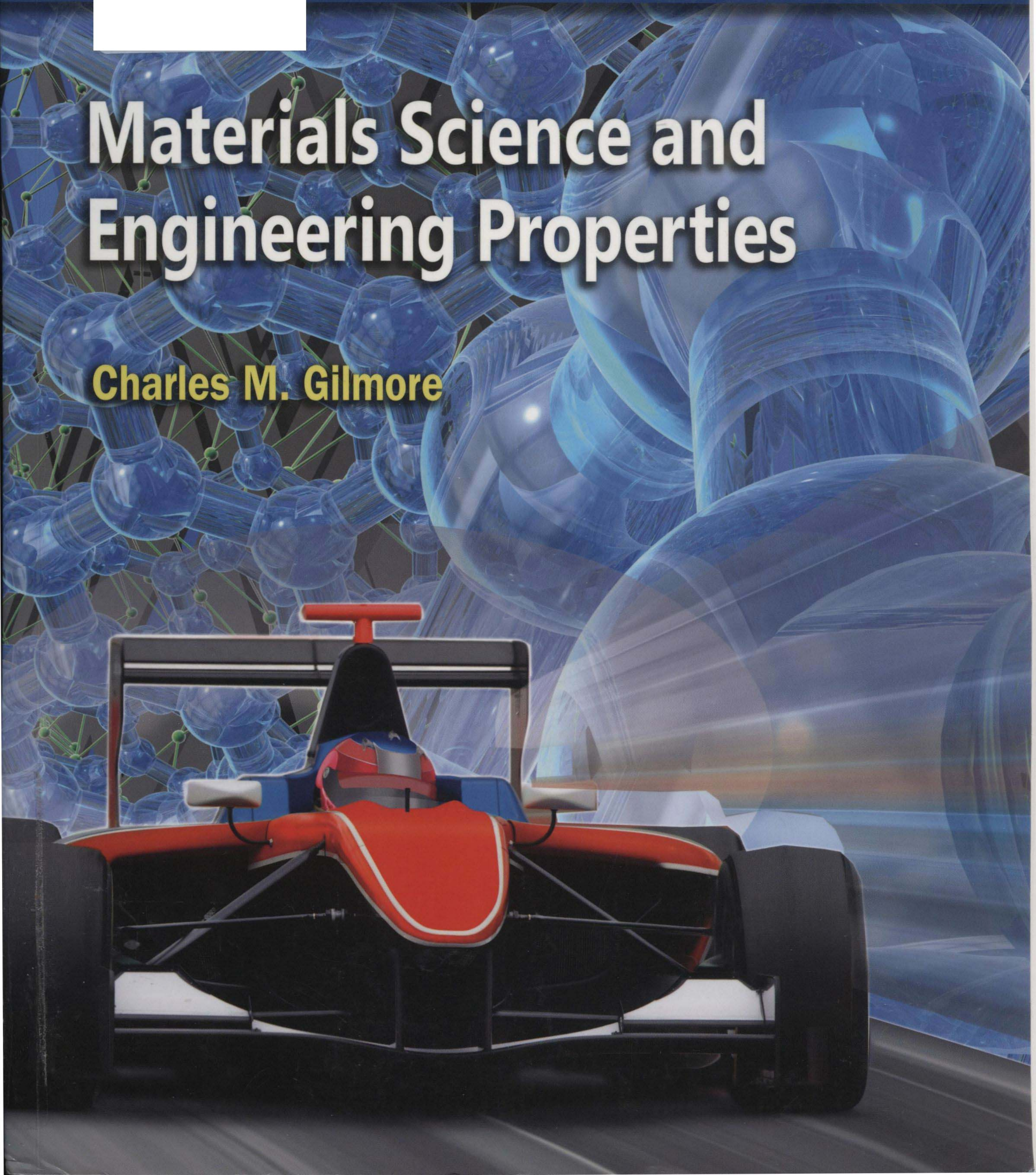
SI EDITION

Materials Science and Engineering Properties

Charles M. Gilmore



Materials Science and Engineering Properties

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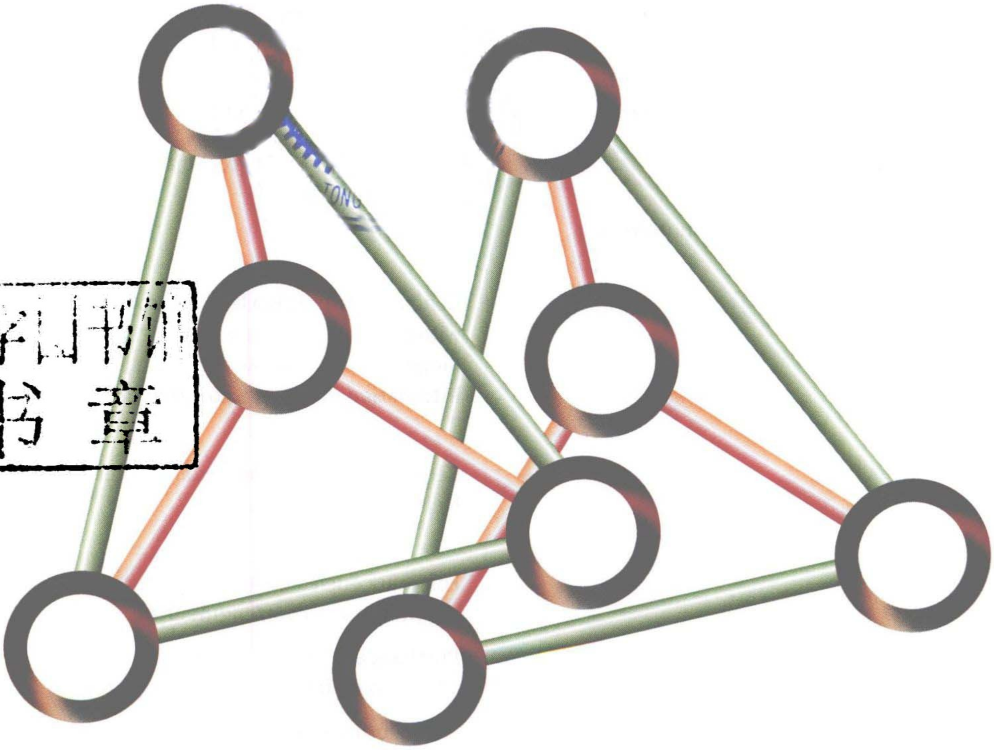
Charles M. Gilmore

George Washington University



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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					
circular mil	cmil	0.0005067	0.0005	square millimeter	mm^2
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-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

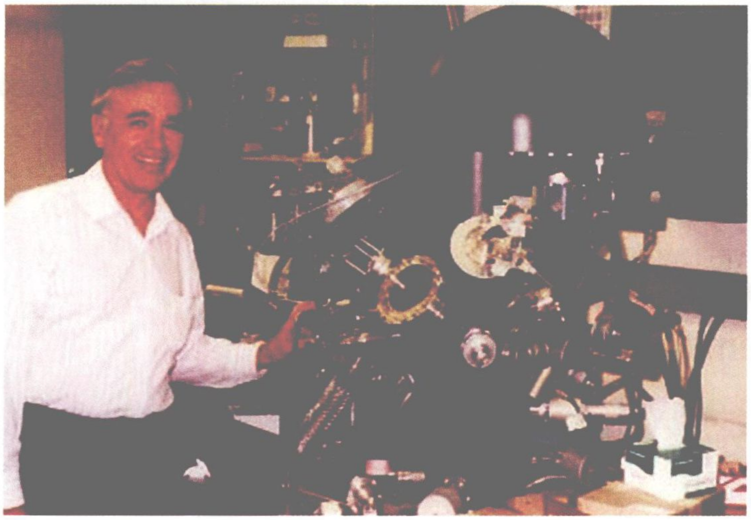
$$T(^\circ\mathrm{C}) = \frac{5}{9}[T(^\circ\mathrm{F}) - 32] = T(\mathrm{K}) - 273.15$$

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

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

This book is dedicated to the important women in my life: To my wife Charlotte and to the memory of my mother Ruth.

ABOUT THE AUTHOR



Charles M. Gilmore is Emeritus Professor of Engineering and Applied Science at the George Washington University. He obtained his B.S. and M.S. degrees in Engineering Mechanics at the Pennsylvania State University and his Ph.D. in Engineering Materials from the University of Maryland. He was employed by the Department of the Navy and the U.S. Naval Research Lab from 1963 to 1971. In 1971 he joined George Washington as an assistant professor. In addition to the position of professor, he was Chairman of the Department of Civil, Mechanical, and Environmental Engineering. In the School of Engineering and Applied Science he served as Associate Dean for Research and as Acting Dean. He developed the graduate program in materials science within the department and was responsible for the undergraduate courses in materials science and materials engineering. Dr. Gilmore was selected as an outstanding teacher by the ASCE student chapter. He is a member of the Sigma Tau and Tau Beta Pi honorary engineering fraternities, where he was an advisor for the George Washington chapter of Tau Beta Pi. He served as co-director of the George Washington University Institute for Materials Science along with Professor David Ramaker of the Department of Chemistry. Dr. Gilmore's research resulted in over 50 refereed publications on molecular dynamics simulation and experiments on the growth of thin films, fatigue and fracture of metals, and x-ray crystallography. Awards for his research include the George Kimball Burgess Award from the American Society for Metals Washington D.C. chapter and an Outstanding Paper award from the Materials Science and Technology Division of the Naval Research Lab. He served as an officer of the Washington D.C. chapter of the American Society for Metals and was the chapter chairman in 1984-1985.

PREFACE

Purpose

The purpose of this textbook is to provide students and instructors with a materials science and engineering properties textbook with sufficient scientific basis that engineering properties of materials can be understood by students. For example, without an understanding of enthalpy, entropy, and Gibbs free energy students are not be able to understand why there are so many different metal microstructures, why water and alcohol mix, but water and gasoline do not mix, and why there are so many different types of phase diagrams. Internal energy, enthalpy, entropy, and Gibbs free energy are carefully developed so that a student without a course in thermodynamics can understand the discussion. However, it is recommended that students have completed an undergraduate course in university physics. The book discusses entropy as possible arrangements of atoms and molecules. In this way students can visualize entropy. The visualization of entropy as possible arrangements of atoms or molecules should help students understand entropy when it is used in thermodynamics courses to explain why heat engines are not 100% efficient. Energy is used as a unifying theme throughout the book to explain engineering properties such as melting temperature, thermal expansion, diffusivity, fracture, corrosion, and creep. The energy of electrons and holes, the Fermi energy, and energy level diagrams are used to explain the conductivity of materials and the operation of electronic and photonic devices such as diodes, lasers, solar cells, and light emitting diodes.

Organization

The textbook uses an integrated approach to treating the engineering properties of ceramics, metals, and polymers. The science of most engineering properties is the same for ceramics, metals, and polymers. For example, the equation for the entropy of mixing metal atoms is similar to the entropy equation for the mixing of polymer long chain molecules. Therefore, the mixing of metal atoms is covered in the same chapter as the mixing of polymers. The equations for the fracture of ceramics, metals, and polymers are all the same. Therefore, fracture of ceramics, metals and polymers is treated in the same chapter, and the differences in resistance to fracture are explained by the differences in chemical bonding. The change in the energy bands of both *pn*-junctions and a metal-polymer-metal junctions resulting from an applied voltage allows students to understand the operation of diodes and solar cells made from these different materials. Therefore, the electrical properties of metals, ceramics, and polymers are covered in the same chapter. If students understand the science behind the engineering properties and the differences in bonding between ceramics, metals, and polymers they can understand why these different materials have different engineering properties.

Textbook

The textbook focuses on materials science and applications to mechanical properties. Students and instructors interested in the mechanical properties of materials are also those most likely to be interested in a treatment of materials science that includes entropy and Gibbs free energy.

The introductory Chapter 1 presents a brief history of the development of materials and of the science necessary for the understanding of materials, the classes of materials, and an introduction to the experimental techniques available to analyze materials. Chapter 1 also presents several interesting case studies of materials applications, such as the use of shape memory alloys for coronary stents. Chapters 2 to 5 cover materials science subjects necessary for the understanding of the structure, microstructure, and engineering properties of materials. Chapters 6 to 14 cover mechanical properties of materials, how to make strong solids, mechanical properties of engineering materials, the effects of temperature and time on mechanical properties, electrochemical effects on materials including corrosion, electroprocessing, batteries, and fuel cells, fracture and fatigue, composite materials, material processing, and material selection for mechanical design. Chapter 15 is a more advanced treatment of experimental methods than is presented in the introduction.

Supplementary Web Content

Chapters 16, 17, and 18 on electrical, magnetic, and photonic properties of materials, respectively, are posted on the accompanying website. These chapters present more advanced coverage of these topics than is presently available in other materials science and engineering textbooks. There are also chapter appendices on the website that contain the derivations of equations and advanced subjects related to the textbook.

Chapter Organization

Each chapter begins with a photograph and description intended to arouse interest in the subject matter of the chapter. A list of goals tells the student and instructor what is to be accomplished. An introductory section describes why the subjects in this chapter are important and presents background and historical information. Scientific background necessary to understand the chapter is covered first followed by the discussion of engineering properties and applications. Example problems are included throughout the chapter. Figures and graphs are extensively included to provide students with a visual impression of the subjects. A summary covers the main points presented. There is a list of authors for supplemental reading, and a complete list of references in the back of the book.

Chapter Problems

Each chapter provides homework questions to test the student's grasp of the concepts in the chapter. Multiple choice questions are patterned after those in the Engineer in Training exam. An additional set of problems allows for analysis of concepts in the chapter. Design problems and questions are included where appropriate.

Audience and Prerequisites

The textbook is appropriate for a 3 credit course in materials science and engineering for sophomore or junior students in engineering or applied science with an emphasis on mechanical properties. The text with appendices of advanced subject material and chapters on electrical, magnetic, and photonic properties of materials is appropriate for more advanced study such as honors courses, higher credit courses, or an introductory graduate course for students that did not have an undergraduate course in materials science. It is assumed that students have completed university level chemistry and physics that includes chemical bonding, an introduction to quantum mechanics and quantum numbers, and an introduction to thermodynamics. These subjects are covered in sufficient detail in the text that a student can learn these subjects in this course, but it is recommended that students cover these subjects in prerequisite courses. A course in differential and integral calculus is essential.

Supplements for Students and Instructors

The website includes derivations of equations, additional advanced subject matter, and additional chapters on electrical, magnetic, and photonic properties of materials. The website also provides links to videos produced by the National Science Foundation and other organizations on subjects such as careers in materials science and engineering, the discovery of new materials, and the processing of materials to produce unique products.

Supplements for Instructors

In addition, the instructor's website provides a Solutions Manual with the answers to all questions and complete solutions to all problems, PowerPoint slides of all figures, and PowerPoint lecture slides.

MindTap Online Reader and Course

In addition to the print version, this textbook is also available online through MindTap, a personalized learning program. Students who purchase the MindTap version will have access to the book's MindTap Reader and will be able to complete homework and assessment material online, through their desktop, laptop, or iPad. If your class is using a Learning Management System (such as Blackboard, Moodle, or Angel) for tracking course content, assignments, and grading, you can seamlessly access the MindTap suite of content and assessments for this course.

In MindTap, instructors can:

- Personalize the Learning Path to match the course syllabus by rearranging content, hiding sections, or appending original material to the textbook content
- Connect a Learning Management System portal to the online course and Reader
- Customize online assessments and assignments
- Track student progress and comprehension with the Progress app
- Promote student engagement through interactivity and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes and highlight content for easy reference, and check their understanding of the material.

Acknowledgments

Writing this textbook is the most significant accomplishment of my career as an engineer and teacher. The textbook would not have been possible without the contributions of many people. For as long as I can remember I planned to be an engineer because my grandfather Walter Brown and my father Charles E.M. Gilmore were both engineers, and my mother Ruth E. Brown Gilmore constantly encouraged my engineering studies. The textbook started as handout supplements to an assigned course textbook, because none of the textbooks available had the treatment I desired. Over many years the supplements evolved into chapters and finally into a draft textbook. I thank many years of engineering students at George Washington University for enduring the evolution of this textbook, for finding errors, criticizing confusing discussions and organization, and for suggesting alterations. During the development of the textbook many faculty at George Washington University reviewed chapters and made improvements including Professors David Ramaker, Douglas Jones, Martha Pardavi-Horvath, Mark Reeves, and Can Korman. I also thank the following for reviewing chapters or sections and making improvements: my former doctoral students Dr. M. Ashraf Imam and Dr. Wontae Chang, who are both now at the U.S. Naval Research Lab, Dr. Peter Matic of the U.S Naval Research Lab and Adjunct Professor at GWU, Dr. Catherine Cottell Adjunct Professor at GWU, and Ronald Reese, who is Emeritus Professor of Physics at Washington and Lee University. Ron Reese is the author of "University Physics" published by Cengage Learning. Whenever I have a question about physics I know I will get the correct answer from Ron's textbook. Ron and his wife Edith have been friends ever since we took a white water canoe course together nearly fifty years ago. Despite the best efforts of these friends and colleagues, any errors that remain are my responsibility. I thank Harold Adams, Fellow AIA, for assisting me with chapter and cover design and colors. I thank Mark Wagner, supervising engineering lab technician for the Department of Mechanical and Aerospace Engineering at George Washington, for helping me with experiments and photos for the text.

Independent outside reviewers contributed greatly to the evolution of the textbook. I thank the following reviewers for taking time out of their busy schedules to carefully review the book and to provide constructive comments.

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Finally I thank Charlotte, my wife of 50 years, for enduring the many years of my sitting at my computer composing this book when we could have been on a cruise to an exotic sea. We will take that cruise once the book is published.

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