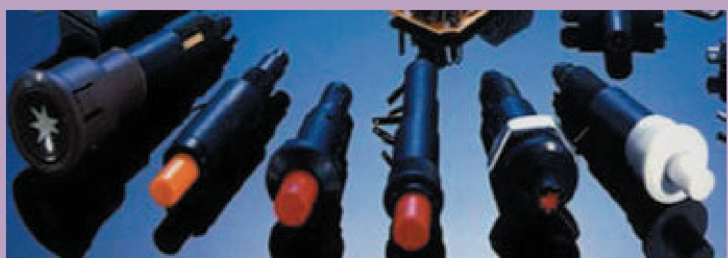
Level of Structure	Example of Technologies
Atomic Structure (~10^{-10} m or 1 Å)	Diamond is based on carbon-carbon covalent bonds. Materials with this type of bonding are expected to be relatively hard. Thin films of diamond are used for providing a wear-resistant edge in cutting tools.  **Figure 2-1** Diamond-coated cutting tools. (*Courtesy of NCD Technologies*)
Atomic Arrangements: Long-Range Order (LRO) (~10 nm to cm)	When ions in lead-zirconium-titanate $[Pb(Zr_xTi_{1-x})O_3]$(PZT) are arranged such that they exhibit tetragonal and/or rhombohedral crystal structures (see Chapter 3), the material is piezoelectric (i.e., it develops a voltage when subjected to pressure or stress). PZT ceramics are used widely for many applications including gas igniters, ultrasound generation, and vibration control.  **Figure 2-2** Piezoelectric PZT-based gas igniters. When the piezoelectric material is stressed (by applying a pressure), a voltage develops and a spark is created between the electrodes. (*Courtesy of Morgan Technical Ceramics Ltd UK*)

Table 2-1 Levels of structure *(Continued)*

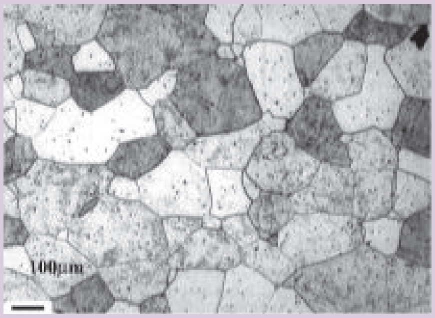
Level of Structure	Example of Technologies
Atomic Arrangements: Short-Range Order (SRO) (1 to 10 Å)	Ions in silica (SiO_2) glass exhibit only a short-range order in which Si^{4+} and O^{2-} ions are arranged in a particular way (each Si^{4+} is bonded with four O^{2-} ions in a tetrahedral coordination, with each O^{2-} ion being shared by two tetrahedra). This order, however, is not maintained over long distances, thus making silica glass amorphous. Amorphous glasses based on silica and certain other oxides form the basis for the entire fiber-optic communications industry.  **Figure 2-3** Optical fibers based on a form of silica that is amorphous. (*Nick Rowe/ Photodisc Green/GettyImages*)
Nanostructure (~10^{-9} to 10^{-7} m, 1 to 100 nm)	Nano-sized particles (~5–10 nm) of iron oxide are used in ferrofluids or liquid magnets. An application of these liquid magnets is as a cooling (heat transfer) medium for loudspeakers.  **Figure 2-4** Ferrofluid. (*Courtesy of Ferrotec USA Corporation*)
Microstructure (~>10^{-7} to 10^{-4} m, 0.1 to 100 μm)	The mechanical strength of many metals and alloys depends strongly on the grain size. The grains and grain boundaries in this accompanying micrograph of steel are part of the microstructural features of this crystalline material. In general, at room temperature, a finer grain size leads to higher strength. Many important properties of materials are sensitive to the microstructure.  **Figure 2-5** Micrograph of stainless steel showing grains and grain boundaries. (*Micrograph courtesy of Dr. A.J. Deardo, Dr. M. Hua and Dr. J. Garcia*)

Table 2-1 Levels of structure *(Continued)*

Level of Structure	Example of Technologies
Macrostructure ($\sim>10^{-4}$ m, $\sim>$100,000 nm or 100 μm)	Relatively thick coatings, such as paints on automobiles and other applications, are used not only for aesthetics, but also to provide corrosion resistance.

Figure 2-6 A number of organic and inorganic coatings protect the car from corrosion and provide a pleasing appearance. (*George Dolgikh/Shutterstock.com*)

2-2 The Structure of the Atom

The concepts mentioned next are covered in typical introductory chemistry courses. We are providing a brief review. An atom is composed of a nucleus surrounded by electrons. The nucleus contains neutrons and positively charged protons and carries a net positive charge. The negatively charged electrons are held to the nucleus by an electrostatic attraction. The electrical charge q carried by each electron and proton is 1.60×10^{-19} coulomb (C).

The **atomic number** of an element is equal to the number of protons in each atom. Thus, an iron atom, which contains 26 protons, has an atomic number of 26. The atom as a whole is electrically neutral because the numbers of protons and electrons are equal.

Most of the mass of the atom is contained within the nucleus. The mass of each proton and neutron is 1.67×10^{-24} g, but the mass of each electron is only 9.11×10^{-28} g. The **atomic mass unit**, or amu, is 1/12 the mass of carbon 12 (i.e., the carbon atom with twelve **nucleons**–six protons and six neutrons). The **atomic mass** M is equal to the total mass of the average number of protons and neutrons in the atom in atomic mass units and is also the mass in grams of the Avogadro number N_A of atoms. The quantity $N_A = 6.022 \times 10^{23}$ atoms/mol is the number of atoms or molecules in a mole. Therefore, the atomic mass has units of g/mol. As an example, one mole of iron contains 6.022×10^{23} atoms and has a mass of 55.847 g. Calculations including a material's atomic mass and the Avogadro number are helpful to understanding more about the structure of a material. Example 2-1 illustrates how to calculate the number of atoms for silver, a metal and a good electrical conductor.

Example 2-1 *Calculating the Number of Atoms in Silver*

Calculate the number of atoms in 100 g of silver.

SOLUTION

The number of atoms can be calculated from the atomic mass and the Avogadro number. From Appendix A, the atomic mass, or weight, of silver is 107.868 g/mol. The number of atoms is

$$\text{Number of Ag atoms} = \frac{(100\text{ g})(6.022 \times 10^{23}\text{ atoms/mol})}{107.868\text{ g/mol}}$$
$$= 5.58 \times 10^{23}$$

2-3 The Electronic Structure of the Atom

Electrons occupy discrete energy levels within the atom. Each electron possesses a particular energy with no more than two electrons in each atom having the same energy. Since each element possesses a different set of these energy levels, the differences between the energy levels also are unique. Both the energy levels and the differences between them are known with great precision for every element, forming the basis for many types of **spectroscopy**. Using a spectroscopic method, the identity of elements in a sample may be determined.

Quantum Numbers The energy level to which each electron belongs is identified by four **quantum numbers**. The four quantum numbers are the principal quantum number n, the azimuthal or secondary quantum number l, the magnetic quantum number m_l, and the spin quantum number m_s.

The principal quantum number reflects the grouping of electrons into sets of energy levels known as shells. Azimuthal quantum numbers describe the energy levels within each shell and reflect a further grouping of similar energy levels, usually called orbitals. The magnetic quantum number specifies the orbitals associated with a particular azimuthal quantum number within each shell. Finally, the **spin quantum number** (m_s) is assigned values of $+1/2$ and $-1/2$, which reflect the two possible values of "spin" of an electron.

According to the **Pauli Exclusion Principle**, within each atom, no two electrons may have the same four quantum numbers, and thus, each electron is designated by a unique set of four quantum numbers. The number of possible energy levels is determined by the first three quantum numbers.

1. The principal quantum number n is assigned integer values 1, 2, 3, 4, 5, . . . that refer to the quantum shell to which the electron belongs. A **quantum shell** is a *set* of fixed energy levels to which electrons belong.

   Quantum shells are also assigned a letter; the shell for $n = 1$ is designated K, for $n = 2$ is L, for $n = 3$ is M, and so on. These designations were carried over from the nomenclature used in optical spectroscopy, a set of techniques that predates the understanding of quantized electronic levels.
2. The *number* of energy levels in *each* quantum shell is determined by the **azimuthal quantum number** l and the magnetic quantum number m_l. The azimuthal quantum numbers are assigned $l = 0, 1, 2, \ldots, n - 1$. For example, when $n = 2$, there are two azimuthal quantum numbers, $l = 0$ and $l = 1$. When $n = 3$, there are three azimuthal quantum numbers, $l = 0$, $l = 1$, and $l = 2$. The azimuthal quantum numbers are designated by lowercase letters; one speaks, for instance, of the d orbitals:

s for $l = 0$	d for $l = 2$
p for $l = 1$	f for $l = 3$

3. The number of values for the magnetic quantum number m_l gives the number of energy levels, or orbitals, for each azimuthal quantum number. The total number of magnetic quantum numbers for each l is $2l + 1$. The values for m_l are given by whole numbers between $-l$ and $+l$. For example, if $l = 2$, there are $2(2) + 1 = 5$ magnetic quantum numbers with values $-2, -1, 0, +1$, and $+2$. The combination of l and m_l specifies a particular orbital in a shell.
4. No more than two electrons with opposing electronic spins ($m_s = +1/2$ and $-1/2$) may be present in each orbital.

By carefully considering the possible numerical values for n, l, and m_l, the range of *possible* quantum numbers may be determined. For instance, in the K shell (that is, $n = 1$), there is just a single s orbital (as the only allowable value of l is 0 and m_l is 0). As a result, a K shell may contain no more than two electrons. As another example, consider an M shell. In this case, $n = 3$, so l takes values of 0, 1, and 2 (there are s, p, and d orbitals present). The values of l reflect that there is a single s orbital ($m_l = 0$, a single value), three p orbitals ($m_l = -1$, 0, $+1$, or three values), and five d orbitals ($m_l = -2, -1, 0, +1, +2$, or five discrete values).

The shorthand notation frequently used to denote the electronic structure of an atom combines the numerical value of the principal quantum number, the lowercase letter notation for the azimuthal quantum number, and a superscript showing the number of electrons in each type of orbital. The shorthand notation for neon, which has an atomic number of ten, is

$$1s^2 2s^2 2p^6$$

Deviations from Expected Electronic Structures

The energy levels of the quantum shells do not fill in strict numerical order. The **Aufbau Principle** is a graphical device that predicts deviations from the expected ordering of the energy levels. The Aufbau principle is shown in Figure 2-7. To use the Aufbau Principle, write the possible combinations of the principal quantum number and azimuthal quantum number for each quantum shell. The combinations for each quantum shell should be written on a single line. As the principal quantum number increases by one, the number of combinations within each shell increases by one (i.e., each row is one entry longer than the prior row). Draw arrows through the rows on a diagonal from the upper right to the lower left as shown in Figure 2-7. By following the arrows, the order in which the energy levels of each quantum level are filled is predicted.

For example, according to the Aufbau Principle, the electronic structure of iron, atomic number 26, is

$$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^6$$

Conventionally, the principal quantum numbers are arranged from lowest to highest when writing the electronic structure. Thus, the electronic structure of iron is written

$$1s^2 2s^2 2p^6 3s^2 3p^6 \quad \boxed{3d^6 4s^2}$$

The unfilled $3d$ level (there are five d orbitals, so in shorthand $d^1, d^2, \ldots, d^{10}$ are possible) causes the magnetic behavior of iron.

Note that not all elements follow the Aufbau principle. A few, such as copper, are exceptions. According to the Aufbau Principle, copper should have the electronic structure $1s^2 2s^2 2p^6 3s^2 3p^6 3d^9 4s^2$, but copper actually has the electronic structure

$$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} \quad \boxed{4s^1}$$

Generally, electrons will occupy each orbital of a given energy level singly before the orbitals are doubly occupied. For example, nitrogen has the electronic structure

$$1s^2 \quad \boxed{2s^2 2p^3}$$

Each of the three p orbitals in the L shell contains one electron rather than one orbital containing two electrons, one containing one electron, and one containing zero electrons.

Valence

The **valence** of an atom is the number of electrons in an atom that participate in bonding or chemical reactions. Usually, the valence is the number of electrons in the

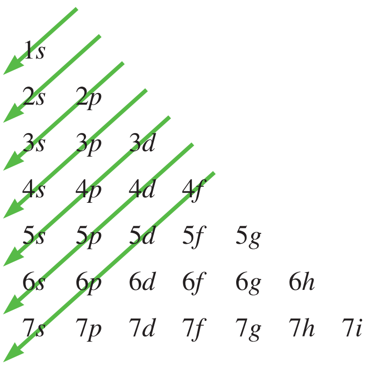


Figure 2-7 The Aufbau Principle. By following the arrows, the order in which the energy levels of each quantum level are filled is predicted: $1s$, $2s$, $2p$, $3s$, $3p$, etc. Note that the letter designations for $l = 4, 5, 6$ are g, h, and i.

outer s and p energy levels. The valence of an atom is related to the ability of the atom to enter into chemical combination with other elements. Examples of the valence are

$$\text{Mg: } 1s^2 2s^2 2p^6 \quad \boxed{3s^2} \qquad \text{valence} = 2$$
$$\text{Al: } 1s^2 2s^2 2p^6 \quad \boxed{3s^2 3p^1} \qquad \text{valence} = 3$$
$$\text{Si: } 1s^2 2s^2 2p^6 \quad \boxed{3s^2 3p^2} \qquad \text{valence} = 4$$

Valence also depends on the immediate environment surrounding the atom or the neighboring atoms available for bonding. Phosphorus has a valence of five when it combines with oxygen, but the valence of phosphorus is only three—the electrons in the $3p$ level—when it reacts with hydrogen. Manganese may have a valence of 2, 3, 4, 6, or 7!

Atomic Stability and Electronegativity

If an atom has a valence of zero, the element is inert (non-reactive). An example is argon, which has the electronic structure

$$1s^2 2s^2 2p^6 \quad \boxed{3s^2 3p^6}$$

Other atoms prefer to behave as if their outer s and p levels are either completely full, with eight electrons, or completely empty. Aluminum has three electrons in its outer s and p levels. An aluminum atom readily gives up its outer three electrons to empty the $3s$ and $3p$ levels. The atomic bonding and the chemical behavior of aluminum are determined by how these three electrons interact with surrounding atoms.

On the other hand, chlorine contains seven electrons in the outer $3s$ and $3p$ levels. The reactivity of chlorine is caused by its desire to fill its outer energy level by accepting an electron.

Electronegativity describes the tendency of an atom to gain an electron. Atoms with almost completely filled outer energy levels—such as chlorine—are strongly electronegative and readily accept electrons. Atoms with nearly empty outer levels—such as sodium—readily give up electrons and have low electronegativity. High atomic number elements also have low electronegativity because the outer electrons are at a greater distance from the positive nucleus, so that they are not as strongly attracted to the atom. Electronegativities for some elements are shown in Figure 2-8. Elements with low electronegativity (i.e., <2.0) are sometimes described as **electropositive**.

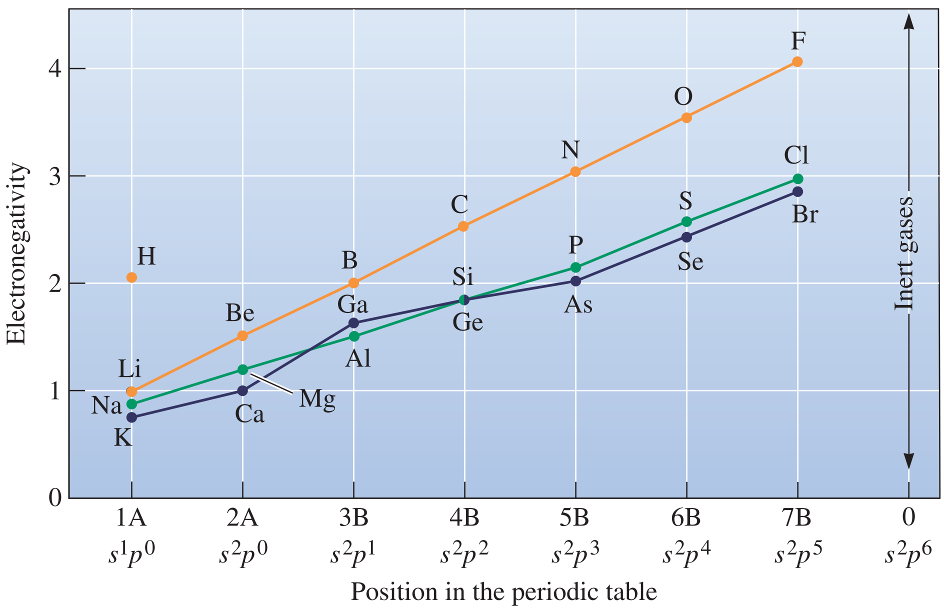


Figure 2-8 The electronegativities of selected elements relative to the position of the elements in the periodic table.

2-4 The Periodic Table

The periodic table contains valuable information about specific elements and can also help identify trends in atomic size, melting point, chemical reactivity, and other properties. The familiar periodic table (Figure 2-9) is constructed in accordance with the electronic structure of the elements. Rows in the periodic table correspond to quantum shells, or principal quantum numbers. Columns typically refer to the number of electrons in the outermost *s* and *p* energy levels and correspond to the most common valence. In engineering, we are mostly concerned with

(a) Polymers (plastics) (primarily based on carbon, which appears in Group 4B);

(b) Ceramics (typically based on combinations of many elements appearing in Groups 1 through 5B, and such elements as oxygen, carbon, and nitrogen); and

(c) Metallic materials (typically based on elements in Groups 1 or 2 or transition metal elements).

Many technologically important semiconductors appear in Group 4B (e.g., silicon, diamond, germanium). Semiconductors also can be combinations of elements from Groups 2B and 6B [e.g., cadmium selenide (CdSe), based on cadmium from Group 2 and selenium from Group 6]. These are known as **II–VI** (two-six) **semiconductors**. Similarly, gallium arsenide (GaAs) is a **III–V** (three-five) **semiconductor** based on gallium from Group 3B and arsenic from Group 5B. Many **transition elements** (e.g., titanium, vanadium, iron, nickel, cobalt, etc.) are particularly useful for magnetic and optical materials due to their electronic configurations that allow multiple valences.

The ordering of the elements in the periodic table and the origin of the Aufbau Principle become even clearer when the rows for the Lathanoid and Actinoid series are inserted into their correct positions (see Figure 2-10) rather than being placed below the periodic table to conserve space. Figure 2-10 indicates the particular orbital being filled by each additional electron as the atomic number increases. Note that exceptions are indicated for those elements that do not follow the Aufbau Principle.

Trends in Properties

The periodic table contains a wealth of useful information (e.g., atomic mass, atomic number of different elements, etc.). It also points to trends in atomic size, melting points, and chemical reactivity. For example, carbon (in its diamond form) has the highest melting point (3550°C). Melting points of the elements below carbon decrease [i.e., silicon (1410°C), germanium (937°C), tin (232°C), and lead (327°C)]. Note that the melting temperature of Pb is higher than that of Sn. The periodic table indicates trends and not exact variations in properties.

We can discern trends in other properties from the periodic table. Diamond is a material with a very large bandgap (i.e., it is not a very effective conductor of electricity). This is consistent with the fact that carbon (in diamond form) has the highest melting point among Group 4B elements, which suggests the interatomic forces are strong (see Section 2-6). As we move down the column, the bandgap decreases (the bandgaps of Si and Ge are 1.11 and 0.67 eV, respectively). Moving farther down, one form of tin is a semiconductor. Another form of tin is metallic. If we look at Group 1A, we see that lithium is highly electropositive (i.e., an element with atoms that want to participate in chemical interactions by donating electrons and are therefore highly reactive). Likewise, if we move down Column 1A, we can see that the chemical reactivity of elements increases.

Thus, the periodic table gives us useful information about formulas, atomic numbers, and atomic masses of elements. It also helps us in predicting or rationalizing trends in properties of elements and compounds. This is why the periodic table is very useful to both scientists and engineers.