

GLOBAL  
EDITION



# Introduction to **MATERIALS SCIENCE FOR ENGINEERS**

EIGHTH EDITION

James F. Shackelford

ALWAYS LEARNING

PEARSON

# CONSTANTS AND CONVERSION FACTORS

## Constants

Avogadro's number, $N_A$	$0.6023 \times 10^{24} \text{ mol}^{-1}$
Atomic mass unit, amu	$1.661 \times 10^{-24} \text{ g}$
Electric permittivity of a vacuum, $\epsilon_0$	$8.854 \times 10^{-12} \text{ C}/(\text{V} \cdot \text{m})$
Electron mass	$0.9110 \times 10^{-27} \text{ g}$
Elementary charge, $e$	$0.1602 \times 10^{-18} \text{ C}$
Gas constant, $R$	$8.314 \text{ J}/(\text{mol} \cdot \text{K})$ $1.987 \text{ cal}/(\text{mol} \cdot \text{K})$
Boltzmann's constant, $k$	$13.81 \times 10^{-24} \text{ J/K}$ $86.20 \times 10^{-6} \text{ eV/K}$
Planck's constant, $h$	$0.6626 \times 10^{-33} \text{ J} \cdot \text{s}$
Speed of light (in vacuum), $c$	$0.2998 \times 10^9 \text{ m/s}$
Bohr magneton, $\mu_B$	$9.274 \times 10^{-24} \text{ A} \cdot \text{m}^2$

## SI Prefixes

giga, G	$10^9$
mega, M	$10^6$
kilo, k	$10^3$
milli, m	$10^{-3}$
micro, $\mu$	$10^{-6}$
nano, n	$10^{-9}$
pico, p	$10^{-12}$

## Conversion Factors

Length	1 meter = $10^{10} \text{ \AA} = 10^9 \text{ nm}$
	= 3.281 ft
	= 39.37 in.
Mass	1 kilogram = 2.205 $\text{lb}_m$
Force	1 newton = 0.2248 $\text{lb}_f$
Pressure	1 pascal = $1 \text{ N/m}^2$
	= $0.1019 \times 10^{-6} \text{ kg}_f/\text{mm}^2$
	= $9.869 \times 10^{-6} \text{ atm}$
	= $0.1450 \times 10^{-3} \text{ lb}_f/\text{in.}^2$
Viscosity	1 Pa · s = 10 poise
Energy	1 joule = $1 \text{ W} \cdot \text{s}$
	= $1 \text{ N} \cdot \text{m}$
	= $1 \text{ V} \cdot \text{C}$
	= 0.2389 cal
	= $6.242 \times 10^{18} \text{ eV}$
	= 0.7377 $\text{ft} \cdot \text{lb}_f$
Temperature	$^\circ\text{C} = \text{K} - 273$
	= $(^\circ\text{F} - 32)/1.8$
Current	1 ampere = $1 \text{ C/s}$
	= $1 \text{ V}/\Omega$

# PERIODIC TABLE OF THE ELEMENTS

I A																										0
1 H 1.008	II A																				2 He 4.003					
3 Li 6.941	4 Be 9.012															5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18					
11 Na 22.99	12 Mg 24.31															VIII				13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95	
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.71	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80									
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98.91	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.4	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30									
55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.22	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.2	83 Bi 208.98	(210)	(210)	(222)									
87 Fr (223)	88 Ra 226.03	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)																					

58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (254)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lw (260)

## ATOMIC AND IONIC RADII OF SELECTED ELEMENTS<sup>a</sup>

Atomic number	Symbol	Atomic radius (nm)	Ion	Ionic radius (nm)
3	Li	0.152	Li <sup>+</sup>	0.078
4	Be	0.114	Be <sup>2+</sup>	0.054
5	B	0.097	B <sup>3+</sup>	0.02
6	C	0.077	C <sup>4+</sup>	< 0.02
7	N	0.071	N <sup>5+</sup>	0.01–0.02
8	O	0.060	O <sup>2-</sup>	0.132
9	F	—	F <sup>-</sup>	0.133
11	Na	0.186	Na <sup>+</sup>	0.098
12	Mg	0.160	Mg <sup>2+</sup>	0.078
13	Al	0.143	Al <sup>3+</sup>	0.057
14	Si	0.117	Si <sup>4+</sup>	0.039
15	P	0.109	P <sup>5+</sup>	0.03–0.04
16	S	0.106	S <sup>2-</sup>	0.174
17	Cl	0.107	Cl <sup>-</sup>	0.181
19	K	0.231	K <sup>+</sup>	0.133
20	Ca	0.197	Ca <sup>2+</sup>	0.106
21	Sc	0.160	Sc <sup>2+</sup>	0.083
22	Ti	0.147	Ti <sup>4+</sup>	0.064
23	V	0.132	V <sup>4+</sup>	0.061
24	Cr	0.125	Cr <sup>3+</sup>	0.064
25	Mn	0.112	Mn <sup>2+</sup>	0.091
26	Fe	0.124	Fe <sup>2+</sup>	0.087
27	Co	0.125	Co <sup>2+</sup>	0.082
28	Ni	0.125	Ni <sup>2+</sup>	0.078
29	Cu	0.128	Cu <sup>+</sup>	0.096
30	Zn	0.133	Zn <sup>2+</sup>	0.083
31	Ga	0.135	Ga <sup>3+</sup>	0.062
32	Ge	0.122	Ge <sup>4+</sup>	0.044
35	Br	0.119	Br <sup>-</sup>	0.196
39	Y	0.181	Y <sup>3+</sup>	0.106
40	Zr	0.158	Zr <sup>4+</sup>	0.087
41	Nb	0.143	Nb <sup>4+</sup>	0.074
42	Mo	0.136	Mo <sup>4+</sup>	0.068
46	Pd	0.137	Pd <sup>2+</sup>	0.050
47	Ag	0.144	Ag <sup>+</sup>	0.113
48	Cd	0.150	Cd <sup>2+</sup>	0.103
50	Sn	0.158	Sn <sup>4+</sup>	0.074
53	I	0.136	I <sup>-</sup>	0.220
55	Cs	0.265	Cs <sup>+</sup>	0.165
56	Ba	0.217	Ba <sup>2+</sup>	0.143
74	W	0.137	W <sup>4+</sup>	0.068
78	Pt	0.138	Pt <sup>2+</sup>	0.052
79	Au	0.144	Au <sup>+</sup>	0.137
80	Hg	0.150	Hg <sup>2+</sup>	0.112
82	Pb	0.175	Pb <sup>2+</sup>	0.132
92	U	0.138	U <sup>4+</sup>	0.105

<sup>a</sup>For a complete listing, see Appendix 2.

## PHYSICAL AND CHEMICAL DATA FOR SELECTED ELEMENTS<sup>a</sup>

Atomic number	Element	Symbol	Atomic mass (amu)	Density of solid (at 20°C) (Mg/m <sup>3</sup> = g/cm <sup>3</sup> )	Crystal structure (at 20°C)	Melting point (°C)	Atomic number
1	Hydrogen	H	1.008			-259.34 (T.P.)	1
2	Helium	He	4.003			-271.69	2
3	Lithium	Li	6.941	0.533	bcc	180.6	3
4	Beryllium	Be	9.012	1.85	hcp	1,289	4
5	Boron	B	10.81	2.47		2,092	5
6	Carbon	C	12.01	2.27	hex.	3,826 (S.P.)	6
7	Nitrogen	N	14.01			-210.0042 (T.P.)	7
8	Oxygen	O	16.00			-218.789 (T.P.)	8
9	Fluorine	F	19.00			-219.67 (T.P.)	9
10	Neon	Ne	20.18			-248.587 (T.P.)	10
11	Sodium	Na	22.99	0.966	bcc	97.8	11
12	Magnesium	Mg	24.31	1.74	hcp	650	12
13	Aluminum	Al	26.98	2.70	fcc	660.452	13
14	Silicon	Si	28.09	2.33	dia. cub.	1,414	14
15	Phosphorus	P	30.97	1.82	ortho.	44.14	15
				(white)		(white)	
16	Sulfur	S	32.06	2.09	ortho.	115.22	16
17	Chlorine	Cl	35.45			-100.97 (T.P.)	17
18	Argon	Ar	39.95			-189.352 (T.P.)	18
19	Potassium	K	39.10	0.862	bcc	63.71	19
20	Calcium	Ca	40.08	1.53	fcc	842	20
21	Scandium	Sc	44.96	2.99	fcc	1,541	21
22	Titanium	Ti	47.90	4.51	hcp	1,670	22
23	Vanadium	V	50.94	6.09	bcc	1,910	23
24	Chromium	Cr	52.00	7.19	bcc	1,863	24
25	Manganese	Mn	54.94	7.47	cubic	1,246	25
26	Iron	Fe	55.85	7.87	bcc	1,538	26
27	Cobalt	Co	58.93	8.8	hcp	1,495	27
28	Nickel	Ni	58.71	8.91	fcc	1,455	28
29	Copper	Cu	63.55	8.93	fcc	1,084.87	29
30	Zinc	Zn	65.38	7.13	hcp	419.58	30
31	Gallium	Ga	69.72	5.91	ortho.	29.7741 (T.P.)	31
32	Germanium	Ge	72.59	5.32	dia. cub.	938.3	32
33	Arsenic	As	74.92	5.78	rhomb.	603 (S.P.)	33
34	Selenium	Se	78.96	4.81	hex.	221	34
35	Bromine	Br	79.90			-7.25 (T.P.)	35
36	Krypton	Kr	83.80			-157.385	36
37	Rubidium	Rb	85.47	1.53	bcc	39.48	37
38	Strontium	Sr	87.62	2.58	fcc	769	38
39	Yttrium	Y	88.91	4.48	hcp	1,522	39
40	Zirconium	Zr	91.22	6.51	hcp	1,855	40
41	Niobium	Nb	92.91	8.58	bcc	2,469	41
42	Molybdenum	Mo	95.94	10.22	bcc	2,623	42

<sup>a</sup>For a complete listing, see Appendix 1.

Atomic number	Element	Symbol	Atomic mass (amu)	Density of solid (at 20°C) (Mg/m <sup>3</sup> = g/cm <sup>3</sup> )	Crystal structure (at 20°C)	Melting point (°C)	Atomic number
43	Technetium	Tc	98.91	11.50	hcp	2,204	43
44	Ruthenium	Ru	101.07	12.36	hcp	2,334	44
45	Rhodium	Rh	102.91	12.42	fcc	1,963	45
46	Palladium	Pd	106.4	12.00	fcc	1,555	46
47	Silver	Ag	107.87	10.50	fcc	961.93	47
48	Cadmium	Cd	112.4	8.65	hcp	321.108	48
49	Indium	In	114.82	7.29	fcc	156.634	49
50	Tin	Sn	118.69	7.29	bct	231.9681	50
51	Antimony	Sb	121.75	6.69	rhomb.	630.755	51
52	Tellurium	Te	127.60	6.25	hex.	449.57	52
53	Iodine	I	126.90	4.95	ortho.	113.6 (T.P.)	53
54	Xenon	Xe	131.30			-111.7582 (T.P.)	54
55	Cesium	Cs	132.91	1.91	bcc	28.39	55
				(-10°)			
56	Barium	Ba	137.33	3.59	bcc	729	56
57	Lanthanum	La	138.91	6.17	hex.	918	57
58	Cerium	Ce	140.12	6.77	fcc	798	58
59	Praseodymium	Pr	140.91	6.78	hex.	931	59
60	Neodymium	Nd	144.24	7.00	hex.	1,021	60
61	Promethium	Pm	(145)		hex.	1,042	61
62	Samarium	Sm	150.40	7.54	rhomb.	1,074	62
63	Europium	Eu	151.96	5.25	bcc	822	63
64	Gadolinium	Gd	157.25	7.87	hcp	1,313	64
65	Terbium	Tb	158.93	8.27	hcp	1,356	65
66	Dysprosium	Dy	162.50	8.53	hcp	1,412	66
67	Holmium	Ho	164.93	8.80	hcp	1,474	67
68	Erbium	Er	167.26	9.04	hcp	1,529	68
69	Thulium	Tm	168.93	9.33	hcp	1,545	69
70	Ytterbium	Yb	173.04	6.97	fcc	819	70
71	Lutetium	Lu	174.97	9.84	hcp	1,663	71
72	Hafnium	Hf	178.49	13.28	hcp	2,231	72
73	Tantalum	Ta	180.95	16.67	bcc	3,020	73
74	Tungsten	W	183.85	19.25	bcc	3,422	74
75	Rhenium	Re	186.20	21.02	hcp	3,186	75
76	Osmium	Os	190.20	22.58	hcp	3,033	76
77	Iridium	Ir	192.22	22.55	fcc	2,447	77
78	Platinum	Pt	195.09	21.44	fcc	1,769.0	78
79	Gold	Au	196.97	19.28	fcc	1,064.43	79
80	Mercury	Hg	200.59			-38.836	80
81	Thallium	Tl	204.37	11.87	hcp	304	81
82	Lead	Pb	207.20	11.34	fcc	327.502	82
83	Bismuth	Bi	208.98	9.80	rhomb.	271.442	83
92	Uranium	U	238.03	19.05	ortho.	1,135	92

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# Introduction to MATERIALS SCIENCE FOR ENGINEERS

**James F. Shackelford**

University of California, Davis

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





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# Preface

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

The words “materials engineering” give us a label for Part II of the book that deals with “Materials and Their Applications.” First, we discuss the five categories of *structural materials*: metals, ceramics, and glasses (Chapter 11) and polymers and composites (Chapter 12). In both chapters, we give examples of each type of structural material and describe their processing, the techniques used to produce the materials. In Chapter 13, we discuss *electronic materials* and discover a sixth

category of materials, semiconductors, based on an electrical rather than bonding classification system. Metals are generally good electrical conductors, while ceramics, glasses, and polymers are generally good insulators, and semiconductors are intermediate. The exceptional discovery of superconductivity in certain ceramic materials at relatively high temperatures augments the long-standing use of superconductivity in certain metals at very low temperatures. Chapter 14 covers optical behavior that determines the application of many materials, from traditional glass windows to some of the latest advances in telecommunications. A wide variety of *materials* is also discussed in Chapter 14. Traditional metallic and ceramic magnets are being supplemented by superconducting metals and ceramics, which can provide some intriguing design applications based on their magnetic behavior. Finally, in Chapter 15 (Materials in Engineering Design), we see that our previous discussions of properties have left us with “design parameters.” Herein lies a final bridge between the principles of materials science and the use of those materials in modern engineering designs. We also must note that chemical degradation, radiation damage, wear, and recycling must be considered in making a final judgment on a materials application.

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

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

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

Subsequent editions have reinforced that balanced approach with the timely addition of new materials that are playing key roles in the economy of the twenty-first century: lightweight metal alloys, “high tech” ceramics for advanced structural applications, engineering polymers for metal substitution, advanced composites for aerospace applications, increasingly miniaturized semiconductor devices, high-temperature ceramic superconductors, fullerene carbons, graphene,

engineered biomaterials, and biological materials. Since the debut of the first edition, we have also seen breakthroughs in materials characterization, such as the evolution of the high-resolution transmission electron microscope (HRTEM), and in materials processing, such as additive manufacturing (AM). “Feature boxes” have been introduced in recent editions. These one- or two-page case studies labeled “The Material World” are located in each chapter to provide a focus on some fascinating topics in the world of both engineered and natural materials. A feature continued from the Seventh Edition is to emphasize the concept of “Powers of Ten.” In Chapter 1, we point out that an underlying principle of materials science is that understanding the behavior of materials in engineering designs (on the human scale) is obtained by looking at mechanisms that occur at various fine scales, such as the atomic-scale diffusion of carbon atoms involved in the heat treatment of steel. There is a full ten orders of magnitude difference between the size of typical engineered products and the size of typical atoms. Much of modern engineering practice has depended on engineering designs based on micrometer-scale structures, such as the transistors in an integrated circuit. Increasingly, engineers are designing systems involving the nanometer-scale. At various times throughout the text, a Powers of Ten icon will be used to highlight discussions that demonstrate this structure-property relationship.

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## New to This Edition

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

- Updated discussions of the expanding importance of materials in nanotechnology throughout the text;
- Examples of the role of materials in flat screen and flat panel technology throughout the text;
- Addition of graphene to the discussion of advances in carbon materials in Chapter 3;
- Coverage of the rapidly emerging field of additive manufacturing (by 3D printing) in Chapter 11;
- A candid discussion of the increasing role of biological materials in materials science and how that expands the definition of this field (Feature Box in Chapter 12);
- Expanded coverage of ferroelectrics and piezoelectrics in Chapter 13;
- Coverage of optical and magnetic materials in a new Chapter 14;
- Expanded coverage of corrosion in Chapter 15.

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## Supplementary Material

A *Solutions Manual* is available to adopters of this textbook. The Solutions Manual contains fully worked-out solutions to the practice and homework problems **only**. The Solutions Manual is available from the publisher. The Instructors



Resource Center (IRC) for this book contains the entire Solutions Manual in PDF format. An important addition to the IRC is a complete set of all figures and tables from the textbook in PowerPoint® format. This set of slides was prepared by the University of California, Davis Extension in conjunction with an online course based on this book and can be very useful to faculty in preparing their own lectures. Information about the online course can be obtained from the author.

**MasteringEngineering™.** [www.masteringengineering.com](http://www.masteringengineering.com). The Mastering™ platform is the most effective and widely used online tutorial, homework, and assessment system for the sciences and engineering. Now including Materials Science and Engineering, this online tutorial homework program provides instructors customizable, easy-to-assign, and automatically graded assessments, plus a powerful gradebook for tracking student and class performance.

**Pearson eText.** The integration of Pearson eText within MasteringEngineering gives students with eTexts easy access to the electronic text when they are logged into MasteringEngineering. Pearson eText pages look exactly like the printed text, offering additional functionality for students and instructors including highlighting, bookmarking, and multiple view formats.

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## Acknowledgments

Finally, I want to acknowledge a number of people who have been immensely helpful in making this book possible. My family has been more than the usual “patient and understanding.” They are a constant reminder of the rich life beyond the material plane. Peter Gordon (first edition), David Johnstone (second and third editions), Bill Stenquist (fourth and fifth editions), Dorothy Marrero (sixth edition), and Holly Stark (seventh edition) are much appreciated in their roles as editors. Program Manager Clare Romeo has been indispensable in shepherding this edition to completion. Lilian Davila at the University of California, Merced skillfully produced the computer-generated crystal structure images. A special appreciation is due to my colleagues at the University of California, Davis and to the many reviewers of all editions, especially D. J. Montgomery, John M. Roberts, D. R. Rossington, R. D. Daniels, R. A. Johnson, D. H. Morris, J. P. Mathers, Richard Fleming, Ralph Graff, Ian W. Hall, John J. Kramer, Enayat Mahajerin, Carolyn W. Meyers, Ernest F. Nippes, Richard L. Porter, Eric C. Skaar, E. G. Schwartz, William N. Weins, M. Robert Baren, John Botsis, D. L. Douglass, Robert W. Hendricks, J. J. Hren, Sam Hruska, I. W. Hull, David B. Knoor, Harold Koelling, John McLaughlin, Alvin H. Meyer, M. Natarajan, Jay Samuel, John R. Schlup, Theodore D. Taylor, Ronald Kander, Alan Lawley, Joanna McKittrick, Kathleen R. Rohr, James F. Fitz-Gerald, Valery Bliznyuk, David Bahr, K. Srinagesh, Stacy Gleixner, and Raj Vaidyanathan. I would especially like to thank the reviewers for the eighth edition: Jeffrey Fergus, Auburn University; Christoph Steinbruchel, Rensselaer Polytechnic Institute; Wayne Elban, Loyola University Maryland; Giovanni Zangari, University of Virginia; Guanshui Xu, University of California at Riverside; Atin Sinha, Albany State

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JAMES F. SHACKELFORD  
*Davis, California*

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# your work...

## PART A

What is the planar density on the  $\langle 111 \rangle$  plane in a simple cubic (SC) unit cell w/ equal size atoms?



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

Area of Plane



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

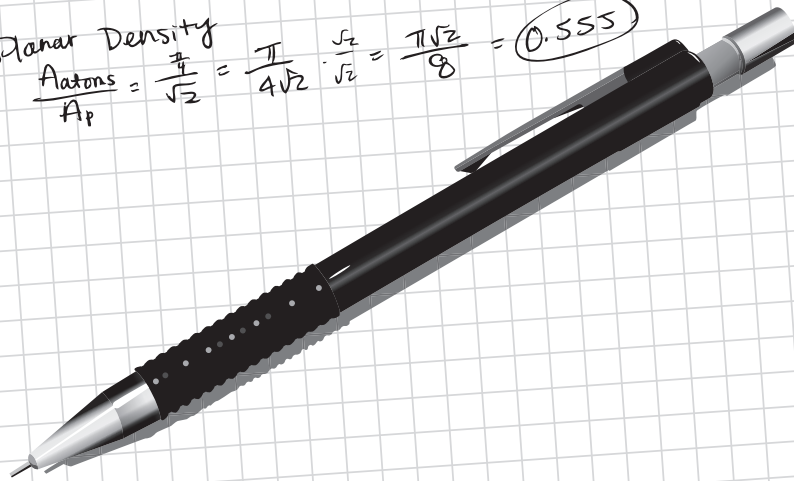
Area of Atoms



$$\begin{aligned} A_{\text{atoms}} &= \frac{1}{4} \cdot \pi r^2 \cdot 4 \quad r = \frac{1}{2} \\ &= \pi \left(\frac{1}{2}\right)^2 \quad \text{fraction area of atoms on a plane} \\ &= \frac{\pi}{4} \end{aligned}$$

Planar Density

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

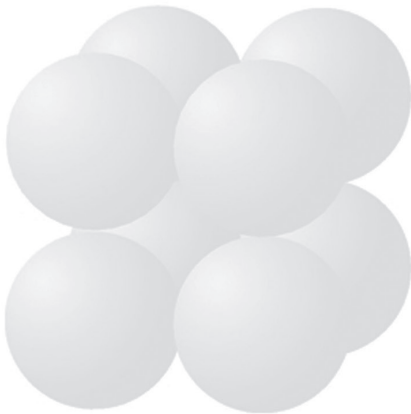


# your answer **specific feedback**

## Part A

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

(Figure 1)



Express your answer numerically.

$PD =$

[Hints](#)

[My Answers](#)

[Give Up](#)

[Review Part](#)

### Try Again; 5 attempts remaining

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

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## About the Author

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**James F. Shackelford** has BS and MS degrees in Ceramic Engineering from the University of Washington and a Ph.D. in Materials Science and Engineering from the University of California, Berkeley. He is currently Distinguished Professor Emeritus in the Department of Chemical Engineering and Materials Science at the University of California, Davis. For many years, he served as the Associate Dean for Undergraduate Studies in the College of Engineering and later as the Director of the University Honors Program that serves students from a wide spectrum of majors. He teaches and conducts research in the structural characterization and processing of materials, focusing on glasses and biomaterials. A member of the American Ceramic Society and ASM International, he was named a Fellow of the American Ceramic Society in 1992, was named a Fellow of ASM International in 2011, and received the Outstanding Educator Award of the American Ceramic Society in 1996. In 2003, he received a Distinguished Teaching Award from the Academic Senate of the University of California, Davis. In 2012, he received the Outstanding Teaching Award of the College of Engineering at UC Davis. He has published well over 100 archived papers and books including *Introduction to Materials Science for Engineers* now in its eighth edition and which has been translated into Chinese, German, Italian, Japanese, Korean, Portuguese, and Spanish.

# CHAPTER 1

# Materials for Engineering



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

- 1.1 The Material World
- 1.2 Materials Science and Engineering
- 1.3 Six Materials That Changed Your World
- 1.4 Processing and Selecting Materials
- 1.5 Looking at Materials by Powers of Ten

## 1.1 The Material World

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

Contemporary archaeologists note that an earlier but less well known “Copper Age” existed between roughly 4000 B.C. and 3000 B.C. in Europe, in which relatively pure copper was used before tin became available. The limited utility of those copper products provided an early lesson in the importance of proper alloy additions. The **Iron Age** defines the period from 1000 B.C. to 1 B.C. By 500 B.C., iron alloys had largely replaced bronze for tool and weapon making in Europe (Figure 1.1).

Although archaeologists do not refer to a “pottery age,” the presence of domestic vessels made from baked clay has provided some of the best



**FIGURE 1.1** Celtic Iron Age tools from 1st century B.C. Germany. (© Ancient Art & Architecture Collection Ltd / Alamy.)

descriptions of human cultures for thousands of years. Similarly, glass artifacts have been traced back to 4000 B.C. in Mesopotamia.

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

## 1.2 Materials Science and Engineering

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

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

## 1.3 Six Materials That Changed Your World

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

### STEEL BRIDGES—INTRODUCING METALS

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

Among the most familiar uses of structural steel are bridges, and one of the most famous and beautiful examples is the Golden Gate Bridge connecting San Francisco, California with Marin County to the north (Figure 1.2). The opening on May 27, 1937, allowed 200,000 local residents to stroll across the impressive new structure. The following day, a ribbon cutting ceremony inaugurated automobile traffic that has continued to be an important part of the fabric of life in the San Francisco Bay area for more than 75 years. For many years, the Golden Gate held the title of “longest suspension bridge” in the world (2,737 meters). Although new bridge technologies have provided newer holders of that title, the Golden Gate is still, in the words of a local historian, a “symphony in steel.”





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

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

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

## LUCALOX LAMPS—INTRODUCING CERAMICS

Aluminum (Al) is a common metal, but aluminum *oxide*, a compound of aluminum and oxygen such as  $\text{Al}_2\text{O}_3$ , is typical of a fundamentally different family of engineering materials, **ceramics**. Aluminum oxide has two principal advantages over metallic aluminum. First,  $\text{Al}_2\text{O}_3$  is chemically stable in a wide

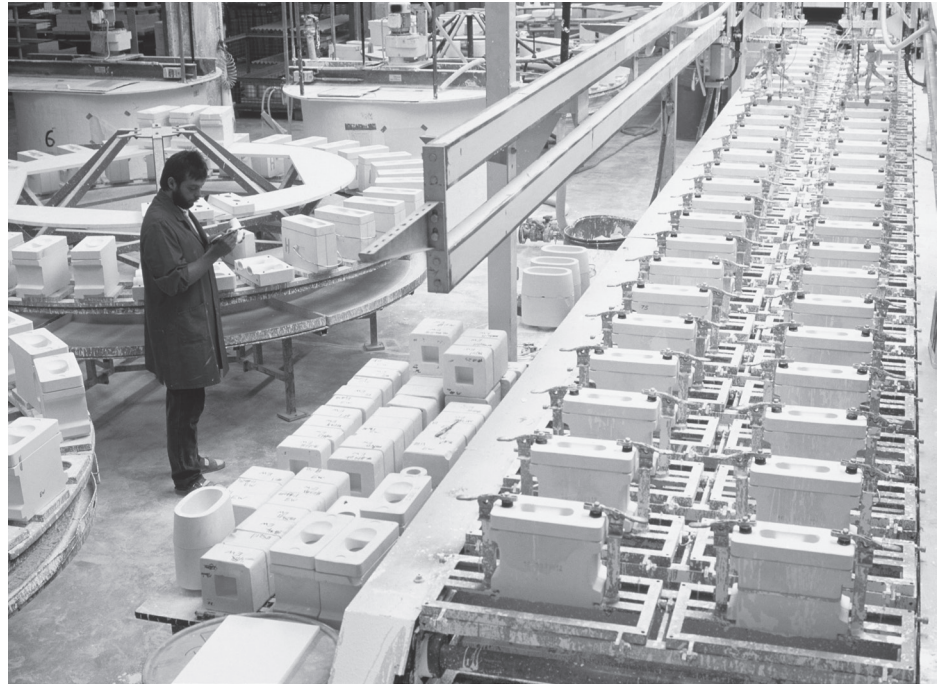


**FIGURE 1.3** *The Sundial Bridge in Redding, California is a modern masterpiece of bridge design.*

1 H																	2 He																												
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne																												
11 Na	12 Mg	III B	IV B	V B	VI B	VII B	VIII			I B	II B	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar																												
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr																												
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe																												
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn																												
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg																																								
<table border="1"> <tbody> <tr> <td>58 Ce</td> <td>59 Pr</td> <td>60 Nd</td> <td>61 Pm</td> <td>62 Sm</td> <td>63 Eu</td> <td>64 Gd</td> <td>65 Tb</td> <td>66 Dy</td> <td>67 Ho</td> <td>68 Er</td> <td>69 Tm</td> <td>70 Yb</td> <td>71 Lu</td> </tr> <tr> <td>90 Th</td> <td>91 Pa</td> <td>92 U</td> <td>93 Np</td> <td>94 Pu</td> <td>95 Am</td> <td>96 Cm</td> <td>97 Bk</td> <td>98 Cf</td> <td>99 Es</td> <td>100 Fm</td> <td>101 Md</td> <td>102 No</td> <td>103 Lw</td> </tr> </tbody> </table>																		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu																																
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw																																

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

variety of severe environments, whereas metallic aluminum would be oxidized (a term discussed further in Chapter 15). In fact, a common reaction product in the chemical degradation of aluminum is the more chemically stable oxide. Second, the ceramic  $\text{Al}_2\text{O}_3$  has a significantly higher melting point ( $2020^\circ\text{C}$ ) than does the metallic Al ( $660^\circ\text{C}$ ), which makes  $\text{Al}_2\text{O}_3$  a popular **refractory** (i.e., a



**FIGURE 1.5** A technician observes the production of chemically stable and high-temperature resistant oxide ceramics. Such materials have a wide range of applications in modern industry. (Maximilian Stock Ltd / Photo Researchers, Inc.)

high-temperature-resistant material of wide use in industrial furnace construction). The production of such oxide ceramics for modern industry is shown in Figure 1.5.

With its superior chemical and temperature-resistant properties, why isn't  $\text{Al}_2\text{O}_3$  used for applications such as automotive engines in place of metallic aluminum? The answer to this question lies in the most limiting property of ceramics—brittleness. Aluminum and other metals have high ductility, a desirable property that permits them to undergo relatively severe impact loading without fracture, whereas aluminum oxide and other ceramics lack this property. Thus, ceramics are eliminated from many structural applications because they are brittle.

A significant achievement in materials technology is the development of transparent ceramics, which has made possible new products and substantial improvements in others (e.g., commercial lighting). To make traditionally opaque ceramics, such as aluminum oxide ( $\text{Al}_2\text{O}_3$ ), into optically transparent materials required a fundamental change in manufacturing technology. Commercial ceramics are frequently produced by heating crystalline powders to high temperatures until a relatively strong and dense product results. Traditional ceramics made in this way contained a substantial amount of residual porosity (see also the Feature Box, “Structure Leads to Properties”), corresponding to the open space between the original powder particles prior to high-temperature processing. A significant reduction in porosity resulted from a relatively simple invention\* that involved adding a small amount of impurity (0.1 wt % MgO), which caused the high-temperature densification process for the  $\text{Al}_2\text{O}_3$  powder to go to completion.

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



**FIGURE 1.6** These high-temperature sodium vapor street lamps are made possible by use of a translucent  $\text{Al}_2\text{O}_3$  cylinder for containing the sodium vapor. (David Nunuk / Photo Researchers, Inc.)

IA																										0					
1	II A																				2										
H																III A IV A V A VI A VII A					He										
3	4															5	6	7	8	9	10										
Li	Be															B	C	N	O	F	Ne										
11	12															13	14	15	16	17	18										
Na	Mg	III B	IV B	V B	VI B	VII B	VIII					I B	II B	Al	Si	P	S	Cl	Ar												
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36														
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr														
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54														
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe														
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86														
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn														
87	88	89	104	105	106																										
Fr	Ra	Ac	Rf	Db	Sg																										
																		58	59	60	61	62	63	64	65	66	67	68	69	70	71
																		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
																		90	91	92	93	94	95	96	97	98	99	100	101	102	103
																		Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lw

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

Cylinders of translucent  $\text{Al}_2\text{O}_3$  became the heart of the design of high-temperature ( $1000^\circ\text{C}$ ) sodium vapor lamps, which provide substantially higher illumination than do conventional lightbulbs (100 lumens/W compared to 15 lumens/W). Commercial sodium vapor lamps are shown in Figure 1.6.

Aluminum oxide is typical of the traditional ceramics, with magnesium oxide ( $\text{MgO}$ ) and **silica** ( $\text{SiO}_2$ ) being other good examples. In addition,  $\text{SiO}_2$  is the basis of a large and complex family of **silicates**, which includes clays and clay-like minerals. Silicon nitride ( $\text{Si}_3\text{N}_4$ ) is an important nonoxide ceramic used in a variety of structural applications. The vast majority of commercially important ceramics are chemical compounds made up of at least one metallic element (see Figure 1.4) and one of five **nonmetallic** elements (C, N, O, P, or S). Figure 1.7 illustrates the various metals (in light color) and the five key nonmetals (in dark color) that can be combined to form an enormous range of ceramic materials. Bear in mind that many commercial ceramics include compounds and solutions of many more than two elements, just as commercial metal alloys are composed of many elements.



## THE MATERIAL WORLD

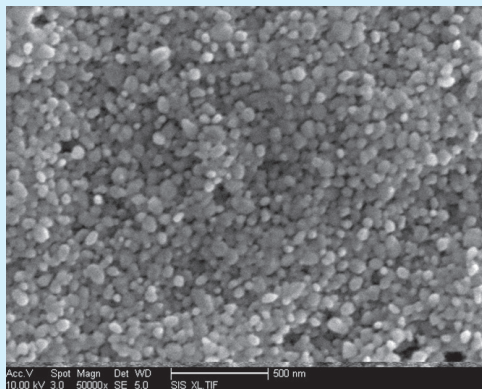
## Structure Leads to Properties

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

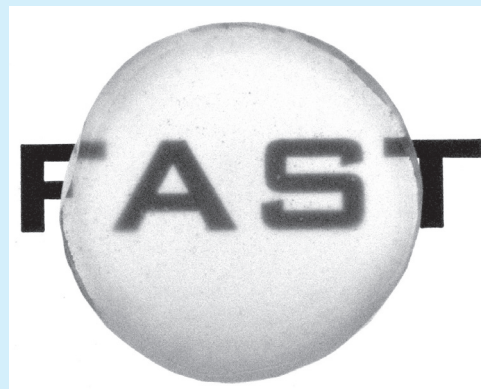
The dramatic effect that fine-scale structure has on large-scale properties is well illustrated by the development of transparent ceramics, just discussed in the introduction to ceramic materials. The microscopic-scale residual porosity in a traditional aluminum oxide leads to loss of visible light transmission (i.e., a loss in transparency) by providing a light-scattering mechanism. Each  $\text{Al}_2\text{O}_3$ –air interface at a pore surface is a source of light refraction (change of direction). Only about 0.3% porosity can cause  $\text{Al}_2\text{O}_3$  to be translucent (capable of transmitting a diffuse image), and 3% porosity can cause the material to be completely opaque. The elimination of porosity provided by the Lucalox patent (adding 0.1 wt % MgO) produced a pore-free microstructure and a nearly transparent material

with an important additional property—excellent resistance to chemical attack by high-temperature sodium vapor.

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



(a)

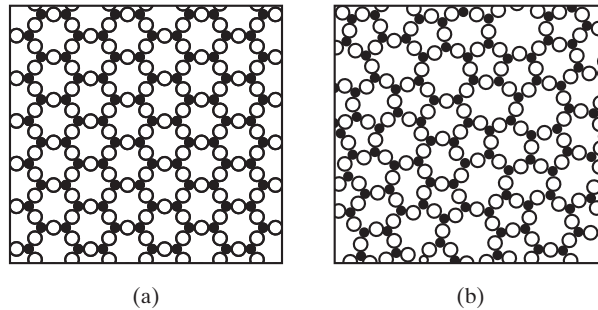


(b)

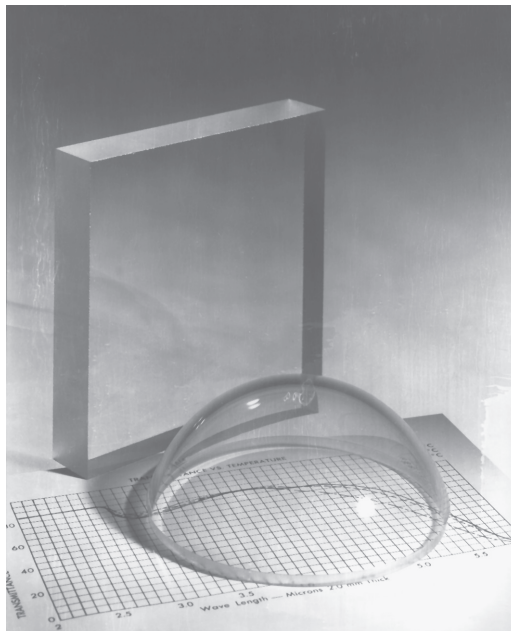
(Courtesy of T. B. Tien and J. R. Groza, University of California, Davis.)

## OPTICAL FIBERS—INTRODUCING GLASSES

The metals and ceramics just introduced have a similar structural feature on the atomic scale: They are **crystalline**, which means that their constituent atoms are stacked together in a regular, repeating pattern. A distinction between metallic- and ceramic-type materials is that, by fairly simple processing techniques, many ceramics can be made in a **noncrystalline** form (i.e., their atoms are stacked in irregular, random patterns), which is illustrated in Figure 1.8. The general term for noncrystalline solids with compositions comparable to those of crystalline ceramics is **glass** (Figure 1.9). Most common glasses are silicates; ordinary window glass is approximately 72% silica ( $\text{SiO}_2$ ) by weight, with the balance of the material



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



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

being primarily sodium oxide ( $\text{Na}_2\text{O}$ ) and calcium oxide ( $\text{CaO}$ ). Glasses share the property of brittleness with crystalline ceramics. Glasses are important engineering materials because of other properties, such as their ability to transmit visible light (as well as ultraviolet and infrared radiation) and chemical inertness.

A major revolution in the field of telecommunications occurred with the transition from traditional metal cable to optical glass fibers (Figure 1.10). Although Alexander Graham Bell had transmitted speech several hundred meters over a beam of light shortly after his invention of the telephone, technology did not permit the practical, large-scale application of this concept for nearly a century. The key to the rebirth of this approach was the invention of the laser in 1960. By 1970, researchers at Corning Glass Works had developed an **optical fiber** with a loss as low as 20 dB/km at a wavelength of 630 nm (within the visible range). By the mid-1980s, silica fibers had been developed with losses as low as 0.2 dB/km at 1.6  $\mu\text{m}$  (in the infrared range). As a result, telephone conversations and any other form of digital data can be transmitted as laser light pulses rather than as the electrical signals used in copper cables. Glass fibers are excellent examples of **photonic materials**, in which signal transmission occurs by photons rather than by the electrons of electronic materials.

Glass-fiber bundles of the type illustrated in Figure 1.10 were put into commercial use by Bell Systems in the mid-1970s. The reduced expense and size, combined with an enormous capacity for data transmission, led to a rapid growth in the construction of optical communication systems. Now, virtually all telecommunications are transmitted in this way. Ten billion digital bits can be transmitted per second along an optical fiber in a contemporary system carrying tens of thousands of telephone calls.

### NYLON PARACHUTES—INTRODUCING POLYMERS

A major impact of modern engineering technology on everyday life has been made by the class of materials known as **polymers**. An alternative name for this category is **plastics**, which describes the extensive formability of many polymers

**FIGURE 1.10** *The small cable on the right contains 144 glass fibers and can carry more than three times as many telephone conversations as the traditional (and much larger) copper-wire cable on the left. (© Bettmann/CORBIS.)*





**FIGURE 1.11** Miscellaneous internal parts of a parking meter are made of an acetal polymer. Engineered polymers are typically inexpensive and are characterized by ease of formation and adequate structural properties. (Courtesy of the DuPont Company, Engineering Polymers Division.)

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

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

As the descriptive title implies, *plastics* commonly share with metals the desirable mechanical property of ductility. Unlike brittle ceramics, polymers are frequently lightweight, low-cost alternatives to metals in structural design applications. The nature of chemical bonding in polymeric materials will be explored in Chapter 2. Important bonding-related properties include lower strength



IA																										0					
1 H	II A																			5 B	6 C	7 N	8 O	9 F	10 Ne						
3 Li	4 Be																	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar								
11 Na	12 Mg	III B	IV B	V B	VI B	VII B	VIII						I B	II B																	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr														
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe														
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn														
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg																										
																		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
																		90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

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



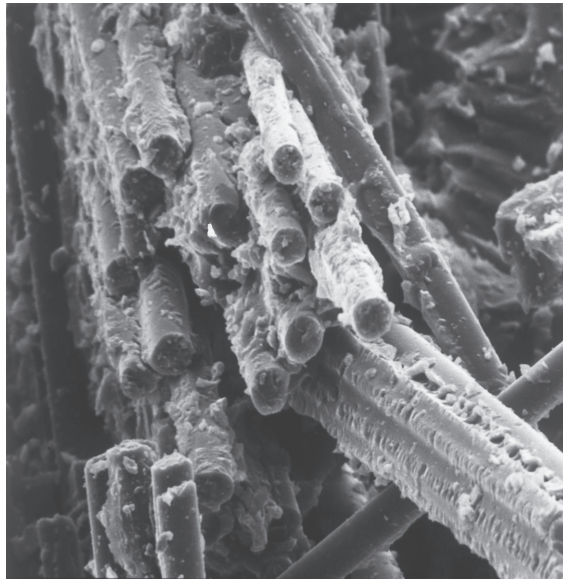
**FIGURE 1.13** Since its development during World War II, nylon fabric remains the most popular material of choice for parachute designs. (Courtesy of Stringer/Agence France Presse/Getty Images.)

compared with metals and lower melting point and higher chemical reactivity compared with ceramics and glasses. In spite of their limitations, polymers are highly versatile and useful materials. Substantial progress has been made in recent decades in the development of engineering polymers with sufficiently high strength and stiffness to permit substitution for traditional structural metals.

### KEVLAR®-REINFORCED TIRES—INTRODUCING COMPOSITES

The structural engineering materials we have discussed so far—metals, ceramics/glasses, and polymers—contain various elements and compounds that can be classified by their chemical bonding. Metals are associated with metallic bonding, ceramics/glasses with ionic bonding, and polymers with covalent bonding. Such classifications are described further in Chapter 2. Another important set of materials is made up of some combinations of individual materials from the previous categories. This fourth group is **composites**, and an excellent example is **fiberglass**. This composite of glass fibers embedded in a polymer matrix is commonplace (Figure 1.14). Characteristic of good composites, fiberglass has the best properties of each component, producing a product that is superior to either of the components separately. The high strength of the small-diameter glass fibers is combined with the ductility of the polymer matrix to produce a strong material capable of withstanding the normal loading required of a structural material. There is no need to illustrate a region of the periodic table as characteristic of composites, since they involve virtually the entire table except for the noble gases (column 0), equivalent to an overlay of the periodic table coverage for metals, ceramics, and polymers combined.

**Kevlar** fiber reinforcements provide significant advances over traditional glass fibers for **polymer–matrix composites**. Kevlar is a DuPont trade name for



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



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

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

## SILICON CHIPS—INTRODUCING SEMICONDUCTORS

Although polymers are highly visible engineering materials that have had a major impact on contemporary society, semiconductors are relatively invisible but have had a comparable social impact. Technology has clearly revolutionized society, but solid-state electronics has revolutionized technology itself. A relatively small group of elements and compounds has an important electrical property, *semiconduction*, in which they are neither good electrical conductors nor good electrical insulators. Instead, their ability to conduct electricity is intermediate. These materials are called **semiconductors**, and in general they do not fit into any of the structural materials categories based on atomic bonding. As discussed earlier, metals are inherently good electrical conductors. Ceramics and polymers (nonmetals) are generally poor conductors, but good insulators. An important section of the periodic table is shown in dark color in Figure 1.16 These three