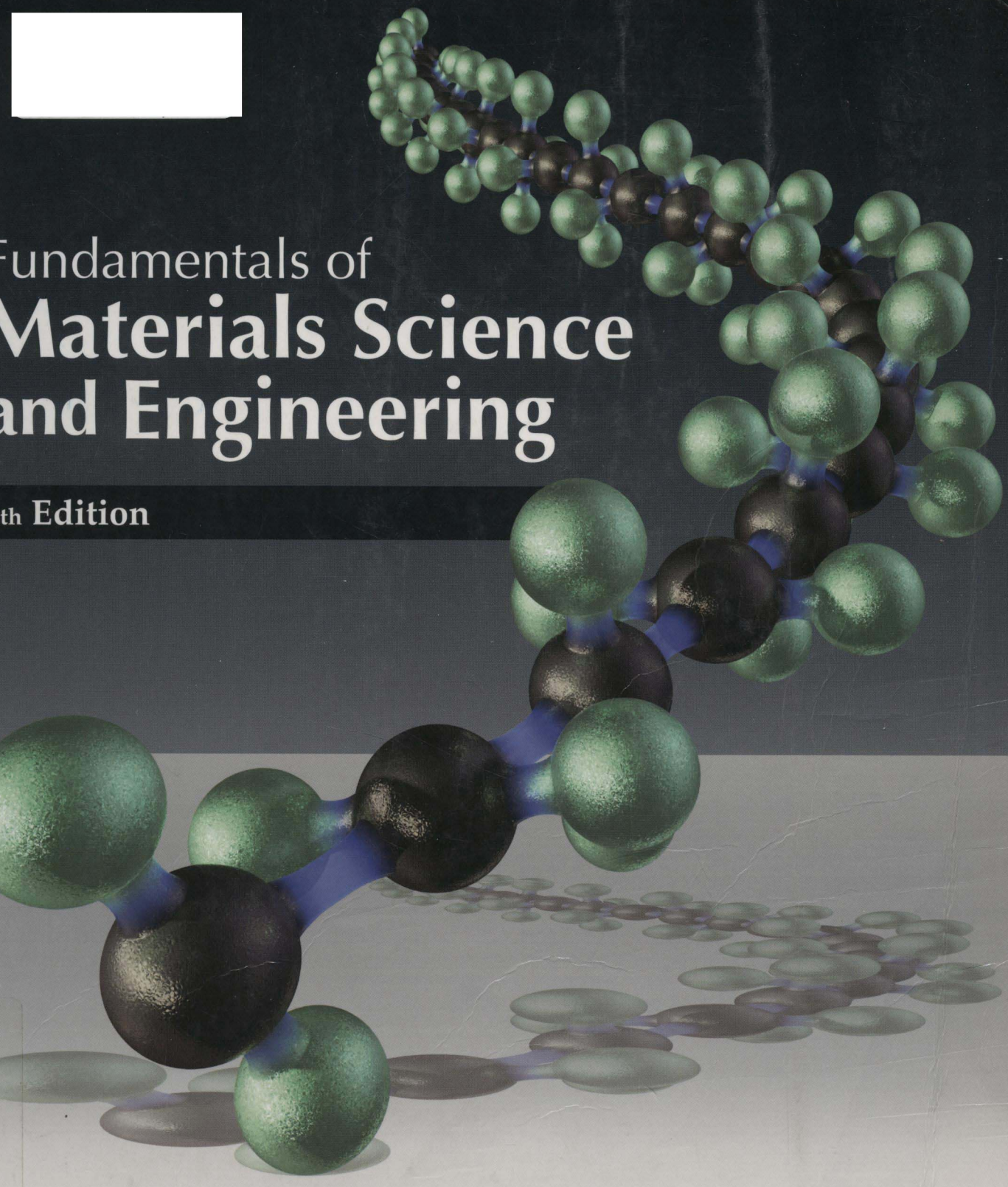
William D. Callister, Jr. David G. Rethwisch



Fundamentals of Materials Science and Engineering

4th Edition

SI Version

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Fundamentals of Materials Science and Engineering

SI VERSION

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Characteristics of Selected Elements

Element	*Symbol*	*Atomic Number*	*Atomic Weight (amu)*	*Density of Solid, 20°C (g/cm^3)*	*Crystal Structure,[a] 20°C*	*Atomic Radius (nm)*	*Ionic Radius (nm)*	*Most Common Valence*	*Melting Point (°C)*
Aluminum	Al	13	26.98	2.71	FCC	0.143	0.053	3+	660.4
Argon	Ar	18	39.95	—	—	—	—	Inert	−189.2
Barium	Ba	56	137.33	3.5	BCC	0.217	0.136	2+	725
Beryllium	Be	4	9.012	1.85	HCP	0.114	0.035	2+	1278
Boron	B	5	10.81	2.34	Rhomb.	—	0.023	3+	2300
Bromine	Br	35	79.90	—	—	—	0.196	1−	−7.2
Cadmium	Cd	48	112.41	8.65	HCP	0.149	0.095	2+	321
Calcium	Ca	20	40.08	1.55	FCC	0.197	0.100	2+	839
Carbon	C	6	12.011	2.25	Hex.	0.071	~0.016	4+	(sublimes at 3367)
Cesium	Cs	55	132.91	1.87	BCC	0.265	0.170	1+	28.4
Chlorine	Cl	17	35.45	—	—	—	0.181	1−	−101
Chromium	Cr	24	52.00	7.19	BCC	0.125	0.063	3+	1875
Cobalt	Co	27	58.93	8.9	HCP	0.125	0.072	2+	1495
Copper	Cu	29	63.55	8.94	FCC	0.128	0.096	1+	1085
Fluorine	F	9	19.00	—	—	—	0.133	1−	−220
Gallium	Ga	31	69.72	5.90	Ortho.	0.122	0.062	3+	29.8
Germanium	Ge	32	72.64	5.32	Dia. cubic	0.122	0.053	4+	937
Gold	Au	79	196.97	19.32	FCC	0.144	0.137	1+	1064
Helium	He	2	4.003	—	—	—	—	Inert	−272 (at 26 atm)
Hydrogen	H	1	1.008	—	—	—	0.154	1+	−259
Iodine	I	53	126.91	4.93	Ortho.	0.136	0.220	1−	114
Iron	Fe	26	55.85	7.87	BCC	0.124	0.077	2+	1538
Lead	Pb	82	207.2	11.35	FCC	0.175	0.120	2+	327
Lithium	Li	3	6.94	0.534	BCC	0.152	0.068	1+	181
Magnesium	Mg	12	24.31	1.74	HCP	0.160	0.072	2+	649
Manganese	Mn	25	54.94	7.44	Cubic	0.112	0.067	2+	1244
Mercury	Hg	80	200.59	—	—	—	0.110	2+	−38.8
Molybdenum	Mo	42	95.94	10.22	BCC	0.136	0.070	4+	2617
Neon	Ne	10	20.18	—	—	—	—	Inert	−248.7
Nickel	Ni	28	58.69	8.90	FCC	0.125	0.069	2+	1455
Niobium	Nb	41	92.91	8.57	BCC	0.143	0.069	5+	2468
Nitrogen	N	7	14.007	—	—	—	0.01–0.02	5+	−209.9
Oxygen	O	8	16.00	—	—	—	0.140	2−	−218.4
Phosphorus	P	15	30.97	1.82	Ortho.	0.109	0.035	5+	44.1
Platinum	Pt	78	195.08	21.45	FCC	0.139	0.080	2+	1772
Potassium	K	19	39.10	0.862	BCC	0.231	0.138	1+	63
Silicon	Si	14	28.09	2.33	Dia. cubic	0.118	0.040	4+	1410
Silver	Ag	47	107.87	10.49	FCC	0.144	0.126	1+	962
Sodium	Na	11	22.99	0.971	BCC	0.186	0.102	1+	98
Sulfur	S	16	32.06	2.07	Ortho.	0.106	0.184	2−	113
Tin	Sn	50	118.71	7.27	Tetra.	0.151	0.071	4+	232
Titanium	Ti	22	47.87	4.51	HCP	0.145	0.068	4+	1668
Tungsten	W	74	183.84	19.3	BCC	0.137	0.070	4+	3410
Vanadium	V	23	50.94	6.1	BCC	0.132	0.059	5+	1890
Zinc	Zn	30	65.41	7.13	HCP	0.133	0.074	2+	420
Zirconium	Zr	40	91.22	6.51	HCP	0.159	0.079	4+	1852

[a]Dia. = Diamond; Hex. = Hexagonal; Ortho. = Orthorhombic; Rhomb. = Rhombohedral; Tetra. = Tetragonal.

Values of Selected Physical Constants

Quantity	*Symbol*	*SI Units*	*cgs Units*
Avogadro's number	N_A	6.022×10^{23} molecules/mol	6.022×10^{23} molecules/mol
Boltzmann's constant	k	1.38×10^{-23} J/atom·K	1.38×10^{-16} erg/atom·K 8.62×10^{-5} eV/atom·K
Bohr magneton	μ_B	9.27×10^{-24} A·m^2	9.27×10^{-21} erg/gauss[a]
Electron charge	e	1.602×10^{-19} C	4.8×10^{-10} statcoul[b]
Electron mass	—	9.11×10^{-31} kg	9.11×10^{-28} g
Gas constant	R	8.31 J/mol·K	1.987 cal/mol·K
Permeability of a vacuum	μ_0	1.257×10^{-6} henry/m	Unity[a]
Permittivity of a vacuum	ϵ_0	8.85×10^{-12} farad/m	Unity[b]
Planck's constant	h	6.63×10^{-34} J·s	6.63×10^{-27} erg·s 4.13×10^{-15} eV·s
Velocity of light in a vacuum	c	3×10^8 m/s	3×10^{10} cm/s

[a] In cgs-emu units.
[b] In cgs-esu units.

Unit Abbreviations

A = ampere	in. = inch	N = newton
Å = angstrom	J = joule	nm = nanometer
Btu = British thermal unit	K = degrees Kelvin	P = poise
C = Coulomb	kg = kilogram	Pa = Pascal
°C = degrees Celsius	lb_f = pound force	s = second
cal = calorie (gram)	lb_m = pound mass	T = temperature
cm = centimeter	m = meter	μm = micrometer (micron)
eV = electron volt	Mg = megagram	W = watt
°F = degrees Fahrenheit	mm = millimeter	psi = pounds per square inch
ft = foot	mol = mole	
g = gram	MPa = megapascal	

SI Multiple and Submultiple Prefixes

Factor by Which Multiplied	*Prefix*	*Symbol*
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^{-2}	centi[a]	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

[a] Avoided when possible.

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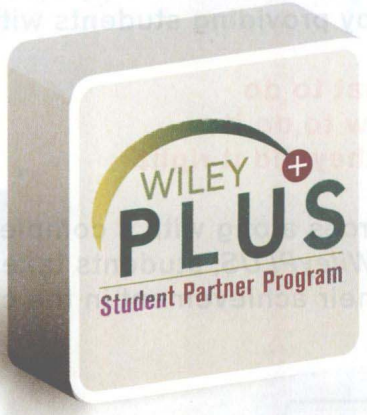
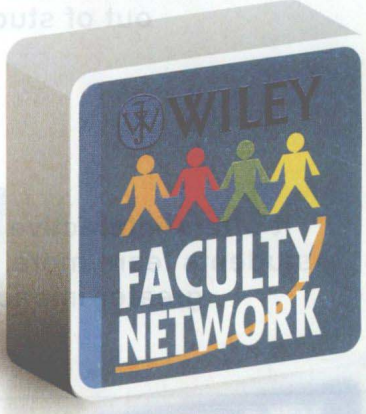


Student support from an experienced student user



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Dedicated to the memory of
J.Gerald Byrne, 1930-2010
Renowned metallurgist, noble gentleman, and passionate skier

Preface

In this fourth edition we have retained the objectives and approaches for teaching materials science and engineering that were presented in previous editions. **The first, and primary, objective** is to present the basic fundamentals on a level appropriate for university/college students who have completed their freshmen calculus, chemistry, and physics courses. To achieve this goal, we have endeavored to use terminology that is familiar to the student who is encountering the discipline of materials science and engineering for the first time, and also to define and explain all unfamiliar terms.

The **second objective** is to present the subject matter in a logical order, from the simple to the more complex. Each chapter builds on the content of previous ones.

The third objective, or philosophy, that we strive to maintain throughout the text is that if a topic or concept is worth treating, then it is worth treating in sufficient detail and to the extent that students have the opportunity to fully understand it without having to consult other sources; in addition, in most cases, some practical relevance is provided. Discussions are intended to be clear and concise and to begin at appropriate levels of understanding.

The fourth objective is to include features in the book that will expedite the learning process. These learning aids include the following:

- Numerous illustrations, in full color, and photographs to help visualize what is being presented
- Learning objectives, to focus student attention on what they should be getting from each chapter
- "Why Study ..." and "Materials of Importance" items that provide relevance to topic discussions
- "Concept Check" questions that test whether a student understands the subject matter on a conceptual level
- Key terms, and descriptions of key equations, highlighted in the margins for quick reference
- End-of-chapter questions and problems designed to progressively develop students' understanding of concepts and facility with skills
- Answers to selected problems, so that students can check their work
- A glossary, list of symbols, and references to facilitate understanding of the subject matter

The fifth objective is to enhance the teaching and learning process by using the newer technologies that are available to most instructors and students of engineering today.

ORGANIZATION OF THE TEXT

There are two common approaches for materials science and engineering—one that we call the "traditional" approach, and the other that most refer to as the "integrated" approach. With the integrated approach, one particular structure, characteristic, or property for all three material types is presented before moving on to the discussion of another structure/characteristic/property. This is the order of presentation in this book, which is depicted by the following schematic diagram:

Structures	Defects	Diffusion	Mechanical Properties
Metals	Metals	Metals	Metals
Ceramics	Ceramics	Ceramics	Ceramics
Polymers	Polymers	Polymers	Polymers

Some instructors prefer this organizational approach for the following reasons: (1) Students come to realize and appreciate differences in the characteristics and properties of the various material types, and (2) when considering properties and processing, all material types should be included.

With the traditional approach, structures/characteristics/properties of metals are presented first, followed by analogous discussions for ceramic materials and polymers. Our book, *Materials Science and Engineering SI Version, Eighth Edition,* is organized in this manner.

NEW TO THIS EDITION

New/Revised Content

Several important changes have been made with this fourth edition. One of the most significant is the incorporation of several new sections, as well as revisions/amplifications of other sections. New sections/discussions are as follows:

- Diffusion in semiconducting materials (Section 6.6).
- Flash memory (in Section 12.15).
- "Biodegradable and Biorenewable Polymers/Plastics" Materials of Importance piece in Chapter 20.
- Fundamentals of Engineering homework problems and questions for most chapters. These appear at the end of Questions and Problems sections and provide students the opportunity to practice answering and solving questions and problems similar to those found on Fundamentals of Engineering examinations.
- Math Skills Review in *WileyPLUS*. Instructors have told us that it is not always the materials science concepts with which students have difficulty, but rather remembering and applying in the materials science context the math skills learned in their prerequisite courses. The Math Skills Review in *WileyPLUS* provides remediation resources, including:
  - Reading content
  - Office Hours videos—video discussions of key concepts and topics related to math
  - Practice interactives
  - Question assignments

Sections that have been revised/amplified include the following:

- There is an expanded discussion on nanomaterials (Section 1.5).
- There is a more comprehensive discussion on the construction of crystallographic directions in hexagonal unit cells, and also of conversion from the three-index scheme to the four-index scheme (Section 3.13).

- Discussions on toughness (Section 7.6) and fracture toughness testing (Section 9.8) have been revised.
- There is a revised and enlarged treatment of hardness and hardness testing of ceramics (Section 7.17).
- There is an expanded discussion on titanium alloys (Section 13.3).
- In Chapter 15, the "Nanocomposites in Tennis Balls" Materials of Importance piece is updated and is now "Nanocomposite Barrier Coatings."
- There are updates on magnetic storage (hard disk drives and magnetic tapes; Section 18.11).
- There are updates and revisions in Chapter 20 (Economic, Environmental, and Societal Issues in Materials Science and Engineering), especially on recycling.
- End-of-Chapter summaries have been revised to reflect answers and responses to the extended lists of learning objectives, to better serve students as a study guide.
- There is a Summary Table of Important Equations at the end of each chapter.
- There is a Summary List of Symbols at the end of each chapter.
- There are new chapter-opener photos and layouts, focusing on applications of materials science to help engage students and motivate a desire to learn more about materials science.
- Virtually all homework problems requiring computations have been refreshed.

Processing/Structure/Properties/Performance Correlations

One new feature that has been incorporated throughout this edition is a tracking of relationships among the processing, structure, properties, and performance components for four different materials: steel alloys, glass-ceramics, polymer fibers, and silicon semiconductors. This concept is outlined in Chapter 1 (Section 1.7), which includes the presentation of a "topic timeline." This timeline notes locations (by chapter) where discussions involving the processing, structure, properties, and performance of each of these four material types are found.

Summaries with concept maps are also included at the ends of those chapters where some aspect of processing, structure, properties, and/or performance for at least one of the materials is discussed.

Materials of Importance

In Materials of Importance sections we discuss familiar and interesting materials and materials applications. These pieces lend some relevance to topical coverage and are given in most chapters in the book. They include the following:

- Carbonated Beverage Containers (Chapter 1)
- Water (Its Volume Expansion upon Freezing) (Chapter 2)
- Carbon Nanotubes (Chapter 3)
- Tin (Its Allotropic Transformation) (Chapter 3)
- Catalysts (and Surface Defects) (Chapter 5)
- Aluminum for Integrated Circuit Interconnects (Chapter 6)
- Shrink-Wrap Polymer Films (Chapter 8)
- Lead-Free Solders (Chapter 10)
- Shape-Memory Alloys (Chapter 11)
- Aluminum Electrical Wires (Chapter 12)
- Metal Alloys Used for Euro Coins (Chapter 13)

- Piezoelectric Ceramics (Chapter 13)
- Phenolic Billiard Balls (Chapter 13)
- Nanocomposite Barrier Coatings (Chapter 15)
- Invar and Other Low-Expansion Alloys (Chapter 17)
- An Iron–Silicon Alloy That Is Used in Transformer Cores (Chapter 18)
- Light-Emitting Diodes (Chapter 19)
- Biodegradable and Biorenewable Polymers/Plastics (Chapter 20)

Discipline-Specific Module—Mechanical Engineering

A discipline-specific module appears on the book's website (Student Companion Site; *http://www.wiley.com/college/callister*). This module treats materials science/engineering topics not covered in the printed text that are relevant to mechanical engineering.

All Homework Problems Now in Print

Approximately one-half of the end-of-chapter homework problems and questions in the previous edition were in electronic format only (i.e., appeared only on the book's website). In this edition, *all homework problems and questions are in the printed version.*

Case Studies

A collection of case studies appeared in prior editions, which are now posted as a library on the book's website (Student Companion Site). Case studies found in this library includes the following:

- Materials Selection for a Torsionally Stressed Cylindrical Shaft
- Automobile Valve Spring
- Failure of an Automobile Rear Axle
- Artificial Total Hip Replacement
- Chemical Protective Clothing

STUDENT LEARNING RESOURCES (http://www.wiley.com/college/callister)

Also found on the book's website (under Student Companion Site) are several important instructional elements for the student that complement the text; these include the following:

1. VMSE: Virtual Materials Science and Engineering. This is an expanded version of the software program that accompanied the previous edition. It consists of the following.

Interactive simulations and animations that enhance the learning of key concepts in materials science and engineering. For example, students can view and manipulate molecules in a three dimensional–like environment to visualize and achieve better understanding of molecular structures, and much more! Screenshots (similar to those

VMSE screenshots showing three different views of the unit cell for the diamond cubic crystal structure. Each of these may be drag-rotated so as provide a better understanding of this crystal structure.

shown on the previous page) have been added in the margin to give a preview of what the reader will be able to see and manipulate in VMSE.

A materials properties/cost database. This database has been designed to facilitate materials selection decisions that are based on material properties and costs. The database contains data, in spreadsheet form, for 177 different materials, virtually the same set of materials that appear in Appendices B and C of the textbook.

Throughout the book, whenever there is some text or a problem that is supplemented by VMSE, a small icon that denotes the associated module is included in one of the margins (some of which are accompanied by VMSE screenshots). These modules and their corresponding icons are as follows:

Metallic Crystal Structures and Crystallography		Phase Diagrams	
Ceramic Crystal Structures		Diffusion	
Repeat Unit and Polymer Structures		Tensile Tests	
Dislocations		Solid-Solution Strengthening	

Students can access VMSE via the book's website at *http://www.wiley.com/college/callister*.

2. *Answers to Concept Check questions.* Students can visit the website to find the correct answers to the Concept Check questions.

3. *Extended learning objectives.* This is a more extensive list of learning objectives than is provided at the beginning of each chapter. These direct the student to study the subject material to a greater depth.

4. *Direct access to online self-assessment exercises.* This is a Web-based assessment program that contains questions and problems similar to those found in the text; these problems and questions are organized and labeled according to textbook sections. An answer or solution that is entered by the user in response to a question or problem is graded immediately, and comments are offered for incorrect responses. The student may use this electronic resource to review course material and to assess his or her mastery and understanding of topics covered in the text.

5. *Index of learning styles.* Upon answering a 44-item questionnaire, a user's learning-style preference (i.e., the manner in which information is assimilated and processed) is assessed.

6. *Student lecture slides.* These PowerPoint® slides are virtually identical to the lecture slides provided to an instructor for use in the classroom. The student set has been designed to allow for note-taking on printouts.

7. *Discipline-Specific Module—Mechanical Engineering.* This was described previously.

INSTRUCTORS' RESOURCES

The Instructor Companion Site (*http://www.wiley.com/college/callister*) is available for instructors who have adopted this text. Please visit the website to register for access. Resources that are available include the following:

1. *Instructor Solutions Manual.* Detailed solutions of all end-of-chapter questions and problems (in both Word® and Adobe Acrobat® PDF formats).

2. *Photographs, illustrations, and tables that appear in the book (i.e., an image gallery and art PowerPoint slides).* These are in both PPT and JPEG formats so that an instructor can print them for handouts or prepare slides or transparencies in his or her desired format.

3. *A set of PowerPoint lecture slides.* These slides, developed by Peter M. Anderson (Ohio State University) and adapted by the authors, follow the flow of topics in the text and include materials from the text and from other sources. Instructors may use the slides as is or edit them to fit their teaching needs.

4. *A list of classroom demonstrations and laboratory experiments.* These portray phenomena and/or illustrate principles that are discussed in the book; references are also provided that give more detailed accounts of these demonstrations.

5. *Student learning resources.* In addition, all of the student learning resources described earlier are available on the Instructor Companion Site.

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WileyPLUS is an innovative, research-based online environment for effective teaching and learning.

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