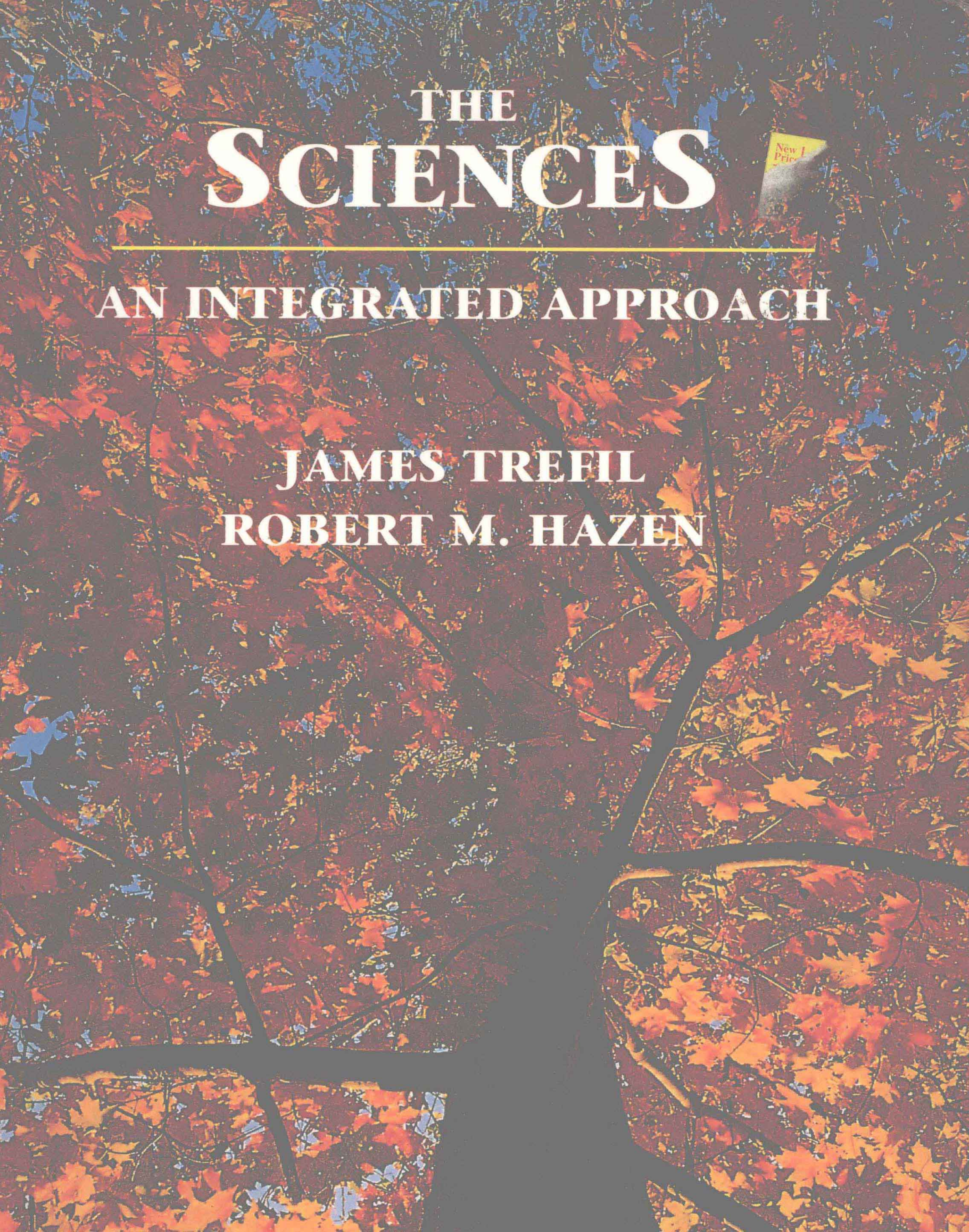
THE SCIENCES

AN INTEGRATED APPROACH

JAMES TREFIL
ROBERT M. HAZEN



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John Wiley & Sons, Inc.

New York • Chichester • Brisbane • Toronto • Singapore

ACQUISITIONS EDITOR Kaye Pace
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MARKETING MANAGER Catherine Faduska
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DESIGN A Good Thing, Inc.
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This book was set in Stone Serif by Bi-Comp, Inc. and printed and bound by Von Hoffmann Press, Inc.

Recognizing the importance of preserving what has been written, it is a policy of John Wiley & Sons, Inc. to have books of enduring value published in the United States printed on acid-free paper, and we exert our best efforts to that end.

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Library of Congress Cataloging in Publication Data:
Trefil, James S., 1938—
The sciences : an integrated approach / James Trefil and Robert M. Hazen.
p. cm.
Includes bibliographical references (p.).
ISBN 0-471-58931-4 (pbk. : alk. paper)
1. Science. 2. Science—Study and teaching(Higher)—United States. I. Hazen, Robert M., 1948– . II. Title.
Q161.2.T74 1995
500—dc20 94-36672
CIP

Printed in the United States of America

10 9 8 7 6 5

The Sciences

Preface

Pick up a newspaper any day of the week and you will find a dozen articles that relate to science and technology. There are always stories on the weather, energy, the environment, medical advances—the list goes on and on. Is the average American college graduate prepared to understand the scientific component of these issues? In most cases the answer is no.

A week prior to graduation at a major U.S. university, 25 seniors, selected at random, were asked a simple question: "What is the difference between an atom and a molecule?" Only one-third of the students could answer the question correctly. Even allowing for the festive mood of the graduates (all of whom had a full year of laboratory science), this result does not instill confidence in our ability to produce students who are in command of rudimentary facts about their physical universe. There can be little doubt that we are faced with a generation of students who complete their education without learning even the most basic concepts about science. They lack the critical knowledge to make informed decisions regarding environmental issues, resource management, and medical advances.

Science Education Today

We have written this book to address two problems that pervade the organization and presentation of science at U.S. colleges and universities. First, many introductory science courses are geared toward science majors. Specialization is vital for these students—typically a small percent of all college students—who must learn an appropriate vocabulary and develop skills in experimental method and mathematical manipulations to solve problems. Unfortunately, few of these science majors ever gain a broad overview of the sciences, nor do they understand how their chosen specialty fits into the larger scheme of science and society. A physics major may never learn about the modern revolution in genetics and the biology major is unlikely to appreciate the nature and importance of semiconductors in our technological society.

Specialization, however, is not well suited for the majority of students—the nonscience majors, for whom experimental technique and mathematical rigor often divorce science from its familiar day-to-day context. Introductory science courses designed for science majors fail to foster scientific understanding among the nonscience majors. Without a broad context, many students neither understand the distinctive process of science, nor do they retain the abstract content of what they have been taught. Ultimately, this needlessly narrow approach to science education alienates most nonmajors, who graduate with the perception that science is difficult, boring, and irrelevant to their everyday interests.

The second problem with most introductory science courses at the college level, even among those science courses specifically designed for nonscientists, is that they rarely integrate physics, astronomy, chemistry, Earth science, and biology. Such departmentally based courses cannot produce graduates who are broadly literate in science. The students who take introductory geology learn nothing about lasers or nuclear reactions, while those who take "Physics for Poets" remain uninformed about the underlying causes of earthquakes and volcanoes. And neither physics nor geology classes touch on such vital modern fields as genetics, environmental chemistry, space exploration, or materials science. Therefore, students must take courses in at least four departments to gain a basic overview of the sciences.

Perhaps most disturbing, few students—science majors or nonmajors—ever learn how the often arbitrary divisions of specialized knowledge fit into the overall

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sweep of the sciences. In short, traditional science curricula of most colleges and universities fail to provide the basic science education that is necessary to understand the many scientific and technological issues facing our society.

This first edition of *The Sciences: An Integrated Approach* is the culmination of a collective effort of dozens of faculty and thousands of students who used a preliminary edition during the 1993–1994 academic year. The content and scope of this book was shaped by their numerous constructive comments and suggestions—an integrated effort that is reflected throughout the text.

The Need for a New Science Education

The central goal of science education must be to give every student the ability to place important public issues such as the environment, energy, and medical advances in a scientific context. Students should understand the scientific process, be familiar with the role of experiments in probing nature, and recognize the importance of mathematics in describing its behavior. They should be able to read and appreciate popular accounts of major discoveries in physics, astronomy, chemistry, geology, and biology, as well as advances in medicine, information technology, and new materials. And, most important, they should understand that a few universal laws describe the beavhior of our physical surroundings—laws that operate every day, in every action of our lives. Achieving this kind of scientific proficiency requires a curriculum quite different from the traditional, departmentally based requirements for majors.

Most societal issues concerning science and technology draw on a broad range of knowledge. For example, to understand the debate over nuclear waste disposal, one needs to know how nuclei decay to produce radiation (physics), how radioactive atoms interact with their environment (chemistry), how radioactive elements from waste can enter the biosphere (Earth science), and how the radiation will affect living things (biology). These scientific aspects must be weighed with other societal issues—economics, energy demand, perceptions of risk, and demographics, for example. Other public issues, such as global warming, space research, alternative energy sources, and AIDS prevention also depend on a spectrum of scientific concepts, as well as other social concerns.

Many recent studies recognize the urgent need for reform in science education and advocate an interdisciplinary approach. For example, reports by the American Association for the Advancement of Science (*Science for All Americans—Project 2061,* Washington, 1989; *The Liberal Art of Science,* Washington, 1990), by the National Research Council (*National Science Education Standards,* Washington, 1994), and by the White House (*Science in the National Interest,* Washington, 1994), which all document this need. However, appropriate interdisciplinary courses are not yet widely taught nor have any appropriate textbooks or other support materials been available. This text, based on a course "Great Ideas in Science," which has been developed over the past seven years at George Mason University, is an attempt to fill those gaps. Our approach recognizes that science forms a seamless web of knowledge about the universe. Our integrated course encompasses physics, chemistry, astronomy, Earth sciences, and biology, and emphasizes general principles and their application to real-world situations rather than esoteric detail.

Many ways exist to achieve this synthesis, but any general treatment should take advantage of the fact that virtually everything in science is based on a few simple overarching principles. Newton's laws, the atomic model, natural selection, and the genetic code would make every scientist's list of these "great ideas." By returning to general science courses for all students, we have the means to achieve our goal—to produce college graduates who appreciate that scientific understanding is one of the crowning achievements of the human mind, that the universe is a place of magnificent order, and that science provides the most powerful means to discover knowledge that can help us understand and shape our world.

The Organization of This Book

This text adopts a distinctive and innovative approach to science education, based on the principle that general science courses are a key to a balanced and effective college-level science education for nonmajors and a broadening experience for science majors. We organize the text around a series of 25 scientific concepts. The most basic principle, the starting point of all science, is the idea that the universe can be studied by observation and experiment (Chapter 1). A surprising number of students—even science majors—have no clear idea how this central concept sets science apart from religion, philosophy, and the arts as a way to understand our place in the cosmos.

Once students understand the nature of science and its practice, they can appreciate some of the basic principles shared by all sciences: Newton's laws governing force and motion (Chapter 2); the laws of thermodynamics that govern energy and entropy (Chapters 3 and 4); the equivalence of electricity and magnetism (Chapters 5 and 6); and the atomic structure of all matter (Chapters 7–10). These concepts apply to everyday life, explaining, for example, the compelling reasons for wearing seat belts, the circulation of the blood, the dynamics of a pot of soup, the regulation of public airwaves, and the rationale for dieting. In one form or another, all of these ideas appear in virtually every elementary science textbook, but often in abstract form. As educators we must strive to make them part of every student's day-to-day experience.

Having established these general principles, we go on to examine specific natural systems such as atoms, the Earth, or living things. The realm of the nucleus (Chapter 11) and subatomic particles (Chapter 12), for example, must follow the basic rules governing all matter and energy. An optional chapter on the theory of relativity (Chapter 13) examines the consequences of a universe in which all observers discern the same laws of nature.

Plate tectonics and the cycles of rocks, water, and the atmosphere unify the Earth sciences (Chapters 14–16). The laws of thermodynamics, which decree that no feature on the Earth's surface is permanent, can be used to explain geologic time, gradualism, and the causes of earthquakes and volcanoes. The fact that matter is composed of atoms tells us that individual atoms in the Earth system—for example, in a grain of sand, a gold ring, or a student's most recent breath—have been recycling for billions of years.

In sections on astronomy and cosmology (Chapters 17 and 18) students learn that stars and planets form and move as predicted by Newton's laws, that stars eventually burn up according to the laws of thermodynamics, that nuclear reactions fuel stars by the conversion of mass into energy, and that stars produce light as a consequence of electromagnetism.

Living things (Chapters 19–25) are arguably the most complex systems that scientists attempt to understand. We identify seven basic principles that apply to all living systems: all living things obey the laws of chemistry and physics; all living things incorporate a few simple molecular building blocks; all living things are made of cells; all living things use the same genetic code; all living things evolved by natural selection; living things use many strategies to maintain and reproduce life; and interdependent collections of living things (ecosystems) recycle matter while energy flows through them.

The text has been designed so that four chapters—quantum mechanics (8), particle physics (12), relativity (13), and cosmology (18)—may be skipped without loss of continuity.

Special Features

In an effort to aid student learning and underscore the interconnections among the sciences, we have attempted to relate scientific principles to each student's everyday life. To this end, we have incorporated several distinctive features throughout the book:

Great Ideas. Each chapter begins with a statement of a great unifying idea or theme in science, so that students immediately grasp the chief concept of that chapter. These statements are not intended to be recited or memorized, but rather to provide a framework for placing everyday experience in a broad context.

Random Walks. Each chapter also begins with "A Random Walk," in which we tie the chapter's main theme to common experiences, such as eating, driving a car, or suntanning. These "Random Walks" grew out of our idea of the perfect class: during every class period, we would meet outdoors and walk until we saw something that would illustrate that day's topic.

The Human Body. To help show the interdisciplinary nature of the many concepts we introduce, we have included sections on human physiology and medical advances in most chapters. These sections, for example, relate the anatomy of the eye to electromagnetic radiation, the operation of the central nervous system to electrical conductivity, and the processes of aging to the second law of thermodynamics. In each case we underscore how scientific principles relate immediately to our physical well-being.

Technology. The application of scientific ideas to commerce, industry, and other modern technological concerns is perhaps the most immediate way students encounter science. In most chapters we include examples of these technologies, such as petroleum refining, microwave ovens, and nuclear medicine.

Science in the Making. These historical episodes trace the process of scientific discovery as well as portray the lives of central figures in science. In these episodes we have tried to illustrate the scientific method, examine the interplay of science and society, and reveal the role of serendipity in scientific discovery.

Thinking More about. Each chapter ends with a section that addresses a social or philosophical issue tied to science, such as federal funding of science, nuclear waste disposal, the human genome project, and priorities in medical research.

Mathematical Equations and Worked Examples. Unlike the content of many science texts, formulae and mathematical derivations play a subsidiary role in our treatment. We rely much more on real-world experience and everyday vocabulary. We believe, however, that every student should understand the role of mathematics in science. Therefore, we have included a few key equations and appropriate worked examples in many chapters. Whenever an equation is introduced, it is presented in three steps: first as an English sentence, then as a word equation, and finally in its traditional symbolic form. In this way, students can focus on the meaning rather than on the abstraction of the mathematics. We also include an appendix on English and SI units.

Science by the Numbers. We also think that students should understand the importance of simple mathematical calculations in making estimates and determining orders of magnitude. Thus we have incorporated many nontraditional calculations of this kind—for example—how much solid waste is generated in the United States, how long it would take to erode a mountain, and how many people were required to build Stonehenge.

Key Words. We believe that most science texts suffer from too much complex vocabulary, and we have avoided any unnecessary jargon. Nevertheless, the scientifically literate student must be familiar with many words and concepts that appear regularly in newspaper articles or other material for general readers. In each chapter a number of these words appear in **boldface** type, and they are summarized at the end of the chapters. For example, in Chapter 11 on nuclear physics, key words include proton, neutron, isotope, radioactivity, half life, radiometric dating, fission, fusion, and nuclear reactor—all terms likely to appear in the newspaper.

Many other scientific terms are important, although more specialized; we have highlighted these terms in *italics*. We strongly recommend that students be expected to know the meaning and context of key words but not be expected to memorize these italicized words. We encourage all adopters of this text to provide their own lists of key words and other terms—both ones we have omitted and ones they would eliminate from our list.

Questions. We feature four levels of end-of-chapter questions. "Review Questions" test the most important factual information covered in the text. "Discussion Questions" are also based on material in the text, but they examine student comprehension, and they explore applications and analysis of the scientific concepts. "Problems" are quantitative questions that require students to use mathematical operations. Finally, "Investigations" require additional research outside the classroom. Each instructor should decide which levels of questions are most appropriate for his or her students. We welcome suggestions for additional questions, which will be added to the next edition of this text.

Illustrations. Students come to any science class with years of experience dealing with the physical universe. Everyday life provides an invaluable science laboratory—the physics of sports, the chemistry of cooking, and the biology of being alive. This book has thus been extensively illustrated with familiar color images in an effort to amplify the key ideas and principles. All diagrams and graphs have been designed for maximum clarity and impact.

Supplements

The supplements that accompany the first edition of *The Sciences: An Integrated Approach* assist both the instructor and the student.

The *Instructor's Manual* was prepared by Gail Steehler and Karen Adkisson, both of Roanoke College. The manual contains teaching suggestions, lecture notes, answers to problems in text, practice questions and problems, a list of supplemental readings and films, as well as ideas for beginning and ending lectures. In addition, "Connecting Back" and "Connecting Ahead" sections give instructors suggestions on how to connect the material from different chapters.

The *Test Bank,* prepared by Cynthia Roubie of George Mason University, contains approximately 1250 multiple choice, true/false, and short-answer conceptual questions, as well as essay questions for each chapter.

The *Laboratory Manual,* prepared by Victor Stanionis and the Iona College Science Faculty, contains laboratory experiments that have been written and class-tested at Iona College as well as a few that have been contributed from instructors at other schools.

Acknowledgments

The development of this text has benefited immensely from the help and advice of numerous people. Students in our "Great Ideas in Science" course at George Mason University have played a central role in designing this text. Approximately 1100 students, the majority of whom were nonscience majors, have enrolled in the course over the past seven years. They represent a diverse cross section of American students: more than half were women, while many minority, foreign-born, and adult learners were enrolled. Their candid assessments of course content and objectives as well as their constructive suggestions for improvements have helped to shape our text.

We are also grateful to members of the Core Science Course Committee at George Mason University, including Richard Diecchio (Earth Systems Science), Don Kelso and Harold Morowitz (Biology), Minos Kafatos and Jean Toth-Allen (Physics), and Suzanne Slaydon (Chemistry), who helped to design many aspects of this treatment.

We thank the many teachers across the country who are developing integrated science courses. Their letters to us and responses to our publisher's survey inspired us to write this text.

We especially thank those professors who used and class-tested the preliminary edition, sharing with us the responses of their students and their own analyses. Their classroom experience helped us shape the first edition.

Lauretta Bushar, Beaver College
Tim Champion, Johnson C. Smith University
Ben Chastain, Samford University
Marvin Goldberg, Syracuse University
James Grant and Michael Held, St. Peter's College
Jim Holler, University of Kentucky
Patricia Hughey, Lansing Community College
Joseph Ledbetter and Rick Saparano, Contra Costa College
Leigh Mazany, Dalhousie University
Donald Miller, University of Michigan at Dearborn
Lynn Narasimhan, DePaul University
Ervin Poduska, Kirkwood Community College
Gail Steehler, Roanoke College
Jim Yoder, Hesston College

We have also benefited from detailed chapter reviews by experts in physics, astronomy, chemistry, Earth science, and biology: Paul Fishbane, University of Virginia; John Graham, Carnegie Institution of Washington; Gerry Karp, formerly of the University of Florida, Gainesville; Hallie M. Krider, University of Connecticut; Larry Kodosky, Oakland Community College; Harold Morowitz, George Mason University; Bjorn Mysen, Geophysical Laboratory; Selwyn Sacks, Carnegie Institution of Washington; and John S. Thompson, Texas A&M University at Kingsville.

We gratefully acknowledge the significant contributions of the many reviewers who commented on earlier drafts of this edition. Their insights and teaching experience have been invaluable to us:

Debra J. Barnes, Contra Costa College
Doug Bingham, West Texas State University
Larry Blair, Berea College
Virginia R. Bryan, Southern Illinois University
Joe C. Burnell, University of Indianapolis
W. Barkley Butler, Indiana University of Pennsylvania
Ben B. Chastain, Samford University
LuAnne Clark, Lansing Community College
John Cobley, University of San Francisco
Stan Cohn, DePaul University
Marjorie Collier, St. Peter's College
Rod Cranson, Lansing Community College
Phillip D. Creighton, Salisbury State University
Whitman Cross II, Southern Museum of Flight
John Cruzan, Geneva College
E. Alan Dean, University of Texas at El Paso
J.-Cl. De Bremaeker, Rice University
Normand A. Dion, Franklin Pierce College
William Faissler, Northeastern University
John Freeman, Rice University
William Fyfe, University of Western Ontario
Biswa Ghosh, Hudson County College
J. Howard Hargis, Auburn University
Dennis Hibbert, North Seattle Community College
Dave Hickey, Lansing Community College
Patricia M. Hughey, Lansing Community College

Roger Koeppe, Oklahoma State University
Diona Koerner, Marymount College
Charles J. Kunert, Concordia College
Kathleen H. Lavoie, University of Michigan-Flint
Joseph E. Ledbetter, Contra Costa College
Robert W. Lind, University of Wisconsin-Plattesville
Sam LittlePage, University of Findlay
Becky Lovato, Lansing Community College
Bruce MacLaren, Eastern Kentucky University
Donald Miller, University of Michigan at Dearborn
Michael J. Neilson, University of Alabama
Joseph Ruchlin, Lehman College of CUNY
Frederick D. Shannon, Houghton College
Howard J. Stein, Grand Valley State University
Herbert H. Stewart, Florida Atlantic University
Barbara E. Warkentine, Lehman College of CUNY
Jim Yoder, Hesston College

Iris Knell at George Mason University assisted in manuscript preparation, offered many suggestions for editorial improvements, and provided an atmosphere of cheerful efficiency that helped us to meet the tight production schedule. Judith Peatross cheerfully and efficiently compiled the glossary for us under a tight deadline.

Finally, we applaud the many people at John Wiley who proposed this book and helped to shape every aspect of its planning and production. Our editor Kaye Pace, with grace and persuasion, encouraged us to pursue this project, while she mustered the support of her Wiley colleagues for this unique effort. Barbara Heaney worked closely with us to craft a unique approach to teaching science; her ideas and dedication are reflected in every page. Anne Boynton-Trigg obtained and analyzed the dozens of external reviews that guided so much of this first edition; her perceptive synopses allowed us to address many of the ideas and concerns of science faculty. Erica Liu, Eric Stano, Brent Peich, and Jennifer Brady provided editorial assistance throughout the developmental process, and guided the production of supplements to the text.

Nancy Prinz supervised the accelerated production schedule, handling the countless technical details with efficiency and skill. Pedro Noa designed the text in a way that illustrates the integration of the sciences, and Lucille Buonocore managed the overall production process. Lisa Passmore displayed great resourcefulness in obtaining the numerous photos for this edition, while Edward Starr coordinated the development of other illustrations. Catherine Faduska and Anna Saar supervised the marketing of *The Sciences* with creativity and good humor.

To all the staff at John Wiley we owe a great debt for their enthusiastic support, constant encouragement, and sincere dedication to science education reform.

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Why Study Science

Pick up your local newspaper any morning of the week and glance at the headlines. On a typical day you'll see articles about the weather, environmental concerns, and long-range planning by one of your local utility companies. There might be news about a new treatment for AIDS, an earthquake in California, or government spending for cancer research. Inside the paper will be stories about the job market, foreign trade, and the latest records in sports. The editorial pages might feature comments on genetically engineered tomatoes at your grocery store, plans for a new incinerator for solid waste, or perhaps a trial involving DNA fingerprinting. What do all of these stories have in common? They all affect your life in one way or another, and they all depend to a significant degree on science.

We live in a world of matter and energy, forces and motions. Everything we experience in our lives—every action we take and every sensation we feel—takes place in an ordered universe with regular and predictable phenomena. You have learned to survive in this universe, so many of these scientific ideas are second nature to you. When you drive a car, cook a meal, or play a pickup game of basketball, you instinctively take advantage of a few simple physical laws. As you eat, sleep, work, or play you experience the world as a biological system and must come to terms with the natural laws governing all living things.

Science gives us a powerful tool to understand how our world works and how we interact with our physical surroundings. Science not only incorporates basic ideas and theories about how our universe behaves, but it also provides a framework for learning more and tackling new questions and concerns that come our way. Science represents our best hope for predicting and coping with natural disasters, curing diseases, and discovering new materials and new technologies with which to shape our world. Science also provides an unparalleled view of the magnificent order and symmetry of the universe and its workings—from the unseen world of the atomic nucleus, to the inconceivable vastness of space.

So why should you study science? Chances are you are not going to be a professional scientist—only about one in every hundred Americans is. You probably won't ever have to predict the weather or cure a disease, much less calculate the orbit of a planet or the acidity of a solution. So why not just leave science to the experts? The answer is simple: By learning about the central ideas and methods of science, you will be in a much better position to make informed decisions about issues that affect your work, family, and other aspects of your daily life.

The chances are that your job will depend on advances in science and technology. New technologies are a driving force in economics, business, and even many aspects of law: Semiconductor advances, agricultural methods, and information processing have altered our world. Biological research and drug development plays a crucial role in the medical professions: Genetic diseases, AIDS vaccines, and nutritional information appear in the news every day. New materials and manufacturing techniques drive our industries and present constant challenges to workers in sales and advertising: Plastics, superconductors, and composite materials have changed the way we shape our environment. Even professional athletes must constantly evaluate and use new and improved gear and rely on improved medical treatments and therapies. By studying science you will not only be better able to incorporate these advances into your professional life, but you will also better understand the process by which the advances were made.

Science is no less central to your daily life. As a consumer, you are besieged by new products and processes, not to mention a bewildering variety of warnings about health and safety. As a taxpayer you must vote on issues that directly affect your community—energy taxes, recycling proposals, government spending on research, and more. As a living being, you must make informed decisions about diet and lifestyle. And as a parent, you will have to nurture and guide your children through an ever more complex world. A firm grasp of the principles and methods of science will help you make life's important decisions in a more informed way.

By studying science you become empowered to understand and deal with our changing world, both on the job and at home. But wait, there's more. As an extra bonus, you will be poised to share in the excitement of the scientific discoveries that, week-by-week, transform our understanding of the universe and our place in it.

Science opens up astonishing, unimagined worlds—bizarre life forms in the deep oceans, exploding stars in deep space, and aspects of the history of life and our world more wondrous than any fiction. Dinosaurs, black holes, superconductors, mass extinctions, space travel, and much more await the informed science reader.

With this book as an introduction, you too can share in the greatest ongoing adventure of the human race: the adventure of science.

A Request from the Authors

You are part of an experiment in science education. Colleges have traditionally required students to take one or two semesters of departmentally based science courses—introductory physics, chemistry, or biology, for example. This integrated science course takes a different approach. *The Sciences: An Integrated Approach* targets nonscience majors who take science as part of their general education. Our main objectives are to explore central principles of physical and life sciences, to examine the role these principles play in everyday events, and to investigate the interactions of science and society. Our approach emphasizes the interdisciplinary scientific nature of human health, technology, environmental concerns, and other issues. It has been designed to relate scientific principles to your everyday experience and to help you cope with these important issues.

You can help us to achieve these objectives by suggesting improvements for subsequent editions of this book. What aspects of the book did you like? What could we improve? Were there sections that seemed confusing or too complicated? Were the examples relevant and the problems helpful? Please take some time to let us know, by writing to James Trefil and Robert Hazen, Robinson Professors, George Mason University, Fairfax, VA 22030-4444. We are eager to incorporate your comments and suggestions in subsequent editions, and thank you in advance for sharing in this development.


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Brief Contents

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