SECOND EDITION

PRINCIPLES & PRACTICE OF PHYSICS

ERIC MAZUR

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SI Units, Useful Data, and Unit Conversion Factors

The seven base SI units

Unit	Abbreviation	Physical quantity
meter	m	length
kilogram	kg	mass
second	s	time
ampere	A	electric current
kelvin	K	thermodynamic temperature
mole	mol	amount of substance
candela	cd	luminous intensity

Some derived SI units

Unit	Abbreviation	Physical quantity	In terms of base units
newton	N	force	$kg \cdot m/s^2$
joule	J	energy	$kg \cdot m^2/s^2$
watt	W	power	$kg \cdot m^2/s^3$
pascal	Pa	pressure	$kg/m \cdot s^2$
hertz	Hz	frequency	s^{-1}
coulomb	C	electric charge	$A \cdot s$
volt	V	electric potential	$kg \cdot m^2/(A \cdot s^3)$
ohm	Ω	electric resistance	$kg \cdot m^2/(A^2 \cdot s^3)$
farad	F	capacitance	$A^2 \cdot s^4/(kg \cdot m^2)$
tesla	T	magnetic field	$kg/(A \cdot s^2)$
weber	Wb	magnetic flux	$kg \cdot m^2/(A \cdot s^2)$
henry	H	inductance	$kg \cdot m^2/(A^2 \cdot s^2)$

SI Prefixes

10^n	Prefix	Abbreviation	10^n	Prefix	Abbreviation
10^0	—	—			
10^3	kilo-	k	10^{-3}	milli-	m
10^6	mega-	M	10^{-6}	micro-	μ
10^9	giga-	G	10^{-9}	nano-	n
10^{12}	tera-	T	10^{-12}	pico-	p
10^{15}	peta-	P	10^{-15}	femto-	f
10^{18}	exa-	E	10^{-18}	atto-	a
10^{21}	zetta-	Z	10^{-21}	zepto-	z
10^{24}	yotta-	Y	10^{-24}	yocto-	y

Values of fundamental constants

Quantity	Symbol	Value
Speed of light in vacuum	c_0	3.00×10^8 m/s
Gravitational constant	G	6.6738×10^{-11} N·m²/kg²
Avogadro's number	N_A	$6.02214076 \times 10^{23}$ mol^{-1}
Boltzmann's constant	k_B	1.381×10^{-23} J/K
Charge on electron	e	1.60×10^{-19} C
Permittivity constant	ϵ_0	$8.85418782 \times 10^{-12}$ $C^2/(N \cdot m^2)$
Permeability constant	μ_0	$4\pi \times 10^{-7}$ T·m/A
Planck's constant	h	6.626×10^{-34} J·s
Electron mass	m_e	9.11×10^{-31} kg
Proton mass	m_p	1.6726×10^{-27} kg
Neutron mass	m_n	1.6749×10^{-27} kg
Atomic mass unit	amu	1.6605×10^{-27} kg

Other useful numbers

Number or quantity	Value
π	3.1415927
e	2.7182818
1 radian	57.2957795°
Absolute zero ($T = 0$)	−273.15°C
Average acceleration g due to gravity near Earth's surface	9.8 m/s²
Speed of sound in air at 20 °C	343 m/s
Density of dry air at atmospheric pressure and 20 °C	1.29 kg/m³
Earth's mass	5.97×10^{24} kg
Earth's radius (mean)	6.38×10^6 m
Earth–Moon distance (mean)	3.84×10^8 m

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HARVARD UNIVERSITY

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Brief Contents

Volume 1 of *Principles & Practice of Physics* includes Chapters 1–21. Volume 2 of *Principles & Practice of Physics* includes Chapters 22–34.

About the Author

Eric Mazur is the Balkanski Professor of Physics and Applied Physics at Harvard University, Area Chair of Applied Physics, and a member of the faculty of Education at the Harvard Graduate School of Education. Dr. Mazur is a renowned scientist and researcher in optical physics and in education research, and a sought-after author and speaker.

Dr. Mazur joined the faculty at Harvard shortly after obtaining his Ph.D. at the University of Leiden in the Netherlands. He was awarded Honorary Doctorates from the École Polytechnique and the University of Montreal, the Universidad Nacional Mayor de San Marcos in Lima, Peru, and the Katholieke Universiteit Leuven in Belgium. Dr. Mazur holds honorary professorships at the Institute of Semiconductor Physics of the Chinese Academy of Sciences in Beijing, the Institute of Laser Engineering at the Beijing University of Technology, the Beijing Normal University, Sichuan University, and Nanjing University of Science and Technology. He is a Member of the Royal Academy of Sciences of the Netherlands and a Member of the Royal Holland Society of Sciences and Humanities. In 2014, Dr. Mazur became the inaugural recipient of the Minerva Prize, and in 2018 he received the inaugural International Flipped Learning Award from the American Academy of Learning Arts and Sciences.

Dr. Mazur has held appointments as Visiting Professor or Distinguished Lecturer at Carnegie Mellon University, the Ohio State University, the Pennsylvania State University, Princeton University, Vanderbilt University, Hong Kong University, the University of Leuven in Belgium, and National Taiwan University in Taiwan, among others. From 2015–2017 Dr. Mazur served as Vice-President, President-Elect, and President of the Optical Society.

In addition to his work in optical physics, Dr. Mazur is interested in education, science policy, outreach, and the public perception of science. In 1990, he began developing Peer instruction, a method for teaching large lecture classes interactively. This teaching method has developed a large following, both nationally and internationally, and has been adopted across many science disciplines.

Dr. Mazur is author or co-author of over 300 scientific publications and holds three dozen patents. He has also written on education and is the author of *Peer Instruction: A User's Manual* (Pearson, 1997), a book that explains how to teach large lecture classes interactively. In 2006, he helped produce the award-winning DVD *Interactive Teaching*. He is the co-founder of Learning Catalytics, a platform for promoting interactive problem solving in the classroom, and of Perusall, the first truly AI-driven social learning platform.

To the Student

Let me tell you a bit about myself.

I always knew exactly what I wanted to do. It just never worked out that way.

When I was seven years old, my grandfather gave me a book about astronomy. Growing up in the Netherlands I became fascinated by the structure of the solar system, the Milky Way, the universe. I remember struggling with the concept of infinite space and asking endless questions without getting satisfactory answers. I developed an early passion for space and space exploration. I knew I was going to be an astronomer. In high school I was good at physics, but when I entered university and had to choose a major, I chose astronomy.

It took only a few months for my romance with the heavens to unravel. Instead of teaching me about the mysteries and structure of the universe, astronomy had been reduced to a mind-numbing web of facts, from declinations and right ascensions to semi-major axes and eccentricities. Disillusioned about astronomy, I switched majors to physics. Physics initially turned out to be no better than astronomy, and I struggled to remain engaged. I managed to make it through my courses, often by rote memorization, but the beauty of science eluded me.

It wasn't until doing research in graduate school that I rediscovered the beauty of science. I knew one thing for sure, though: I was never going to be an academic. I was going to do something useful in my life. Just before obtaining my doctorate, I lined up my dream job working on the development of the compact disc, but I decided to spend one year doing postdoctoral research first.

It was a long year. After my postdoc, I accepted a junior faculty position and started teaching. That's when I discovered that the combination of doing research—uncovering the mysteries of the universe—and teaching—helping others to see the beauty of the universe—is a wonderful combination.

When I started teaching, I did what all teachers did at the time: lecture. It took almost a decade to discover that my award-winning lecturing did for my students exactly what the courses I took in college had done for me: It turned the subject that I was teaching into a collection of facts that my students memorized by rote. Instead of transmitting the beauty of my field, I was essentially regurgitating facts to my students.

When I discovered that my students were not mastering even the most basic principles, I decided to completely change my approach to teaching. Instead of lecturing, I asked students to read my lecture notes at home, and then, in class, I taught by questioning—by asking my students to reflect on concepts, discuss in pairs, and experience their own "aha!" moments.

Over the course of more than twenty years, the lecture notes have evolved into this book. Consider this book to be my best possible "lecturing" to you. But instead of listening to me without having the opportunity to reflect and think, this book will permit you to pause and think; to hopefully experience many "aha!" moments on your own.

I hope this book will help you develop the thinking skills that will make you successful in your career. And remember: your future may be—and likely will be—very different from what you imagine.

I welcome any feedback you have. Feel free to send me email or tweets.

I wrote this book for you.

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To the Instructor

As you may recall from the first edition of this book, the idea of using conservation principles derived from a conversation with a dear friend and colleague, Albert Altman, professor at the University of Massachusetts, Lowell, who asked me if I was familiar with the approach to physics taken by Ernst Mach.

Mach treats conservation of momentum before discussing the laws of motion. It involves direct experimental observation, which appealed to me. His formulation of mechanics had a profound influence on Einstein. Most physicists never use the concept of force because it relates only to mechanics. It has no role in quantum physics, for example. The conservation principles, however, hold throughout all of physics. In that sense they are much more fundamental than Newton's laws. Furthermore, conservation principles involve only algebra, whereas Newton's second law is a differential equation.

Physics education research has shown that the concept of force, where most physics books begin, is fraught with pitfalls. What's more, after tediously deriving many results using kinematics and dynamics, most physics textbooks show that you can derive the same results from conservation principles in just one or two lines. Why not do the easy way first?

In this edition Principles and Practice of Physics, I start with conservation of both momentum and energy, and later bring in the concept of force. The approach is more unified and modern—the conservation principles are the theme that runs throughout this entire book.

Additional motives for writing this text came from my own teaching. Most textbooks focus on the acquisition of information and on the development of procedural knowledge. This focus comes at the expense of conceptual understanding or the ability to transfer knowledge to a new context. As explained below, I have structured this text to redress that balance. I also have drawn deeply on the results of physics education research, including that of my own research group.

Organization of this book

As I considered the best way to convey the conceptual framework of mechanics, it became clear that the standard curriculum needed rethinking. For example, standard texts are forced to redefine certain concepts more than once—a strategy that we know befuddles students. (Examples are work, the standard definition of which is incompatible with the first law of thermodynamics, and energy, which is redefined when modern physics is discussed.)

Another point that has always bothered me is the arbitrary division between "modern" and "classical" physics. In most texts, the first thirty-odd chapters present physics essentially as it was known at the end of the 19th century; "modern physics" gets tacked on at the end. There's no need for this separation. Our goal should be to explain physics in the way that works best for students, using our full contemporary understanding. All physics is modern!

That is why my table of contents departs from the "standard organization" in the following specific ways.

Emphasis on conservation laws. As mentioned earlier, this book introduces the conservation laws early and treats them the way they should be: as the backbone of physics. The advantages of this shift are many. First, it avoids many of the standard pitfalls related to the concept of force, and it leads naturally to the two-body character of forces and the laws of motion. Second, the conservation laws enable students to solve a wide variety of problems without any calculus. Indeed, for complex systems, the conservation laws are often the natural (or only) way to solve problems. Third, the book deduces the conservation laws from experimental observations, helping to make clear their connection with the world around us. I and several other instructors have tested this approach extensively in our classes and found markedly improved performance on problems involving momentum and energy, with large gains on assessment instruments like the Force Concept Inventory.

Early emphasis on the concept of system. Fundamental to most physical models is the separation of a system from its environment. This separation is so basic that physicists tend to carry it out unconsciously, and traditional texts largely gloss over it. This text introduces the concept in the context of conservation principles and uses it consistently.

Postponement of vectors. Most introductory physics concerns phenomena that take place along one dimension. Problems that involve more than one dimension can be broken down into one-dimensional problems using vectorial notation. So, a solid understanding of physics in one dimension is of fundamental importance. However, by introducing vectors in more than one dimension from the start, standard texts distract the student from the basic concepts of kinematics.

In this book, I develop the complete framework of mechanics for motions and interactions in one dimension. I introduce the second dimension when it is needed, starting with rotational motion. Hence, students can focus on the actual physics early on.

Table 1 Scheduling matrix

Topic	Chapters	Can be inserted after chapter . . .	Chapters that can be omitted without affecting continuity
Mechanics	1–14		6, 13–14
Waves	15–17	12	16–17
Fluids	18	9	
Thermal Physics	19–21	10	21
Electricity & Magnetism	22–30	12 (but 17 is needed for 29–30)	29–30
Circuits	31–32	26 (but 30 is needed for 32)	32
Optics	33–34	17	34

Just-in-time introduction of concepts. Wherever possible, I introduce concepts only when they are necessary. This approach allows students to put ideas into immediate practice, leading to better assimilation.

Integration of modern physics. A survey of syllabi shows that less than half the calculus-based courses in the United States cover modern physics. I have therefore integrated selected "modern" topics throughout the text. For example, special relativity is covered in Chapter 14, at the end of mechanics. Chapter 32, Electronics, includes sections on semiconductors and semiconductor devices. Chapter 34, Wave and Particle Optics, contains sections on quantization and photons.

Modularity. I have written the book in a modular fashion so it can accommodate a variety of curricula (See Table 1, "Scheduling matrix").

The book contains two major parts, Mechanics and Electricity and Magnetism, plus five shorter parts. The two major parts by themselves can support an in-depth two-semester or three-quarter course that presents a complete picture of physics embodying the fundamental ideas of modern physics. Additional parts can be added for a longer or faster-paced course. The five shorter parts are more or less self-contained, although they do build on previous material, so their placement is flexible. Within each part or chapter, more advanced or difficult material is placed at the end.

Pedagogy

This text draws on many models and techniques derived from my own teaching and from physics education research. The following are major themes that I have incorporated throughout.

Separation of conceptual and mathematical frameworks. Each chapter is divided into two parts: Concepts and Quantitative Tools. The first part, Concepts, develops the full conceptual framework of the topic and addresses many of the common questions students have. It concentrates on the underlying ideas and paints the big picture, whenever possible without equations. The second part of the chapter, Quantitative Tools, then develops the mathematical framework.

Deductive approach; focus on ideas before names and equations. To the extent possible, this text develops arguments deductively, starting from observations, rather than stating principles and then "deriving" them. This approach makes the material easier to assimilate for students. In the same vein, this text introduces and explains each idea before giving it a formal name or mathematical definition.

Stronger connection to experiment and experience. Physics stems from observations, and this text is structured so that it can do the same. As much as possible, I develop the material from experimental observations (and preferably those that students can make) rather than assertions. Most chapters use actual data in developing ideas, and new notions are always introduced by going from the specific to the general—whenever possible by interpreting everyday examples.

By contrast, standard texts often introduce laws in their most general form and then show that these laws are consistent with specific (and often highly idealized) cases. Consequently, the world of physics and the "real" world remain two different things in the minds of students.

Addressing physical complications. I also strongly oppose presenting unnatural situations; real life complications must always be confronted head-on. For example, the use of unphysical words like frictionless or massless sends a message to the students that physics is unrealistic or, worse, that the world of physics and the real world are unrelated entities. This can easily be avoided by pointing out that friction or mass may be neglected under certain circumstances and pointing out why this may be done.

Engaging the student. Education is more than just transfer of information. Engaging the student's mind so the information can be assimilated is essential. To this end, the text is written as a dialog between author and reader (often invoking the reader—you—in examples) and is punctuated by Checkpoints—questions that require the reader to stop and think. The text following a Checkpoint often refers directly to its conclusions. Students will find complete solutions to all the Checkpoints at the back of the book; these solutions are written to emphasize physical reasoning and discovery.

Visualization. Visual representations are central to physics, so I developed each chapter by designing the figures before writing the text. Many figures use multiple representations to help students make connections (for example, a sketch may be combined with a graph and a bar diagram). Also, in accordance with research, the illustration style is spare and simple, putting the emphasis on the ideas and relationships rather than on irrelevant details. The figures do not use perspective unless it is needed, for instance.

Physics for today's student

This new edition focuses on today's physics student who not only learns in the physical classroom but gleans knowledge in a digital environment. The content format is modified for students to actively engage with online content first. The second edition optimizes the delivery of the content by combining both volumes of the first edition (Principles volume and Practice volume) and providing it as one single volume via etext and Mastering Physics.

Best practices reflect the idea that by engaging with the material before coming to class better prepares students to learn. The new edition provides new prelecture videos by both Eric Mazur and his Harvard colleague Greg Kestin (researcher and consultant for NOVA) to help students come to class ready to participate, encourage the understanding of real-world application of physics, and support instructors in building active and relevant classes.

As pointed out earlier, each chapter is divided into two parts. The first part (Concepts) develops the conceptual framework in an accessible way, relying primarily on qualitative descriptions and illustrations. In addition to including Checkpoints, each Concepts section ends with a one-page Self-quiz consisting of qualitative questions. The second part of each chapter (Quantitative Tools) formalizes the ideas developed in the first part in mathematical terms. While concise, it is relatively traditional in nature—teachers should be able to continue to use material developed for earlier courses. To avoid creating the impression that equations are more important than the concepts behind them, no equations are highlighted or boxed. Both parts of the chapters contain worked examples to help students develop problem-solving skills.

At the end of each chapter is a Chapter Summary and a Questions and Problems section. The problems 1) offer a range of levels; 2) include problems relating to client disciplines (life sciences, engineering, chemistry, astronomy, etc.); 3) use the second person as much as possible to draw in the student; and 4) do not spoon-feed the students with information and unnecessary diagrams. The problems are classified into three levels as follows: (•) application of single concept; numerical plug-and-chug; (••) nonobvious application of single concept or application of multiple concepts from current chapter; straightforward numerical or algebraic computation; (•••) application of multiple concepts, possibly spanning multiple chapters. Context-rich problems are designated CR.

Additional material can be found online in Mastering Physics:

1. *Review Questions.* The goal of this section is to allow students to quickly review the corresponding chapter. The questions are straightforward one-liners starting with "what" and "how" (rather than "why" or "what if"). These questions are in Mastering Physics and interactive etext.
2. *Developing a Feel.* The goals of this section are to develop a quantitative feel for the quantities introduced in the chapter; to connect the subject of the chapter to the real world; to train students in making estimates and assumptions; to bolster students' confidence in dealing with unfamiliar material. It can be used for self-study or for a homework or recitation assignment. This section, which has no equivalent in existing books, combines a number of ideas (specifically, Fermi problems and tutoring in the style of the *Princeton Learning Guide*). The idea is to start with simple estimation problems and then build up to Fermi problems (in early chapters Fermi problems are hard to compose because few concepts have been introduced). Because students initially find these questions hard, the section provides many hints, which take the form of guiding questions. A key then provides answers to these "hints." These Developing a Feel questions are now included in Mastering Physics, as well as in the interactive etext.
3. *Worked and Guided Problems.* This section contains worked examples whose primary goal is to teach problem solving. The Worked Problems are fully solved; the Guided Problems have a list of guiding questions and suggestions to help the student think about how to solve the problem. Typically, each Worked Problem is followed by a related Guided Problem. Both are available in Mastering Physics and the interactive etext.

Instructor supplements

Downloadable ***Instructor Resources*** (ISBN 013561113X/9780135611135) includes an Image Library, the Procedure and special topic boxes from *Principles and Practice of Physics*, and a library PhET simulations and PhET Clicker Questions. **Lecture Outlines** with embedded **Clicker Questions in PowerPoint®** are provided, as well as the ***Instructor's Guide*** and ***Instructor's Solutions Manual.***

The ***Instructor's Guide*** (ISBN 0135611091/9780135611098) provides chapter-by-chapter ideas for lesson planning using *Principles & Practice of Physics* in class, including strategies for addressing common student difficulties.

The ***Instructor's Solutions Manual*** (ISBN 0135610893/9780135610893) is a comprehensive solutions manual containing complete answers and solutions to Questions and Problems found at the end of each chapter, as well as all Developing a Feel questions and Guided Problems found in Mastering Physics. The solutions to the Guided Problems use the book's four-step problem-solving strategy (Getting Started, Devise Plan, Execute Plan, Evaluate Result).

Mastering Physics® is the leading online homework, tutorial, and assessment product designed to improve results by helping students quickly master concepts. Students benefit from self-paced tutorials that feature specific wrong-answer feedback, hints, and a wide variety of educationally effective content to keep them engaged and on track. Robust diagnostics and unrivalled gradebook reporting allow instructors to pinpoint the weaknesses and misconceptions of a student or class to provide timely intervention.

Mastering Physics enables instructors to:

- Easily assign **tutorials** that provide individualized coaching.
- Mastering's hallmark **Hints** and **Feedback** offer scaffolded instruction similar to what students would experience in an office hour.
- **Hints** (declarative and Socratic) can provide problem-solving strategies or break the main problem into simpler exercises.
- **Feedback** lets the student know precisely what misconception or misunderstanding is evident from their answer and offers ideas to consider when attempting the problem again.

Learning Catalytics™ is a "bring your own device" student engagement, assessment, and classroom intelligence system available within Mastering Physics. With Learning Catalytics you can:

- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students' critical-thinking skills.
- Access rich analytics to understand student performance.
- Add your own questions to make Learning Catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

The **Test Bank** (ISBN 0135610729/9780135610725) contains more than 2000 high-quality problems, with a range of multiple-choice, true-false, short-answer, and conceptual questions correlated to *Principles & Practice of Physics* chapters. Test files are provided in both TestGen® and Microsoft® Word for Mac and PC.

Instructor supplements are available in the Instructor Resource area of Mastering Physics (www.masteringphysics.com).

Student supplements

Mastering Physics (www.masteringphysics.com) is designed to provide students with customized coaching and individualized feedback to help improve problem-solving skills. Students complete homework efficiently and effectively with tutorials that provide targeted help. By combining trusted author content with digital tools developed to engage students and emulate the office-hour experience, Mastering personalizes learning and improves results for each student. Built for, and directly tied to the text, Mastering Physics gives students a platform to practice, learn, and apply knowledge outside of the classroom.

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Reviewers of *Principles & Practice of Physics*

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Cindy Schwarz, *Vassar College*
Hugh Scott, *Illinois Institute of Technology*
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Shahid Shaheen, *Florida State University*
David Sokoloff, *University of Oregon*
Gay Stewart, *University of Arkansas*
Roger Stockbauer, *Louisiana State University*
William Sturrus, *Youngstown State University*
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Christopher Watts, *Auburn University*
Robert Weidman, *Michigan Technological University*
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Detailed Contents

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1 Foundations

Chances are you are taking this course in physics because someone told you to take it, and it may not be clear to you *why* you should be taking it. One good reason for taking a physics course is that, first and foremost, physics provides a fundamental understanding of the world. Furthermore, whether you are majoring in psychology, engineering, biology, physics, or something else, this course offers you an opportunity to sharpen your reasoning skills. Knowing physics means becoming a better problem solver (and I mean *real* problems, not textbook problems that have already been solved), and becoming a better problem solver is empowering: It allows you to step into unknown territory with more confidence. Before we embark on this exciting journey, let's map out the territory we are going to explore so that you know where we are going.

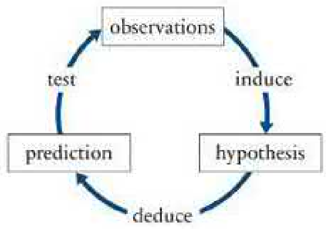
1.1 The scientific method

Physics, from the Greek word for "nature," is commonly defined as the study of matter and motion. Physics is about discovering the wonderfully simple unifying patterns that underlie absolutely everything that happens around us, from the scale of subatomic particles, to the microscopic world of DNA molecules and cells, to the cosmic scale of stars, galaxies, and planets. Physics deals with atoms and molecules; gases, solids, and liquids; everyday objects and black holes. Physics explores motion, light, and sound; the creation and annihilation of matter; evaporation and melting; electricity and magnetism. Physics is all around you: in the Sun that provides your daylight, in the structure of your bones, in your computer, in the motion of a ball you throw. In a sense, then, physics is the study of all there is in the universe. Indeed, biology, engineering, chemistry, astronomy, geology, and so many other disciplines you might name all use the principles of physics.

The many remarkable scientific accomplishments of ancient civilizations that survive to this day testify to the fact that curiosity about the world is part of human nature. Physics evolved from *natural philosophy*—a body of knowledge accumulated in ancient times in an attempt to explain the behavior of the universe through philosophical speculation—and became a distinct discipline during the scientific revolution that began in the 16th century. One of the main changes that occurred in that century was the development of the **scientific method,** an iterative process for going from observations to validated theories.

In its simplest form, the scientific method works as follows (**Figure 1.1**): A researcher makes a number of observations concerning either something happening in the natural world (a volcano erupting, for instance) or something happening during a laboratory experiment (a dropped brick and a dropped Styrofoam peanut travel to the floor at different speeds). These observations then lead the researcher to formulate a **hypothesis,** which is a tentative explanation of the observed phenomenon. The hypothesis is used to predict the outcome of some related natural occurrence (how a similarly shaped mountain near the erupting volcano will behave) or related laboratory experiment (what happens when a book and a sheet of paper are dropped at the same time). If the predictions prove inaccurate, the hypothesis must be modified. If the predictions prove accurate in test after test, the hypothesis is elevated to the status of either a **law** or a **theory.**

Figure 1.1 The scientific method is an iterative process in which a hypothesis, which is inferred from observations, is used to make a prediction, which is then tested by making new observations.



A law tells us *what* happens under certain circumstances. Laws are usually expressed in the form of relationships between observable quantities. A theory tells us *why* something happens and explains phenomena in terms of more basic processes and relationships. A scientific theory is not a mere conjecture or speculation. It is a thoroughly tested explanation of a natural phenomenon, one that is capable of making predictions that can be verified by experiment. The constant testing and retesting are what make the scientific method such a powerful tool for investigating the universe: The results obtained must be repeatable and verifiable by others.

EXERCISE 1.1 Hypothesis or not?

Which of the following statements are hypotheses? (*a*) Heavier objects fall to Earth faster than lighter ones. (*b*) The planet Mars is inhabited by invisible beings that are able to elude any type of observation. (*c*) Distant planets harbor forms of life. (*d*) Handling toads causes warts.

SOLUTION (*a*), (*c*), and (*d*). A hypothesis must be experimentally verifiable. (*a*) I can verify this statement by dropping a heavy object and a lighter one at the same instant and observing which one hits the ground first. (*b*) This statement asserts that the beings on Mars cannot be observed, which precludes any experimental verification and means this statement is not a valid hypothesis. (*c*) Although we humans currently have no means of exploring or closely observing distant planets, the statement is in principle testable. (*d*) Even though we know this statement is false, it *is* verifiable and therefore is a hypothesis.

Because of the constant reevaluation demanded by the scientific method, science is not a stale collection of facts but rather a living and changing body of knowledge. More important, any theory or law *always* remains tentative, and the testing never ends. In other words, it is not possible to prove any scientific theory or law to be absolutely true (or even absolutely false). Thus the material you will learn in this book does not represent some "ultimate truth"—it is true only to the extent that it has not been proved wrong.

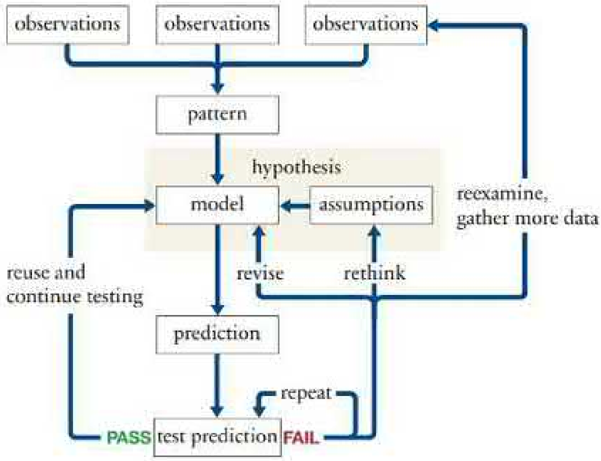
A case in point is *classical mechanics*, a theory developed in the 17th century to describe the motion of everyday objects (and the subject of most of this book). Although this theory produces accurate results for most everyday phenomena, from balls thrown in the air to satellites orbiting Earth, observations made during the last hundred years have revealed that under certain circumstances, significant deviations from this theory occur. It is now clear that classical mechanics is applicable for only a limited (albeit important) range of phenomena, and new branches of physics—*quantum mechanics* and the theory of *special relativity* among them—are needed to describe the phenomena that fall outside the range of classical mechanics.

The formulation of a hypothesis almost always involves developing a **model**, which is a simplified conceptual representation of some phenomenon. You don't have to be trained as a scientist to develop models. Everyone develops mental models of how people behave, how events unfold, and how things work. Without such models, we would not be able to understand our experiences, decide what actions to take, or handle unexpected experiences. Examples of models we use in everyday life are that door handles and door hinges are on opposite sides of doors and that the + button on a TV remote increases the volume or the channel number. In everyday life, we base our models on whatever knowledge we have, real or imagined, complete or incomplete. In science we must build models based on careful observation and determine ways to fill in any missing information.

Let's look at the iterative process of developing models and hypotheses in physics, with an eye toward determining what skills are needed and what pitfalls are to be avoided (**Figure 1.2**). Developing a scientific hypothesis often begins with recognizing patterns in a series of observations. Sometimes these observations are direct, but sometimes we must settle for indirect observations. (We cannot directly observe the nucleus of an atom, for instance, but a physicist can describe the structure of the nucleus and its behavior with great certainty and accuracy.) As Figure 1.2 indicates, the patterns that emerge from our observations must often be combined with simplifying assumptions to build a model. The combination of model and assumptions is what constitutes a hypothesis.

It may seem like a shaky proposition to build a hypothesis on assumptions that are accepted without proof, but making these assumptions—*consciously*—is a crucial step in making sense of the universe. All that is required is that, when formulating a hypothesis, we must be aware

Figure 1.2 Iterative process for developing a scientific hypothesis.



of these assumptions and be ready to revise or drop them if the predictions of our hypothesis are not validated. We should, in particular, watch out for what are called *hidden assumptions*—assumptions we make without being aware of them. As an example, try answering the following question. (Turn to the final section of this book, "Solutions to checkpoints," for the answer.)

> **1.1** I have two coins in my pocket, together worth 30 cents. If one of them is not a nickel, what coins are they?

Advertising agencies and magicians are masters at making us fall into the trap of hidden assumptions. Imagine a radio commercial for a new drug in which someone says, "Baroxan lowered my blood pressure tremendously." If you think that sounds good, you have made a number of assumptions without being aware of them—in other words, hidden assumptions. Who says, for instance, that lowering blood pressure "tremendously" is a good thing (dead people have tremendously low blood pressure) or that the speaker's blood pressure was too high to begin with?

Magic, too, involves hidden assumptions. The trick in some magic acts is to make you assume that something happens, often by planting a false assumption in your mind. A magician might ask, "How did I move the ball from here to there?" while in reality he is using two balls. I won't knowingly put false assumptions into *your* mind in this book, but on occasion you and I (or you and your instructor) may unknowingly make different assumptions during a given discussion, a situation that unavoidably leads to confusion and misunderstanding. Therefore it is important that we carefully analyze our thinking and watch for the assumptions that we build into our models.

If the prediction of a hypothesis fails to agree with observations made to test the hypothesis, there are several ways to address the discrepancy. One way is to rerun the test to see if it is reproducible. If the test keeps producing the same result, it becomes necessary to revise the hypothesis, rethink the assumptions that went into it, or reexamine the original observations that led to the hypothesis.

EXERCISE 1.2 Stopped clock

A battery-operated wall clock no longer keeps time—neither hand moves. Develop a hypothesis explaining why it fails to work, and then make a prediction that permits you to test your hypothesis. Describe two possible outcomes of the test and what you conclude from the outcomes. (*Think* before you peek at the answer below.)

SOLUTION There are many reasons the clock might not run. Here is one example. Hypothesis: The batteries are dead. Prediction: If I replace the batteries with new ones, the clock should work. Possible outcomes: (1) The clock works once the new batteries are installed, which means the hypothesis is supported; (2) the clock doesn't work after the new batteries are installed, which means the hypothesis is not supported and must be either modified or discarded.

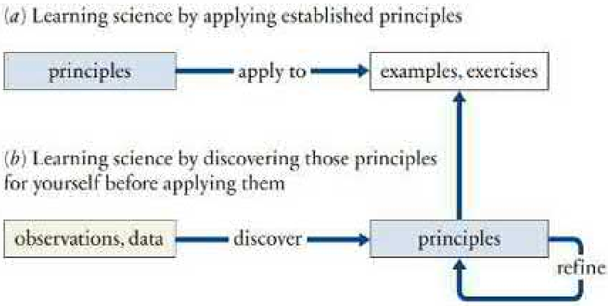
1.2 In Exercise 1.2, each of the conclusions drawn from the two possible outcomes contains a hidden assumption. What are the hidden assumptions?

The development of a scientific hypothesis is often more complicated than suggested by Figures 1.1 and 1.2. Hypotheses do not always start with observations; some are developed from incomplete information, vague ideas, assumptions, or even complete guesses. The refining process also has its limits. Each refinement adds complexity, and at some point the complexity outweighs the benefit of the increased accuracy. Because we like to think that the universe has an underlying simplicity, it might be better to scrap the hypothesis and start anew.

Figure 1.2 gives an idea of the skills that are useful in doing science: interpreting observations, recognizing patterns, making and recognizing assumptions, thinking logically, developing models, and using models to make predictions. It should not come as any surprise to you that many of these skills are useful in just about any context. Learning physics allows you to sharpen these skills in a very rigorous way. So, whether you become a financial analyst, a doctor, an engineer, or a research scientist (to name just a few possibilities), there is a good reason to take physics.

Figure 1.1 also shows that doing science—and physics in particular—involves two types of reasoning: *inductive*, which is arguing from the specific to the general, and *deductive*, arguing from the general to the specific. The most creative part of doing physics involves inductive reasoning, and this fact sheds light on how you might want to learn physics. One way, which is neither very useful nor very satisfying, is for me to simply tell you all the general principles physicists presently agree on and then for

Figure 1.3



you to apply those principles in examples and exercises (**Figure 1.3a**).This approach involves deductive reasoning only and robs you of the opportunity to learn the skill that is the most likely to benefit your career: discovering underlying patterns. Another way is for me to present you with data and observations and make you part of the discovery and refinement of the physics principles (Figure 1.3*b*). This approach is more time-consuming, and sometimes you may wonder why I'm not just *telling* you the final outcome. The reason is that discovery and refinement are at the heart of doing physics!

1.3 After reading this section, reflect on your goals for this course. Write down what you would like to accomplish and why you would like to accomplish this. Once you have done that, turn to the final section of this book, "Solutions to checkpoints," and compare what you have written with what I wrote.

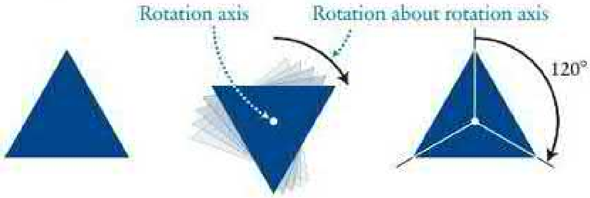
1.2 Symmetry

One of the basic requirements of any law of the universe involves what physicists call *symmetry*, a concept often associated with order, beauty, and harmony. We can define **symmetry** as follows: An object exhibits symmetry when certain operations can be performed on it without changing its appearance. Consider the equilateral triangle in **Figure 1.4a**. If you close your eyes and someone rotates the triangle by 120° while you have your eyes closed, the triangle appears the same when you open your eyes, and you can't tell that it has been rotated. The triangle is said to have *rotational symmetry*, one of several types of geometrical symmetry.

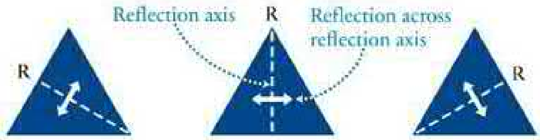
Another common type of geometrical symmetry, *reflection symmetry*, occurs when one half of an object is the mirror image of the other half. The equilateral triangle in Figure 1.4 possesses reflection symmetry about the three axes shown in Figure 1.4*b*. If you imagine folding the triangle in half over each axis, you can see that the two halves are identical. Reflection symmetry occurs all around us: in the arrangement of atoms in crystals (**Figure 1.5a** and *b*) and in the anatomy of most life forms (Figure 1.5*c*), to name just two examples.

Figure 1.4

(*a*) Rotational symmetry: Rotating an equilateral triangle by 120° doesn't change how it looks



(*b*) Reflection symmetry: Across each reflection axis (labeled R), two sides of the triangle are mirror images of each other



The ideas of symmetry—that something appears unchanged under certain operations—apply not only to the shape of objects but also to the more abstract realm of physics. If there are things we can do to an experiment that leave the result of the experiment unchanged, then the phenomenon tested by the experiment is said to possess certain symmetries. Suppose we build an apparatus, carry out a certain measurement in a certain location, then move the apparatus to another location, repeat the measurement, and get the same result in both locations.* By moving the apparatus to a new location (*translating* it) and obtaining the same result, we have shown that the observed phenomenon has *translational symmetry*. Any physical law that describes this phenomenon must therefore mathematically exhibit translational symmetry; that is, the mathematical expression of this law must be independent of the location.

*In moving our apparatus, we must take care to move any relevant external influences along with it. For example, if Earth's gravity is of importance, then moving the apparatus to a location in space far from Earth does not yield the same result.

Likewise, we expect any measurements we make with our apparatus to be the same at a later time as at an earlier time; that is, translation in time has no effect on the measurements. The laws describing the phenomenon we are studying must therefore mathematically exhibit symmetry under translation in time; in other words, the mathematical expression of these laws must be independent of time.

EXERCISE 1.3 Change is no change

Figure 1.6 shows a snowflake. Does the snowflake have rotational symmetry? If yes, describe the ways in which the flake can be rotated without changing its appearance. Does it have reflection symmetry? If yes, describe the ways in which the flake can be split in two so that one half is the mirror image of the other.

Figure 1.6 Exercise 1.3.

SOLUTION I can rotate the snowflake by 60° or a multiple of 60° (120°, 180°, 240°, 300°, and 360°) in the plane of the photograph without changing its appearance (**Figure 1.7*a***). It therefore has rotational symmetry.

I can also fold the flake in half along any of the three blue axes and along any of the three red axes in Figure 1.7*b*. The flake therefore has reflection symmetry about all six of these axes.

Figure 1.7

(*a*) Rotational symmetry (*b*) Reflection symmetry

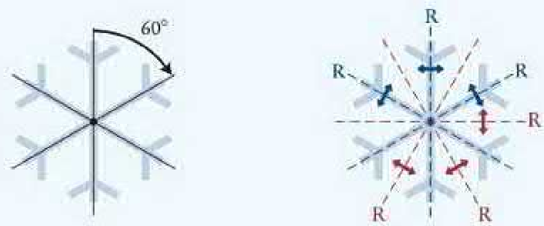
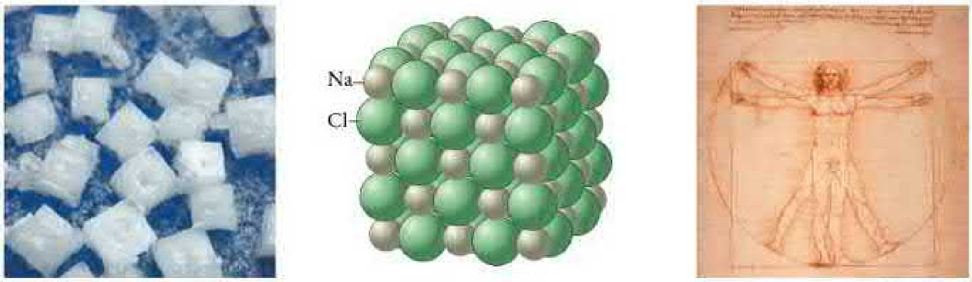


Figure 1.5 The symmetrical arrangement of atoms in a salt crystal gives these crystals their cubic shape.

(*a*) Micrograph of salt crystals

(*b*) Symmetrical arrangement of atoms in a salt crystal

(*c*) Da Vinci's Vitruvian Man shows the reflection symmetry of the human body



A number of such symmetries have been identified, and the basic laws that govern the inner workings of the physical world must reflect these symmetries. Some of these symmetries are familiar to you, such as translational symmetry in space or time. Others, like electrical charge or parity symmetry, are unfamiliar and surprising and go beyond the scope of this course. Whereas symmetry has always implicitly been applied to the description of the universe, it plays an increasingly important role in physics: In a sense the quest of physics in the 21st century is the search for (and test of) symmetries because these symmetries are the most fundamental principles that all physical laws must obey.

1.4 You always store your pencils in a cylindrical case. One day while traveling in the tropics, you discover that the cap, which you have placed back on the case day in, day out for years, doesn't fit over the case. What do you conclude?

1.3 Matter and the universe

The goal of physics is to describe all that happens in the universe. Simply put, the **universe** is the totality of matter and energy combined with the space and time in which all events happen—everything that is directly or indirectly observable. To describe the universe, we use *concepts*, which are ideas or general notions used to analyze natural phenomena.* To provide a quantitative description, these concepts must be expressed quantitatively, which requires defining a procedure for measuring them. Examples are the length or mass of an object, temperature, and time intervals. Such **physical quantities** are the cornerstones of physics. It is the accurate measurement of physical quantities that has led to the great discoveries of physics. Although many of the fundamental concepts we use in this book are familiar ones, quite a few are difficult to define in words, and we must often resort to defining these concepts in terms of the procedures used to measure them.

The fundamental physical quantity by which we map out the universe is **length**—a distance or an extent in space. The length of a straight or curved line is measured by comparing the length of the line with some standard length. In 1791, the French Academy of Sciences defined the standard unit for length, called the **meter** and abbreviated m, as one ten-millionth of the distance from the equator to the North Pole. For practical reasons, the standard was redefined in 1889 as the distance between two fine lines engraved on a bar of platinum-iridium alloy kept at the International Bureau of Weights and Measures near Paris. With the advent of lasers, however, it became possible to measure the speed of light with extraordinary accuracy, and so the meter was redefined in 1983 as the distance traveled by light in vacuum in a time interval of $1/299{,}792{,}458$ of a second. This number is chosen so as to make the speed of light exactly 299,792,458 meters per second and yield a standard length for the meter that is very close to the length of the original platinum-iridium standard. This laser-based standard may never need to be revised.

1.5 Based on the early definition of the meter, one ten-millionth of the distance from the equator to the North Pole, what is Earth's radius?

Now that we have defined a standard for length, let us use this standard to discuss the structure and size scales of the universe. Because of the extraordinary range of size scales in the universe, we shall round off any values to the nearest power of ten. Such a value is called an **order of magnitude.** For example, any number between 0.3 and 3 has an order of magnitude of 1 because it is within a factor of 3 of 1; any number greater than 3 and equal to or less than 30 has an order of magnitude of 10. You determine the order of magnitude of any quantity by writing it in scientific notation and rounding the coefficient in front of the power of ten to 1 if it is equal to or less than 3 or to 10 if it is greater than 3.† For example, 3 minutes is 180 s, which can be written as 1.8×10^2 s. The coefficient, 1.8, rounds to 1, and so the order of magnitude is $1 \times 10^2\ \text{s} = 10^2$ s. The quantity 680, to take another example, can be written as 6.8×10^2; the coefficient 6.8 rounds to 10, and so the order of magnitude is $10 \times 10^2 = 10^3$. And Earth's circumference is 40,000,000 m, which can be written as 4×10^7 m; the order of magnitude of this number is 10^8 m. You may think that using order-of-magnitude approximations is not very scientific because of the lack of accuracy, but the ability to work effectively with orders of magnitude is a key skill not just in science but also in any other quantitative field of endeavor.

All ordinary matter in the universe is made up of basic building blocks called **atoms** (Figure 1.8). Nearly all the matter in an atom is contained in a dense central nucleus, which consists of **protons** and **neutrons,** two types of subatomic particles. A tenuous *cloud* of **electrons,** a third type of subatomic particle, surrounds this nucleus. To an approximation, atoms are spherical and have a diameter of about 10^{-10} m. Spherical atomic nuclei have a diameter of about 10^{-15} m, making atoms mostly empty space. Atoms attract one another when they are a small distance apart but resist being squeezed into one another. The arrangement of atoms in a material helps determine the properties of the material.

*When an important concept is introduced in this book, the main word pertaining to the concept is printed in **boldface type.** All important concepts introduced in a chapter are listed at the back of this book, in the Glossary.

†The reason we use 3 in order-of-magnitude rounding, and not 5 as in ordinary rounding, is that orders of magnitude are logarithmic, and on this logarithmic scale $\log 3 = 0.48$ lies nearly halfway between $\log 1 = 0$ and $\log 10 = 1$.

CONCEPTS

Figure 1.8 Scanning tunneling microscope image showing the individual atoms that make up a silicon surface. The size of each atom is about 1/50,000 the width of a human hair.

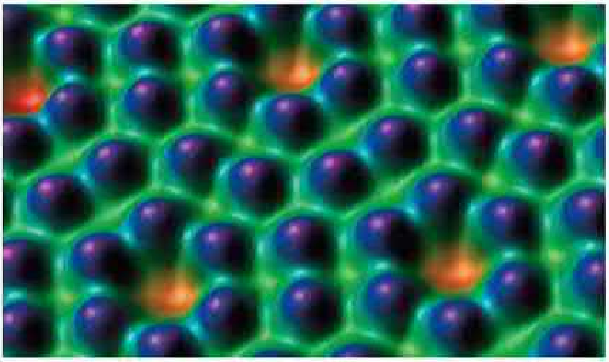


Figure 1.9 shows the relative size of some representative objects in the universe. The figure reveals a lot about the organization of matter in the universe and serves as a visual model of the structure of the universe. Roughly speaking, there is clustering of matter from smaller to larger at four length scales. At the subatomic scale, most of the matter in an atom is compressed into the tiny atomic nucleus, a cluster of subatomic particles. Atoms, in turn, cluster to form the objects and materials that surround us, from viruses to plants, animals, and other everyday objects. The next level is the clustering of matter in stars, some of which, such as the Sun, are surrounded by planets like Earth. Stars, in turn, cluster to form galaxies. As we shall discuss in Chapter 7, this clustering of matter reveals a great deal about the way different objects interact with one another.

EXERCISE 1.4 Tiny universe

If all the matter in the observable universe were squeezed together as tightly as the matter in the nucleus of an atom, what order of magnitude would the diameter of the universe be?

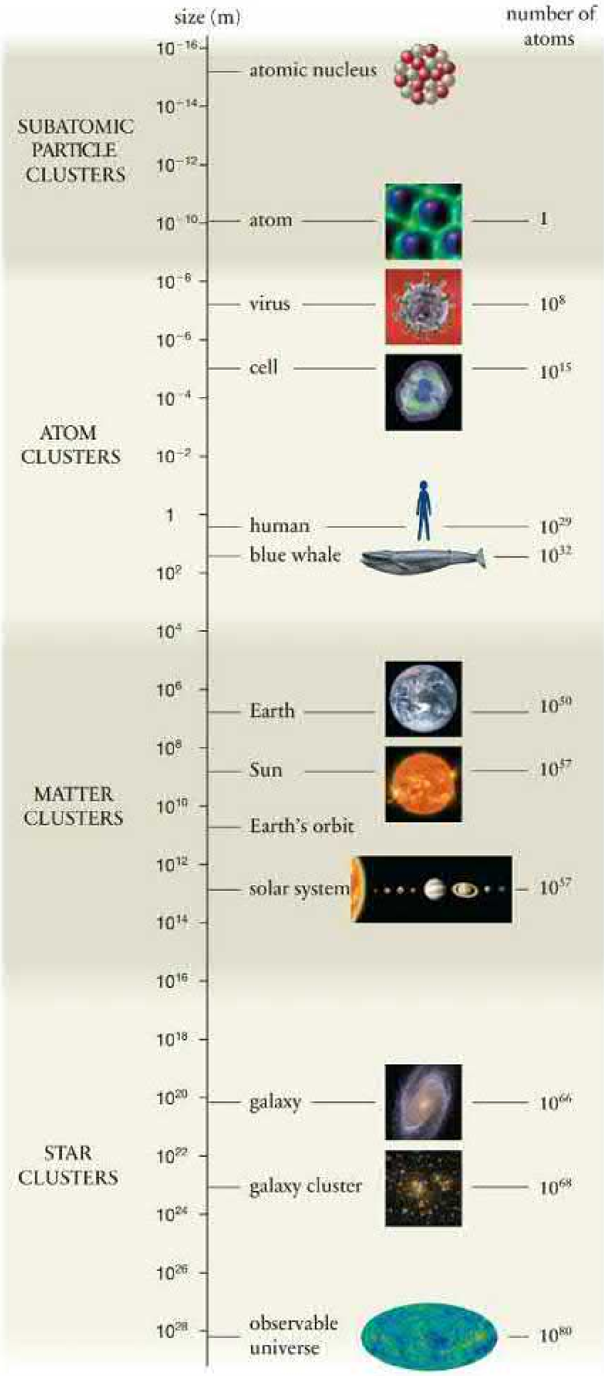
SOLUTION From Figure 1.9 I see that there are about 10^{80} atoms in the universe. I can arrange these atoms in a cube that has 10^{27} atoms on one side because such a cube could accommodate $10^{27} \times 10^{27} \times 10^{27} = 10^{81}$ atoms. Given that the diameter of a nucleus is about 10^{-15} m, the length of a side of this cube would be

$$(10^{27} \text{ atoms})(10^{-15} \text{ m per atom}) = 10^{12} \text{ m},$$

which is a bit larger than the diameter of Earth's orbit around the Sun.

An alternative method for obtaining the answer is to realize that the matter in a single nucleus occupies a cubic volume of about $(10^{-15} \text{ m})^3 = 10^{-45} \text{ m}^3$. If all the matter in the universe were squeezed together just as tightly, it would occupy a volume of about 10^{80} times the volume of an atomic nucleus, or $10^{80} \times 10^{-45} \text{ m}^3 = 10^{35} \text{ m}^3$. The side of a cube of this volume is equal to the cube root of 10^{35} m^3, or 4.6×10^{11} m, which is the same order of magnitude as my first answer.

Figure 1.9 A survey of the size and structure of the universe.



1.6 Imagine magnifying each atom in an apple to the size of the apple. What would the diameter of the apple then be?

CONCEPTS

1.4 Time and change

Profound and mysterious, time is perhaps the greatest enigma in physics. We all know what is meant by *time*, but it is difficult, if not impossible, to explain the idea in words. (Put the book down for a minute and try defining *time* in words before reading on.) One way to describe time is that it is the infinite continual progression of events in the past, present, and future, often experienced as a force that moves the world along. This definition is neither illuminating nor scientifically meaningful because it merely relates the concept of time to other, even less well-defined notions. Time is defined by the rhythm of life, by the passing of days, by the cycle of the seasons, by birth and death. However, even though many individual phenomena, such as the 24-hour cycle of the days, the cycle of seasons, and the swinging of a pendulum, are repetitive, the time we experience does not appear to be repetitive, and in classical physics time is considered to be a continuous succession of events.

The irreversible flow of time controls our lives, pushing us inexorably forward from the past to the future. Whereas we can freely choose our location and direction in all three dimensions in space, time flows in a single direction, dragging us forward with it. Time thus presents less symmetry than the three dimensions of space: Although opposite directions in space are equivalent, opposite directions in time are not equivalent. The "arrow of time" points only into the future, a direction we define as the one we have no memory of. Curiously, most of the laws of physics have no requirement that time has to flow in one direction only, and it is not until Chapter 19 that we can begin to understand why events in time are essentially irreversible.

The arrow of time allows us to establish a *causal relationship* between events. For example, lightning causes thunder and so lightning has to occur *before* the thunder. This statement is true for all observers: No matter who is watching the storm and no matter where that storm is happening, every observer first sees a lightning bolt and only after that hears the thunder because an effect never precedes its cause. Indeed, the very organization of our thoughts depends on the **principle of causality:**

Whenever an event A causes an event B, all observers see event A happening first.

Without this principle, it wouldn't be possible to develop any scientific understanding of how the world works. (No physics course to take!) The principle of causality also makes it possible to state a definition: **Time** is a physical quantity that allows us to determine the sequence in which related events occur.

To apply the principle of causality and sort out causes and effects, it is necessary to develop devices—clocks—for keeping track of time. All clocks operate on the same principle: They repeatedly return to the same state. The rotation of Earth about its axis can serve as a clock if we note the instant the Sun reaches its highest position in the sky on successive days. A swinging pendulum, which repeatedly returns to the same vertical position, can also serve as a clock. The time interval between two events can be determined by counting the number of pendulum swings between the events. The accuracy of time measurements can be increased by using a clock that has frequent repetition of events.

1.7 (*a*) State a possible cause for the following events: (*i*) The light goes out in your room; (*ii*) you hear a loud, rumbling noise; (*iii*) your debit card is rejected at a store. (*b*) Could any of the causes you named have occurred after their associated event? (*c*) Describe how you feel when you experience an event but don't know what caused it—you hear a strange noise when camping, for instance, or an unexpected package is sitting on your doorstep.

The familiar standard unit for measuring time is the **second** (abbreviated s), originally defined as 1/86,400 of a day but currently more accurately defined as the duration of 9,192,631,770 periods of certain radiation emitted by cesium atoms. Figure 1.10 gives an idea of the vast range of time scales in the universe.

The English physicist Isaac Newton stated, "Absolute, true, and mathematical time, of itself and from its own nature, flows equably without relation to anything external." In other words, the notion of past, present, and future is universal—"now" for you, wherever you are at this instant, is also "now" everywhere else in the universe. Although this notion of the universality of time, which is given the name **absolute time,** is intuitive, experiments described in Chapter 14 have shown this notion to be false. Still, for many experiments and for the material we discuss in most of this book, the notion of absolute time remains an excellent approximation.

Now that we have introduced space and time, we can use these concepts to study events. Throughout this book, we focus on **change,** the transition from one state to another. Examples of change are the melting of an ice cube, motion (a change in location), the expansion of a piece of metal, the flow of a liquid. As you will see, one might well call physics the study of the changes that surround us and convey the passage of time. What is most remarkable about all this is that we shall discover that underneath all the changes we'll look at, certain properties remain *unchanged.* These properties give rise to what are called *conservation laws,* the most fundamental and universal laws of physics.

There is a profound aesthetic appeal in knowing that symmetry and conservation are the cornerstones of the laws that govern the universe. It is reassuring to know that an elegant simplicity underlies the structure of the universe and the relationship between space and time.