THE Sciences

AN INTEGRATED APPROACH

8TH EDITION

JAMES TREFIL ■ ROBERT HAZEN

Wiley Binder Version

WILEY

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An Integrated Approach

8th Edition

James Trefil
Robert M. Hazen

WILEY

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Preface

Scientific advances touch our lives every day. We benefit from new materials in the form of cosmetics, appliances, clothing, and sports equipment. We rely on new sources of energy and more efficient ways to use that energy for transportation, communication, heating, and lighting. We call upon science to find new ways to treat disease and to allow people to lead longer, healthier lives. Science represents our best hope in solving the many pressing problems faced by modern societies.

In spite of the central role that science plays in modern life, most Americans are poorly equipped to deal with basic scientific principles and methods. Surveys routinely show that large numbers of Americans are unaware that Earth orbits Sun or that human beings and dinosaurs didn't live at the same time. At a time when molecular biology is making breakthrough discoveries almost daily, only a little over a quarter of Americans understand the term *DNA*, and only about 10% understand the term *molecule*. There can be little doubt that we are faced with a generation of citizens who lack the critical knowledge to make informed personal and professional decisions regarding health, safety, resources, and the environment.

Science Education Today

Science education has been a persistent problem in the United States. Over the last 30 years many reports—the most prominent being *A Nation at Risk* (1983) and *The Gathering Storm* (2006)—warned that our system of science education was failing to produce enough scientists and engineers to drive our economy forward.

In fact, we can define two problems with science education. The first is the aspect on which national reports tend to spend most of their time—the need to produce a technologically skilled workforce. For the relatively small number of students pursuing these sorts of careers, specialized courses are vital, as they must learn an appropriate vocabulary and develop skills in experimental method and mathematical manipulations to solve problems.

The second important task of university education, however, is to deal with the fact that most students are not on track to become scientists or engineers. For these students, the kind of specialized courses taken by those who major in the sciences tends to divorce science from its familiar day-to-day context. All too often, students in these courses leave the university with a view that science is difficult, uninteresting, and irrelevant. It is clear that to equip students to deal with these sorts of issues, those students need to acquire a broad base in all branches of the sciences. The 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. In short, the 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 situation is slowly changing. Since the preliminary edition of *The Sciences: An Integrated Approach* appeared in 1993, hundreds of colleges and universities have begun the process of instituting new integrated science courses as an option for undergraduates. In the process, we have had the opportunity to interact with hundreds of our colleagues across the country, as well as more than 9,000 of our own students at George Mason University, and have received invaluable guidance in preparing this extensively revised edition.

The Need for a New Science Education

In the coming decades, the 1996 publication of the *National Science Education Standards* by the National Research Council may be seen as a pivotal event in American science education. The *Standards*, which represented the collective effort and consensus of more than 20,000 scientists, educators, administrators, and parents, offered a dramatically new vision of science education for all of America. The authors of this book were part of a small team that put together the final version of the *Standards*, and thus have had a ring-side seat as the standards have been modified and adopted in states throughout the country.

A central emphasis throughout the *Standards* is the development of a student's understanding of the scientific process, as opposed to just the accumulation of scientific facts. Emphasis is placed on the role of experiments in probing nature and the importance of mathematics in describing its behavior. Rather than developing esoteric vocabulary and specialized knowledge, the *Standards* strives to empower students 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. Students should develop an understanding that a few universal laws describe the behavior 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. As we pointed out above, most societal issues concerning science and technology draw on a broad range of knowledge. The scientific principles involved must be integrated with other factors such as economics, energy demand, perceptions of risk, and demographics.

The Goals of This Book

This text, based on our course "Great Ideas in Science," which has been developed at George Mason University, is an attempt to respond to the future needs of today's students. 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.

Having set as our goal providing education for people who will not be scientists but who need some knowledge of science to function as citizens, we have to address another issue. There is no question that anyone who actually does science will be required to use high levels of mathematics to carry out his or her work. We would argue, however, that this same level of mathematics is not required by the average person confronting political issues.

There are two central features of *The Sciences: An Integrated Approach* that allow us to offer a text with the expressed goal of helping students achieve scientific literacy. These features are (1) organization around Great Ideas, and (2) an explicit integration of the sciences, starting with the first chapter.

GREAT IDEAS

One of the best-kept secrets in the world is this: the core ideas of the sciences are really quite simple. Furthermore, these core ideas form a framework for our understanding of the universe—they give our ideas structure and form. As we argue in the text, these Great Ideas represent a hierarchy in the sciences that transcend the boundaries of specific disciplines. The conservation of energy, for example, is part of the intellectual framework of sciences from astronomy to zoology.

By organizing our presentation around the central Great Ideas rather than around specific disciplines, students can deal with the universe as it presents itself to them, rather than with disciplinary divisions that have little meaning for them, no matter how important they are to working scientists.

No one can predict what the major subjects of public concern will be in 30 years' time—certainly no one 30 years ago would have guessed that we would be arguing about stem cells today.

What we can guarantee, however, is that whatever those future issues are, they will present themselves in relation to the Great Ideas.

INTEGRATION

Every chapter in this book opens with a list of how the concepts to be discussed relate to every area of science. In the chapters themselves, we use the Special Features described below to bring in aspects of science from other areas. For us, integration is more than a cosmetic feature—it goes to the very heart of science. The universe presents itself to us as a seamless web of interacting phenomena, and our understanding of science should do the same.

The Organization of *The Sciences*

We were, in fact, the first to adopt 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 future elementary and high school teachers, 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 of 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 the 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 8–11). 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. An optional chapter on the theory of relativity (Chapter 7) examines the consequences of a universe in which all observers discern the same laws of nature.

Having established these general principles, we go on to examine specific natural systems such as atoms, Earth, or living things. The realm of the nucleus (Chapter 12) and subatomic particles (Chapter 13), for example, must follow the basic rules governing all matter and energy.

In sections on astronomy and cosmology (Chapters 14–16), 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 electromagnetic processes.

Plate tectonics (Chapter 17) and the cycles of rocks, water, and the atmosphere (Chapter 18) unify the Earth sciences. The laws of thermodynamics, which decree that no feature on Earth's surface is permanent, can be used to explain geological time, gradualism, and the causes of earthquakes and volcanoes.

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: interdependent collections of living things (ecosystems) recycle matter while energy flows through them; living things use many strategies to maintain and reproduce life; 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; and all living things evolved by natural selection.

The sections covering living things has been extensively revised. Chapter 19 includes new information on ecosystems and their importance to the environment. One chapter (20) covers the organization and characteristics of living things. A revised chapter on biotechnology (24) explores several recent advances in our molecular understanding of life that helps to cure diseases and to better the human condition. We end the book with a discussion of evolution (25) that emphasizes observational evidence first.

The text has been designed so that four chapters—relativity (7), quantum mechanics (9), particle physics (13), and cosmology (15)—may be skipped without loss of continuity.

Major Changes in the Eighth Edition

We are always amazed at how much of the scientific content of this book has to be updated when we undertake a new edition, and the eighth edition is no exception. It has been updated to provide the most current scientific coverage and the most useful pedagogical elements to students taking integrated science courses. Additionally, each chapter has new end-of-chapter questions to address new material and to provide students with better study tools.
Some of the most significant changes to this edition include the following:

Chapter 1 This chapter now features an expanded discussion of citizen science, a new way for people to become involved.

Chapter 2 The discussion of deterministic chaos in the "Thinking More About" section has been expanded.

Chapter 3 The section of energy use in the United States and the section on renewable energy sources have been extensively updated to reflect the rapidly changing energy landscape.

Chapter 4 Heat and the Second Law of Thermodynamics contains an expanded discussion of temperature scales and a new "Thinking More About" on the use of fossil fuels.

Chapter 5 A new discussion of the electrification of America underscores the importance of electricity and magnetism in everyday life.

Chapter 6 We feature a new "Technology" section on cell phones.

Chapter 7 We have expanded discussion of the experimental tests of special relativity as well as a new section on gravitational waves.

Chapter 8 The presentation of the periodic table has been modified to stress its role as an organizing principle in chemistry.

Chapter 9 We have updated the section on quantum computing and expanded the "Thinking More About" section on the subject of consciousness.

Chapter 10 We have added a new "Science in the Making" section on "Polymers and the Origins of Life."

Chapter 11 We have updated the section on computers and added a new "Technology" feature on light-emitting diodes.

Chapter 12 The Nucleus of the Atom has an updated section on fusion, emphasizing forefront experiments at NIF and ITER.

Chapter 13 The Ultimate Structure of Matter includes updated material on accelerators, the Higgs Boson, and CERN, as well as a new discussion of quantum loop gravity.

Chapter 14 The Stars contains the updated list of both terrestrial and orbiting observatories, discussion of IceCube and black hole search results, and a new section on space weather.

Chapter 15 Cosmology has been updated to include new results from dark matter searches and a description of the LUX experiments.

Chapter 16 Earth and Other Planets has been expanded to update discussions of space probes and the Mars rovers, present a fuller discussion of the oceans of Europa and planned drilling missions, and greatly expand the discussion of exoplanets and the Kepler spacecraft.

Chapter 17 Plate Tectonics contains an updated discussion of the Fukushima earthquake in 2011 and the personal account of one of the authors (RMH) who was in Japan when it struck.

Chapter 19 Ecology, Ecosystems, and the Environment has been updated with new data on climate change.

Chapter 20 The section on taxonomy now contains a discussion of cladistics as well as an "Ongoing Process of Science" on the taxonomic problems associated with the classification of fungi.

Chapter 22 The Molecules of Life now has a completely revised and simplified "Return to the Integrated Question."

Chapter 23 This chapter now contains an expanded discussion of Mendelian genetics and DNA transcription as well as updated material on the human genome.

Chapter 24 The New Science of Life starts with a new integrated question. It has updated discussions of DNA fingerprinting, genetic engineering, and genetically modified crops, as well as new sections on epigenetics and synthetic biology.

Chapter 25 Evolution includes significantly updated and enhanced coverage on the origin of life (especially chemical evolution), as well as a completely rewritten section on the Neanderthals based on their DNA.

Special Features

In an effort to aid student learning and underscore the integration of 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 experiences into a broad context.

GREAT IDEAS ACROSS THE SCIENCES

Our theme of integration is reinforced with a radiating diagram that appears at the beginning of every chapter. The diagram ties together some of the examples discussed in the text and shows how the Great Idea has been applied to different branches of science and to everyday life.

SCIENCE THROUGH THE DAY

Each chapter begins with a "Science Through the Day" section in which we tie the chapter's main theme to common experiences such as eating, driving a car, or suntanning.

THE SCIENCE OF LIFE

To help show the interdisciplinary nature of the many concepts we introduce, we have included sections on living things in most chapters. Thus, while chapters emphasizing principles specifically related to life are at the end of the book, biological examples appear throughout.

SCIENCE IN THE MAKING

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

THE ONGOING PROCESS OF SCIENCE

Science is a never-ending process of asking questions and seeking answers. In these features, we examine some of the most exciting questions currently being addressed by scientists.

STOP & THINK

At various points in each chapter, we ask students to pause and think about the implications of a scientific discovery or principle.

TECHNOLOGY

The application of scientific ideas to commerce, industry, and other modern technological concerns is perhaps the most immediate way in which students encounter science.

MATHEMATICAL EQUATIONS AND WORKED EXAMPLES

Unlike the content of many science texts, formulas and mathematical derivations play a subsidiary role in our treatment of the subject matter. We rely much more on real-world experiences and on everyday vocabulary. We believe that every student should understand the role of mathematics in science. Therefore, in many chapters, we have included a few key equations and the appropriate worked examples. Whenever an equation is introduced, it is presented in three steps: first as an English sentence, second as a word equation, and finally in its traditional symbolic form. In this way, students can focus on the meaning rather than 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 areas of magnitude. Thus, we have incorporated many nontraditional calculations.

THINKING MORE ABOUT

Each chapter ends with a section that addresses a social or philosophical issue tied to science such as federal funding of the sciences, nuclear waste disposal, cloning, and priorities in medical research.

DISCOVERY LABS

The eighth edition features updated "kitchen sink" labs contributed by Larry McClellan and Meena Jagasia who provide students with additional real-world science applications. These labs may be conducted in a class or lab, or they may be assigned for students to complete at home.

RETURN TO THE INTEGRATED SCIENCE QUESTION

Each chapter of *The Sciences* opens with an Integrated Science Question that draws from the many branches of science discussed in the chapter. New to the eighth edition, we now return to this question at the end of the chapter to illustrate for students how the material draws together to answer this question and creates a problem-solving framework for students to apply to future questions.

OTHER FEATURES

Key Words. Most science texts suffer from too complex a vocabulary. We have tried to avoid unnecessary jargon. Because the scientifically literate student must be familiar with many words and concepts that appear regularly in newspaper articles or other material for general readers, each chapter contains key words that appear in boldface type. These words are also listed at the end of each chapter.

There are many other scientific terms that are more specialized but also important. We have highlighted these terms in italics. We strongly recommend that students learn the meaning and context of all the key words but not be expected to memorize the words that appear in italics. We encourage all adopters of this text to provide their own lists of key words and other terms, both those we might have omitted and those they feel should be eliminated from our list.

Questions. We feature four levels of end-of-chapter questions, and we revise at least 30% of them in each new edition. "Review Questions" test important factual information covered in the text and are provided to emphasize key points. Many of the Review Questions have been substantially rewritten for this edition. "Discussion Questions" are also based on material in the text, but they also examine student comprehension and explore the application and analysis of the scientific concepts. "Problems" are quantitative questions that require students to use mathematical operations, typically those introduced in worked examples or "Science by the Numbers." Finally, "Investigations" require additional research outside the classroom. Each instructor should decide which level of questions is most appropriate for his or her students. We welcome suggestions for additional questions, which we will add to the next edition of this text.

Illustrations. This book has been extensively illustrated with color images in an effort to help amplify the key ideas and principles. All the diagrams and graphs have been designed for maximum clarity and impact.

Great Ideas in Science: A Reader in the Classic Literature of Science. In conjunction with University Readers of San Diego, California, Robert Hazen and James Trefil have edited a collection of 50 excerpts from original sources to illustrate transformational discoveries in science history. The readings are grouped into 25 chapters that parallel this volume. Taken together, these readings reveal dramatic changes in the process and progress of science.

ANCILLARIES FOR THE SCIENCES, EIGHTH EDITION WILEYPLUS LEARNING SPACE

The factors that contribute to success–both in college and in life–aren't comprised of intellectual capabilities alone. In fact, there are other traits, strategies, and even daily habits that contribute to the overall picture of success. Studies show that people who can delay instant gratification, work through tasks even if they are not immediately rewarding, and follow through with a plan have the skills that are not only valuable in the classroom, but also in the workplace and their personal lives.

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- Help students see exactly what they don't know to better prepare for exams
- Give students insight into their strengths and weaknesses so that they can succeed in your course

For Students

Personalize the learning experience.

Different learning styles, different levels of proficiency, different levels of preparation—each of your students is unique. WileyPLUS Learning Space empowers them to take advantage of their individual strengths:

- Students receive timely access to resources that address their demonstrated needs, and they get immediate feedback and remediation when needed.
- Integrated, multimedia resources include:

  Virtual Discovery Labs bring select core concepts to life in an online lab setting.

  Animations illustrate select text concepts.

  Science in the News Video Clips are linked right into the eBook in WileyPLUS for easy in-context access and give students a look into how science works in the real world.

- WileyPLUS Learning Space includes many opportunities for self-assessment linked to the relevant portions of the text. Students can take control of their own learning and practice until they master the material.

For Instructors

Personalize the teaching experience.

WileyPLUS Learning Space empowers you with the tools and resources you need to make your teaching even more effective:

- You can customize your classroom presentation with a wealth of resources and functionality from PowerPoint slides to a database of rich visuals. You can even add your own materials to your WileyPLUS Learning Space course.
- With WileyPLUS Learning Space you can identify those students who are falling behind and intervene accordingly, without having to wait for them to come to office hours.
- WileyPLUS Learning Space simplifies and automates such tasks as student performance assessment, making assignments, scoring student work, keeping grades, and more.

Virtual Discovery Labs authored by Brian Shmaefsky of Lone Star College bring select core concepts to life in an online lab setting. Virtual Discovery Labs offer students an excellent alternative to hands-on lab work with assignable lab reports and question assignments.

Test Bank by David King of Auburn University is available on both the instructor companion site and within WileyPLUS Learning Space. Containing approximately 50 multiple-choice and essay test items per chapter, this test bank offers assessment of both basic understanding and conceptual applications. *The Sciences*, Eighth Edition Test Bank is offered in two formats: MS Word files and a Computerized Test Bank. The easy-to-use test-generation program fully supports graphics, print tests, student answer sheets, and answer keys. The software's advanced features allow you to create an exam to your exact specifications.

Instructor's Manual prepared by Jack Giannattasio, Monmouth University, contains teaching suggestions, lecture notes, answers to problems from the textbook, additional problems, and over 70 creative ideas for in-class activities. Available in WileyPLUS Learning Space and on the instructor companion site.

Science in the News Video Clips and Lecture Launcher Presentations provide instructors with a presentation tool to give students a look into how science works in the real world. Videos can be presented in class or assigned with questions in WileyPLUS Learning Space.

Animations. Select text concepts are illustrated using flash animation, designed for use in classroom presentations.

All line illustrations and photos from *The Sciences*, Eighth Edition in jpeg files and PowerPoint format are available both on the instructor companion site and within WileyPLUS Learning Space.

Biology Visual Library containing all of the line illustrations in the textbook in jpeg format, as well as access to numerous other life science illustrations from other Wiley texts, is available in WileyPLUS and on the instructor companion site.

PowerPoint presentations by John Gudenas of Aurora University are tailored to *The Sciences*, Eighth Edition's topical coverage and learning objectives. These presentations are designed to convey key text concepts, illustrated by embedded text art. An effort has been made to reduce the amount of words on each slide and increase the use of visuals to illustrate concepts. Personal Response System questions are specifically designed to foster student discussion and debate in class.

Book Companion Site (www.wiley.com/college/trefil)

For the Student:

- Quizzes for student self-testing
- Biology NewsFinder; Flash Cards; and Animations

For the Instructor:

- Biology Visual Library; all images in jpg and PowerPoint formats.
- Instructor's Manual; Test Bank; Lecture PowerPoint presentations, and Personal Response System questions, and Instructor Resources are password protected.

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 9,000 students, the majority of whom were non-science majors, have enrolled in the course over the past 24 years. They represent a diverse cross section of American students: more than half were women, and 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 shape our text.

FACULTY INPUT

We thank the many teachers across the country who are developing integrated science courses. Their letters and suggestions to us and responses to our publisher's survey inspired us as we wrote this edition. We especially thank the professors who have used and class-tested the earlier editions, sharing with us the responses of their students and their own analyses. Their classroom experience continues to help us shape the book.

PUBLISHER SUPPORT

Finally, as in the previous editions, we gratefully acknowledge the dedicated people at John Wiley and Sons who originally proposed this textbook and have helped us in developing every aspect of its planning and production for all eight editions. We thank our Senior Editor, Nick Ferrari for his support and innovative ideas. Senior Market Solutions Assistant, Mallory Fryc served with skill and professionalism. Executive Marketing Manager Kristine Ruff championed the book in her marketing and sales efforts.

We also thank the production team of the eighth edition. The project was ably managed by Patricia McFadden and meticulously produced by Jeanine Furino who dealt with the countless technical details associated with an integrated science book. Tom Nery designed the handsome text and the cover. Billy Ray researched the numerous new photos for the eighth edition. Anna Melhorn coordinated the development of our new illustrations. 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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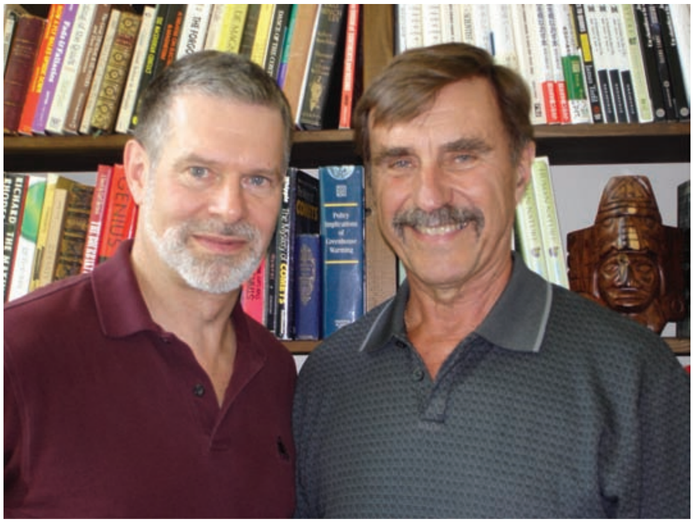

James Trefil (right) has authored or coauthored numerous books on science for the general audience. His interest in science literacy began with a contributed essay to E. D. Hirsch's Cultural Literacy and continued with his work on the Content Review Board for the National Science Education Standards. He is a frequent lecturer on science and the law at state and federal judicial conferences. He received undergraduate degrees from the University of Illinois and Oxford University. After receiving a doctorate in theoretical physics from Stanford University, he held post-doctorate and faculty appointments in Europe and the United States. He is the Clarence Robinson Professor of Physics at George Mason University. He has made contributions to researching elementary particle physics, fluid mechanics, medical physics (including cancer research), and the earth sciences. Trefil was awarded the Gemant Prize of the American Institute of Physics for his efforts to present science to the public. His most recent book is *Science in World History.*

Robert M. Hazen (left) is the Clarence Robinson Professor of Earth Science at George Mason University and Staff Scientist at the Carnegie Institution of Washington's Geophysical Laboratory. Hazen developed a fascination for rocks and minerals as a child growing up in mineral-rich Northern New Jersey, and he pursued that interest as an undergraduate at the Massachusetts Institute of Technology. After receiving a doctorate in earth sciences from Harvard University, he spent a year at Cambridge University as a NATO Postdoctoral Fellow. In addition to teaching courses on scientific literacy, scientific ethics, symmetry in art and science, and visual thinking, he performs research on the roles that minerals may have played in the origin of life. His current studies explore the hypothesis that life arose in a deep, high-pressure environment. Hazen is active in presenting science to the public. He developed a 60-lecture video version of the textbook *The Joy of Science*, which is available nationally through The Teaching Company. He has appeared on numerous radio and television shows, including NOVA and Today. His most recent popular book is *The Story of Earth.*

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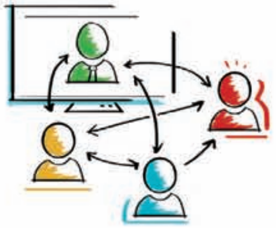

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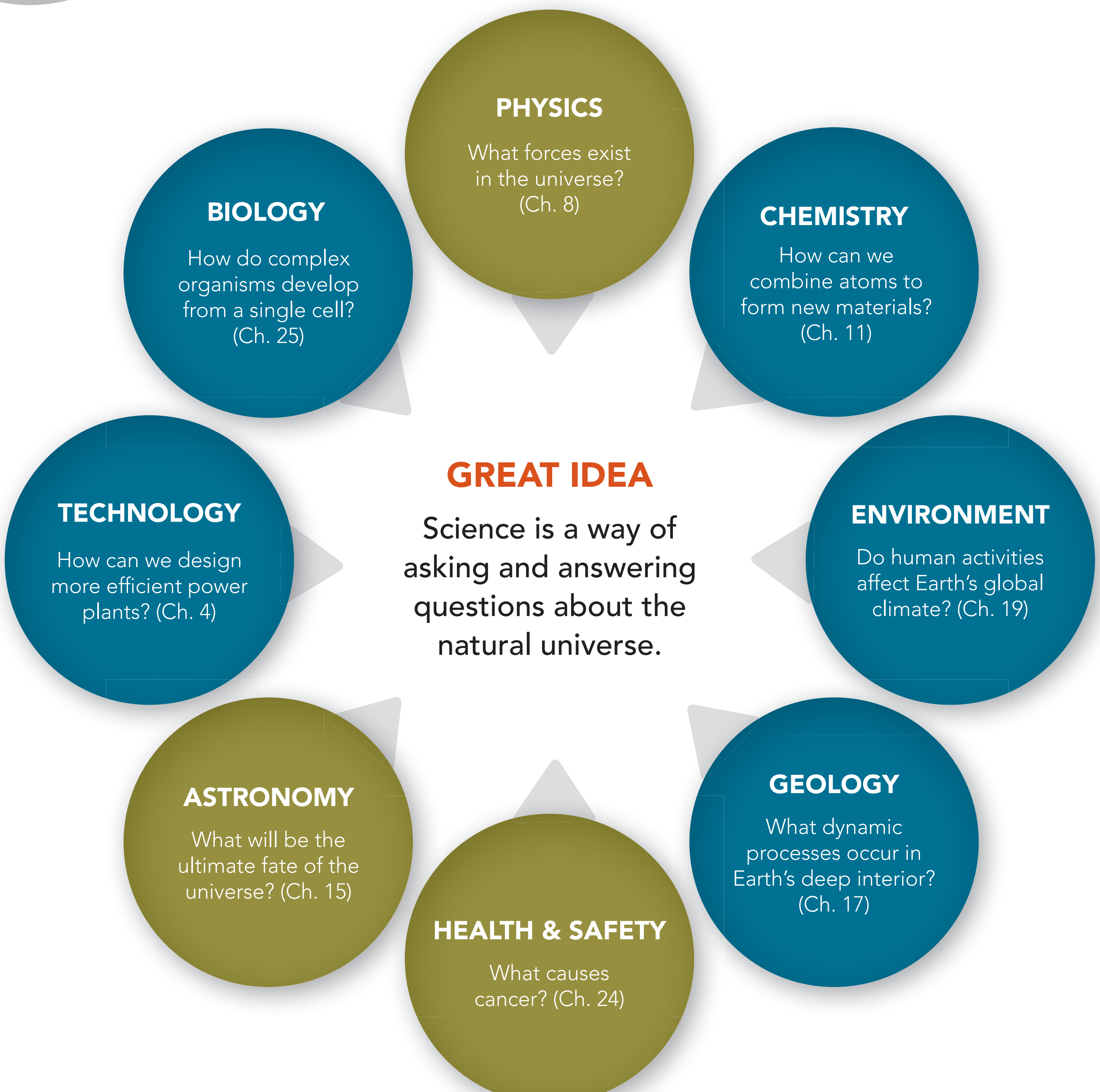
1 Science: A Way of Knowing

How do you know what you know?



(blue circle) = applications of the great idea discussed in this chapter

(olive circle) = other applications, some of which are discussed in other chapters

SCIENCE THROUGH THE DAY

Sunrise

Sunlight streams through your east window. As you wake up, you remember it's Saturday. No classes! And you're headed to the beach with friends. It looks like it's going to be a beautiful day, just like the weather forecast promised.

We take so much about the natural world for granted. Every day the Sun rises at a precisely predictable time in the east. Every day the Sun sets in the west. So, too, the phases of the Moon and the seasons of the year follow their familiar repetitive cycles.

Ancient humans took note of these and many other predictable aspects of nature, and they patterned their lives and cultures accordingly. Today, we formalize this search for regularities in nature, and we call the process science.

Natalia V Guseva/Shutterstock

1.1 The Role of Science

Our lives are filled with choices. What should I eat? Is it safe to cross the street? Should I bother to recycle an aluminum can, or should I just throw it in the trash? Every day we have to make dozens of decisions; each choice is based, in part, on the knowledge that actions in a physical world have predictable consequences. By what process do you make those decisions?

Making Choices

When you pull into a gas station, you have to ask yourself what sort of gasoline to buy for your car (Figure 1-1). Over a period of time you may try many different types—different brands, regular or premium, different levels of ethanol—observing how your car responds to each. In the end, you may conclude that a particular brand and grade suits your car best, and you decide to buy that one in the future. You engage in a similar process of inquiry and experimentation when you buy shampoo, pain relievers, athletic shoes, and scores of other products.

These simple examples illustrate one way we learn about the universe. First, we look at the world to see what is there and to learn how it works. Then we generalize, making rules that seem to fit what we see. Finally, we apply those general rules to new situations we've never encountered before, and we fully expect the rules to work.

There doesn't seem to be anything Earth-shattering about choosing a brand of gasoline or shampoo. But the same basic procedure of asking questions, making observations, and arriving at a conclusion can be applied in a more formal and quantitative way when we want to understand the workings of a distant star or a living cell. In these cases, the enterprise is called science, and the people who study these questions for a living are called scientists.

Why Study Science?

Science gives us our most 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.

FIGURE 1-1 Even something simple like choosing a brand of gasoline can involve observation and experiment.

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 cancer, an earthquake in California, or new advances in biotechnology. The editorial pages might feature comments on cloning humans, arguments for a NASA planetary mission, debates about teaching evolution, or perhaps a trial involving DNA fingerprinting. What do all of these stories have in common? They may 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. The process of science is based on the idea that everything we experience in our lives 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 living biological system and must come to terms with the natural laws governing all living things.

So why should you study science? Chances are you aren't going to be a professional scientist. Even so, your job may well depend on advances in science and technology. New technologies are a driving force in economics, business, and even many aspects of law: new semiconductor technology, agricultural methods, and information processing have altered our world. Biological research and drug development play crucial roles in the medical professions: stories about genetic diseases, flu vaccines, viral epidemics, and nutritional information appear in the news every day. Even professional athletes must constantly evaluate and use new and improved gear, rely on improved medical treatments and therapies, and weigh the potential medical risks of legal performance-enhancing drugs. 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 such advances were made.

Science is no less central to your everyday life away from school or work. 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. 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 deep oceans, exploding stars in deep space, and aspects of the history of life and our world more wondrous than any fiction.

1.2 The Scientific Method

Science is a way of asking and answering questions about the physical universe. It's not simply a set of facts or a catalog of answers, but rather a process for conducting an ongoing dialogue with our physical surroundings. Like any human activity, science is enormously varied and rich in subtleties. Nevertheless, a few basic steps taken together can be said to comprise the **scientific method**.

Observation

If our goal is to learn about the world, then the first thing we have to do is look around us and see what's there. This statement may seem obvious to us in our modern technological age, yet throughout much of history, learned men and women rejected the idea that you can understand the world simply by observing it.

Some Greek philosophers living during the Golden Age of Athens argued that one cannot deduce the true nature of the universe by trusting the senses. The senses lie, they would have said. Only the use of reason and the insights of the human mind can lead us to true understanding. In his famous book *The Republic,* Plato compared human beings to people living in a cave, watching shadows on a wall but unable to see the objects causing the shadows (Figure 1-2). In just the same way, he argued, observing the physical world will never put us in contact with reality, but will doom us to a lifetime of wrestling with shadows. Only with the "eye of the mind" can we break free from illusion and arrive at the truth, Plato argued.

School of Athens, detail of the centre showing Plato and Aristotle with students including Michelangelo and Diogenes, 1510-11 by Raphael (Raffaello Sanzio of Urbino) (1483-1520) ©Vatican Museums and Galleries, Vatican City, Italy/ The Bridgeman Art Library

FIGURE 1-2 Plato argued that humans observing nature were like men watching shadows on the wall of a cave.

In the Middle Ages in Europe, a similar frame of mind was to be found, but with a trust in received wisdom replacing the use of human reason as the ultimate tool in the search for truth. A story (probably apocryphal) about an Oxford College debate on the question "How many teeth does a horse have?" underscores this point. One learned scholar got up and quoted the Greek scientist Aristotle on the subject, and another quoted the theologian St. Augustine to put forward a different answer. Finally, a young man at the back of the hall got up and noted that since there was a horse outside, they could settle the question by looking in its mouth. At this point, the manuscript states, the assembled scholars "fell upon him, smote him hip and thigh, and cast him from the company of educated men."

As these examples illustrate, many distinguished thinkers have attacked the problem of learning about the physical world without actually making observations and measurements. These approaches are perfectly self-consistent and were pursued by people every bit as intelligent as we are. They are not, however, the methods of science, nor did they produce the kinds of advanced technologies and knowledge that we associate with modern societies.

In the remainder of this book, we differentiate between **observations**, in which we observe nature without manipulating it, and **experiments**, in which we manipulate some aspect of nature and observe the outcome. An astronomer, for example, observes distant stars without changing them, while a chemist may experiment by mixing materials together and seeing what happens.

Identifying Patterns and Regularities

When we observe a particular phenomenon over and over again, we begin to get a sense of how nature behaves. We start to recognize patterns in nature. Eventually, we generalize our experience into a synthesis that summarizes what we have learned about the way the world works. We may, for example, notice that whenever we drop something, it falls. This statement represents a summary of the results of many observations.

It often happens that at this stage scientists summarize the results of their observations in mathematical form, particularly if they have been making quantitative **measurements**. Every measurement involves a number that is recorded in some standard *unit of measurement*. In the case of a falling object, for example, you might measure the time (measured in the familiar time unit of seconds) that it takes an object to fall a certain distance (measured in the distance unit of meters, for example). More examples of units of measurement are given in Appendix B.

Quantitative measurements thus provide a more exact description than just noticing that the object falls. The standard scientific procedure is to collect careful measurements in the form of a table of data (see Table 1-1). These data could also be presented in the form of a graph, in which distance of the fall (in meters) is plotted against time of the fall (in seconds; Figure 1-3). As we explore the many different branches of science, from physics to biology, we'll see that most scientific measurements require both a number and a unit of measurement, and we'll encounter many different units in the coming chapters.

After preparing tables and graphs of their data, scientists would notice that the longer something falls, the farther it travels. Furthermore, the distance isn't simply proportional to the time of fall. If one object falls twice as long as another, it will travel four times as far; if it falls three times longer, it will travel nine times as far; and so on. This statement can be summarized in three ways (a format used throughout this book):

In words: **The distance traveled is proportional to the square of the time of travel.**

In equation form:

$$\text{distance} = \text{constant} \times (\text{time})^2$$

In symbols:

$$d = k \times t^2$$

The constant, *k*, has to be determined from the measurements. We'll return to the subject of constants in the next chapter.

Identifying a regularity in nature may take a long time, since it requires an accumulation of experience in a particular area. Furthermore, scientists may go through several phases in their thinking. At first, they may make a *hypothesis*, an educated guess as to what the regularity they are studying will turn out to be—"I think that if I drop things they will fall." Given enough confirmation, the hypothesis can be upgraded to a regularity.

TABLE 1-1 Measurements of Falling Objects

Time of Fall (seconds)	Distance of Fall (meters)
1	5
2	20
3	45
4	80
5	125

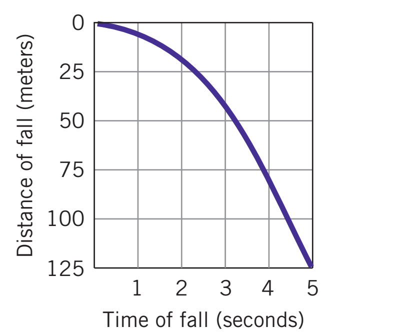


FIGURE 1-3 Measurements of a falling object can be presented visually in the form of a graph. Time of fall in seconds (on the horizontal axis) is plotted versus distance of fall in meters (on the vertical axis).

Mathematics: The Language of Science

To many people science brings to mind obscure equations written in strange, undecipherable symbols. The next time you're in the science area of your college or university, look into an advanced classroom. Chances are you'll see a confusing jumble of formulas on the blackboard. Have you ever wondered why scientists need all those complex mathematical equations? Science is supposed to help us understand the physical world around us, so why can't scientists just use plain English?

Take a stroll outside and look carefully at a favorite tree. Think about how you might describe the tree in as much detail as possible so that a distant friend could envision exactly what you see and distinguish that tree from all others.

A cursory description would note the rough brown bark, branching limbs, and canopy of green leaves, but that description would do little to distinguish your tree from most others. You might use adjectives such as *lofty*, *graceful*, or *stately* to convey an overall impression of the tree (Figure 1-4). Better yet, you could identify the exact kind of tree and specify its stage of growth—a sugar maple at the peak of autumn color, for example—but even then your friend has relatively little to go on.

Gerolf Kalt/©Corbis

FIGURE 1-4 There are many ways of describing a tree.

Your description would be far more accurate if you gave exact dimensions of the tree—measurements expressed in units, such as its height, the distance spanned by its branches, or the diameter of the trunk. You could document the shape and size of leaves, the thickness and texture of the bark, the angles and spacing of the branching limbs, and the tree's approximate age. You could approach measuring the tree from other perspectives as well—by calculating the number of board feet of lumber the tree could yield (Figure 1-5), or how much life-supporting oxygen the tree produces every day. Finally, you could talk about the basic molecular processes that allow the tree to extract energy from sunlight and carry out the other chemical tasks we associate with life.

As we move through these descriptions of the tree, our language becomes more and more quantitative. In some cases, such as supplying a detailed description of the tree's shape or its chemistry, that description could become quite long and cumbersome. That's why scientists employ **mathematics**, which is a concise language that allows them to communicate their results in compact form and often, as an added benefit, allows them to make very precise predictions about expected outcomes of experiments or observations. But anything that can be said in an equation can also be said (albeit in a less concise way) in a plain English sentence. When you encounter equations in your science courses, you should always ask, "What English sentence does this equation represent?" Learning to "read" equations will keep the mathematics from obscuring the simple ideas that lie behind most equations.

DEVELOPMENT OF A THEORY

Once scientists have established a regularity in nature, they can go on to ask an important question: What must the world be like in order for this regularity to exist? They will, in other words, construct a theory—a mental (and usually mathematical) picture of how the world operates. In the next chapter, for example, we will see how the English scientist Isaac Newton formulated a theory about why things fall—a far reaching theory embodied in what we now call the law of universal gravitation. As we shall see below, a theory must be tested against nature, but once it has met this test it represents our best guess as to what the world is like.

We are already encountering terms that we often use when talking about the scientific process, and the way these terms are used are often different from the way they are used in everyday speech. For the sake of clarity, we define some of these terms below:

kozmoat98 / Getty Images, Inc.

FIGURE 1-5 One way of looking at a tree is to think about the lumber it might produce.

Fact: A statement of something that happens in nature—"I dropped my keys and they fell."

Hypothesis: A conjecture, based on past observations or theoretical considerations, about something that will happen—"If I drop my keys again, they will fall."

Law and **Theory**: Scientists, who are normally extremely careful about data and calculations, don't pay a lot of attention to the way they use these terms. In general, whatever label is applied to a set of ideas when it is first proposed usually sticks to it, regardless of how well it fares in making predictions. Thus, "theory" can refer to a fully fleshed out (but as yet untested) hypothesis like the so-called string theories we'll discuss in Chapter 13. It can also, however, refer to a set of ideas that have met many experimental tests and are widely accepted by scientists, such as the theory of general relativity (Chapter 7) and the theory of evolution (Chapter 25). The term "law" is generally used to refer to statements that have met many tests, such as the law of universal gravitation, which we will discuss in Chapter 2. It is important to realize, however, that there is no real distinction in scientific usage between a generally accepted theory and a generally accepted law, nor is there any implied ranking between them. For example, the *law* of universal gravitation is actually part of the much broader and more complete *theory* of general relativity.

Prediction and Testing

In science, every idea must be tested by using it to make **predictions** about how a particular system will behave, then observing nature to see if the system behaves as predicted. The theory of evolution, for example, makes countless specific testable predictions about the similarities and differences of modern living organisms, as well as the nature and distribution of extinct fossil organisms.

Think about the hypothesis that all objects fall when they are dropped. That idea can be tested by dropping all sorts of objects (Figure 1-6). Each drop constitutes a test of our prediction, and the more successful tests we perform, the more confidence we have that the hypothesis is correct. As long as we restrict our tests to solids or liquids on Earth's surface, then the hypothesis is consistently confirmed. Test a helium-filled balloon, however, and we discover a clear exception to the rule. The balloon "falls" up. The original hypothesis, which worked so well for most objects, fails for certain gases. And more tests would show there are other limitations. If you were an astronaut in a space shuttle, every time you held something out and let it go, it would just float in space. Evidently, our hypothesis is invalid in the orbiting space shuttle as well.

This example illustrates an important aspect about testing ideas in science. Tests do not necessarily prove or disprove an idea; instead, they often serve to define the range of situations under which the idea is valid. We may, for example, observe that nature behaves in a certain way only at high temperatures or only at low velocities. In these sorts of situations, it usually happens that the original hypothesis is seen to be a special case of a deeper, more general theory. In the case of the balloon, for example, the simple "things fall down" will be replaced by a much more general theory of gravitation, based on statements called Newton's laws of motion and the law of universal gravitation—laws we'll study in the next chapter. These laws of nature describe and predict the motion of dropped objects both on Earth and in space and, therefore, are a more successful set of statements than the original hypothesis. We will discuss them in more detail in the next chapter.

We will encounter many such laws and theories in this book, all backed by millions of observations and measurements. Remember, however, where these laws and theories come from. They are not written on tablets of stone, nor are they simply good ideas that someone once had. They arise from repeated and rigorous observation and testing. They represent our best understanding of how nature works.

Photri/Age Fotostock America, Inc.

FIGURE 1-6 Equations allow us to describe with precision the behavior of objects in our physical world. One such equation predicts the behavior of falling objects.

We never stop questioning the validity of our hypotheses, theories, or laws of nature. Scientists constantly think up new, more rigorous experiments to test the limits of our theories. In fact, one of the central tenets of science is this:

● **Every law and theory of nature is subject to change, based on new observations.**

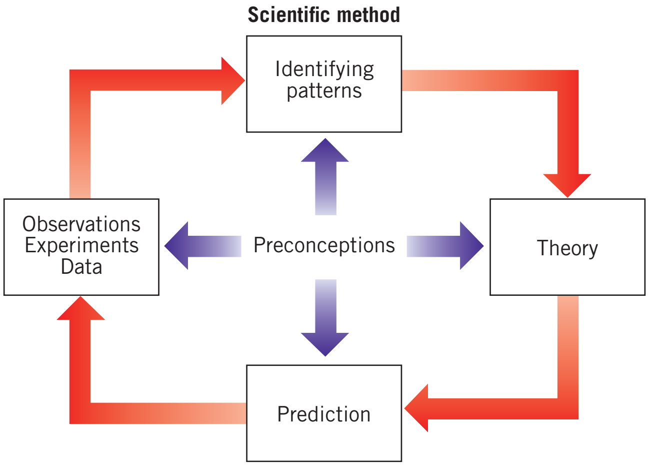


FIGURE 1-7 The scientific method can be illustrated as an endless cycle of collecting observations (data), identifying patterns and regularities in the data, creating theories, making predictions, and collecting more observations.

This is an extremely important statement about science, and one that is often ignored in public debates. It means that it must be possible, in principle, that every statement in a scientific model *could* be false. You should, in other words, be able to imagine an experimental outcome that would prove the statement false, even if that outcome never happens in the real world.

Consider the theory of evolution (see Chapter 25), which makes countless predictions about the historical sequence of organisms that have lived on Earth. According to the current model of life's evolution, for example, dinosaurs became extinct millions of years before human beings appeared. Consequently, if a paleontologist found a human leg bone in the same geological formation with a *Tyrannosaurus rex,* then that discovery would call into question the theory of evolution.

The Scientific Method in Operation

These elements—observation, regularity, theory, prediction, and testing—together comprise the scientific method. In practice, you can think of the method as working as shown in Figure 1-7. It's a never-ending cycle in which observations lead to theories, which lead to more observations.

If observations support a theory, then more tests may be devised. If the theory fails, then the new observations are used to revise it, after which the revised theory is tested again. Scientists continue this process until the limits of existing equipment are reached, in which case researchers often try to develop better instruments to do even more tests. If and when it appears that there's just no point to going further, the hypothesis may be elevated to a law of nature.

It's important to realize, however, that while the orderly cycle shown in Figure 1-7 provides a useful framework to help us think about science, it shouldn't be thought of as a rigid cookbook-style set of steps to follow. Science can be every bit as creative an endeavor as art or music. Because human beings do science, it involves occasional bursts of intuition, sudden leaps, a joyful breaking of the rules, and all the other characteristics we associate with other human activities.

Several other important points should be made about the scientific method:

1. Scientists are not required to observe nature with an "open mind," with no preconceptions about what they are going to find. Most experiments and observations are designed and undertaken with a specific hypothesis in mind, and most researchers have preconceptions about whether that hypothesis is right or wrong. Nevertheless, scientists have to believe the results of their experiments and observations, whether or not they fit preconceived notions. Science demands that whatever our preconceptions, we must be ready to change those ideas if the evidence forces us to do so.
2. There is no "right" place to enter the cycle. Scientists can (and have) started their work by making extensive observations, but they can also start with a theory and test it. It makes no difference where you enter the cycle—eventually the scientific process takes you all the way around.
3. Observations and experiments must be reported in such a way that anyone with the proper equipment can verify the results. Scientific results, in other words, must be **reproducible**, and they must be reproducible by anyone with appropriate equipment and training, not just the original experimenters.
4. The cycle is continuous; it has no end. Science does not provide final answers, nor is it a search for ultimate truth. Instead, it is a way of producing successively more detailed and exact descriptions of wider and wider areas of the physical world—descriptions that allow us to predict more of the behavior of that world with higher and higher levels of confidence.

THE ONGOING PROCESS OF SCIENCE

The Duke Forest Experiments

One of the most important experimental techniques in all the sciences consists of comparing two situations that differ from each other in only one aspect. For example, in experiments on plant growth, you might compare one group of plants that received a particular soil supplement to another group that did not receive that supplement. In the language of science, we call the latter plants the 'control group,' and including such controls is an important part of the design of experiments.

In Chapter 19 we will see that one of the important facts about the current state of our planet is that human activities are increasing the levels of carbon dioxide in the atmosphere. Since plants need atmospheric carbon dioxide to grow, it's important to understand how plant behavior is affected by higher concentrations of the gas. One method of answering this question is to add carbon dioxide to the air in an enclosed space, such as a greenhouse, but it would obviously be more useful to see how increased carbon dioxide affects plants in their normal environment. The so-called 'Free Air CO_2 Enrichment' (FACE) experiments have been designed to study this question, and one of the oldest of these efforts is in a forest managed by Duke University in North Carolina (Figure 1-8).

Jeff Barnard / AP Images

FIGURE 1-8 The Duke Forest experiments measure the effects of atmospheric carbon dioxide on the growth rates of trees.

In the nineteenth century the 7000-acre plot now occupied by Duke Forest was farmed for cotton, but since 1931 it has reverted to forest. In 1982 some areas were clear cut and planted in loblolly pines (a native southern tree). Starting in 1994 seven experimental areas were set up. Each area was surrounded by a hollow pipe 30 m (about 90 feet) in diameter. In four of the areas, carbon dioxide was pumped in through the pipes to raise the gas concentration in the air to what scientists expect it will be in 2050. In the other three areas, to establish the control group, ambient air was pumped in instead. The scientists then monitored the growth of the forests in each area over time.

The results of the experiment were clear. The rate of photosynthesis in the enriched plots increased by 50% and the rate of biomass production increased by 27%. Other aspects of growth, such as root production and the amount of forest litter, increased as well. Over the years, FACE experiments have been conducted in many environments, from the Nevada desert to Tasmanian grasslands to Australian wheat fields. The results vary somewhat depending on the type of plant being studied, water availability, and ozone concentrations, but the general results are similar to those in the Duke forest.

Having said this, it should be stressed that these experiments also indicate that only a relatively small percentage of the carbon dioxide put into the atmosphere by human activity in the future can be offset by enhanced plant growth. If carbon dioxide levels in the atmosphere have to be reduced, some other methods will have to be developed.

SCIENCE IN THE MAKING

Dimitri Mendeleev and the Periodic Table

Discoveries of previously unrecognized patterns in nature, a key step in the scientific method, provide scientists with some of their most exhilarating moments. Dimitri Mendeleev (1834–1907), a popular chemistry professor at the Technological Institute of St. Petersburg in Russia, experienced such a breakthrough in 1869 as he was tabulating data for a new chemistry textbook (Figure 1-9).