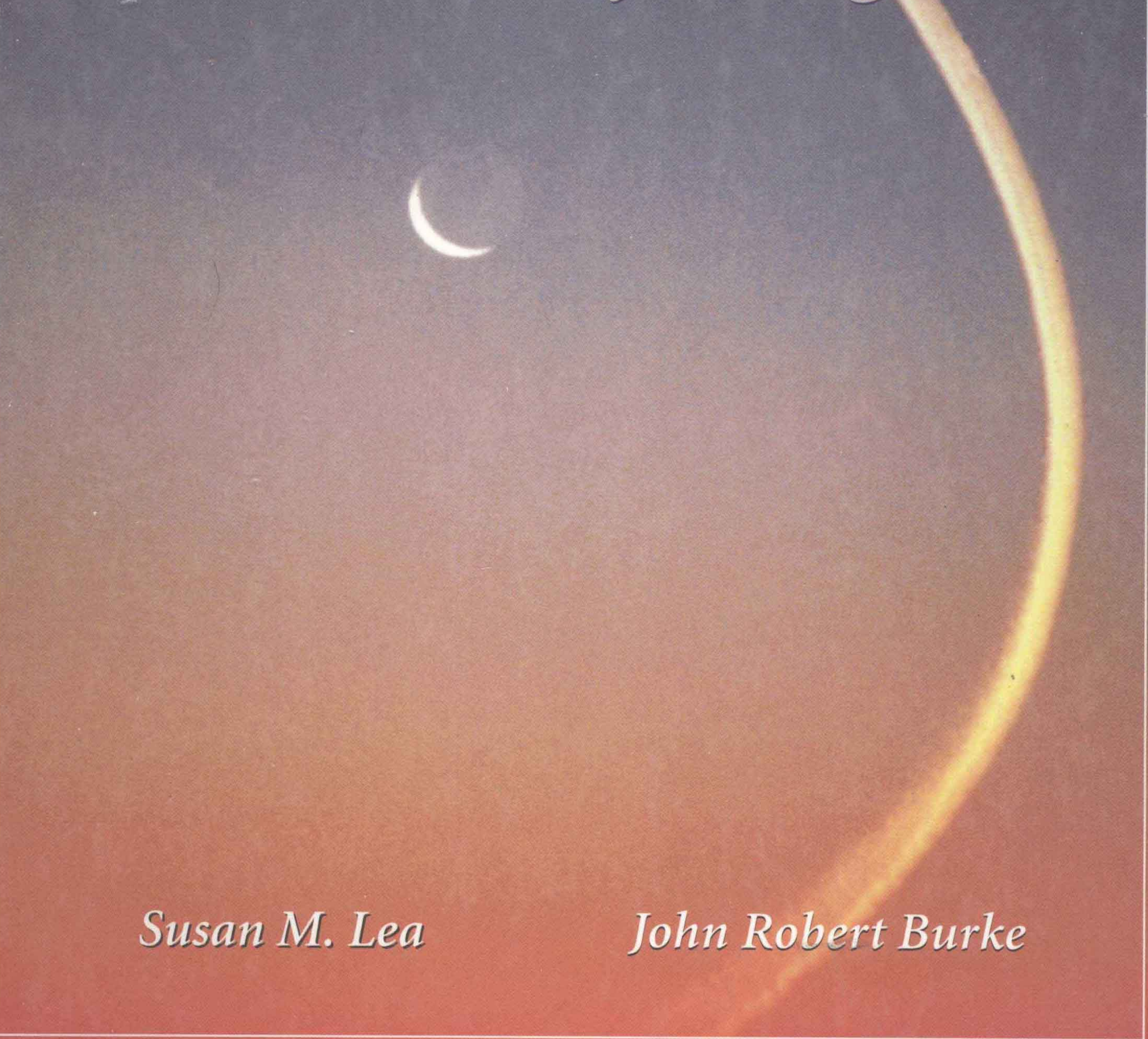
Volume 1

PHYSICS

The Nature of Things



Susan M. Lea   John Robert Burke

Volume One

Physics: The Nature of Things

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Systematic Use of Color in this Text

(Components of vectors are shown in a lighter shade of the same color)

Part I: Newtonian Mechanics

Path of a particle
Unit vector
Position vector
Displacement vector
Velocity vector
Acceleration vector
Force vector
Moving frame box

Part II: Conservation laws

Momentum vector
Gravitational field vector
Angular momentum vector
Torque vector

Part III: Continuous systems

Angular velocity vector
Angular acceleration vector
Streamlines

Part IV: Oscillatory and Wave Motion

Sound wave phasors
Light wave phasors
Light rays

Part V: Thermodynamics

Adiabat
Isotherm
Isochor
Isobar

Part VI: Electromagnetic Fields

Positive charge
Negative charge
Electric field vector
Magnetic field vector
Equipotential surface
Electric dipole
Magnetic dipole
Electric current
Electric displacement vector
Gaussian surface
Amperian curve

Part VII: Electrodynamics

Poynting vector

Part VIII: Twentieth Century Physics

World line
Photon
α-decay
β-decay

To the special people in my life:

my father and mother, my husband Michael and my daughter Jennifer.

Thank you.

Susan Lea

To my father, whose thirst for knowledge was an inspiration.

John Burke

ABOUT THE AUTHORS

Susan Lea is a professor of Physics and Astronomy at San Francisco State University, where she has taught since 1981. Born in Wales, she received her undergraduate degree from Cambridge University, with 1st class honors in applied mathematics and theoretical physics. She did her graduate work at the University of California, Berkeley, receiving a Ph.D in Astrophysics. She worked extensively with data from x-ray satellite missions, including Uhuru, HEAO 1 and the Einstein Observatory. She and her husband own and operate a software company offering optical ray tracing software. She has published extensively in the astronomical journals, but her first refereed paper (in an engineering journal) was on the theory of loudspeaker design! She began teaching physics at the age of 16 (in high school), and hasn't stopped since.

Dr. Lea's interests include flying (she holds a flight instructor certificate with airplane and instrument ratings), horse riding and music.

Professor of Physics at San Francisco State University since 1972, Dr. Burke has enjoyed sharing his love of science with young people deciding on their careers. As a voracious young consumer of science fiction and serious studies of space exploration, Dr. Burke's own path was set by visits to dad's job at then new particle accelerators and by Fred Hoyle's popular astronomy books. "It was so cool to know we could explore atoms or picture the Earth four billion years ago, melted by meteorite bombardment, its core forming from liquid iron dribbling inward." Undergraduate work at Caltech and graduate work in astrophysics at Harvard led to a research specialty in physics of the interstellar medium, with occasional forays into acoustics, economics, and relativity. It was also at Harvard that Dr. Burke's interest in physics eduation bloomed. "I had the opportunity to study teaching with outstanding masters of the craft. Concern for how people come to understand, how they fit science into their lives, and how they learn to think with precision have since guided all my work."

Of course, it's not all work. On occasion "J.R.B." can be caught taking in an early music concert, trekking a wilderness, climbing the odd mountain, or taking his plane into some out-of-the-way airport.

PREFACE

To the Instructor

Our book's title is taken from De Rerum Natura, a work by Lucretius, a Roman writer of the first century AD[1] who tried to persuade his readers by using logical arguments based on observation and experience. This approach is still in style—modern physicists employ the same methods. Like Lucretius, both research physicists and physics students struggle to understand "the nature of things."

Goals

A primary goal of this book is to help science students develop the kinds of logical thinking that they will need to understand physics. These skills are useful in physics and other disciplines as well. Students often find physics the most difficult of the sciences because, even in the introductory courses, it demands much more than the memorization of facts. To study physics successfully, students need to learn to think like physicists. Students must move beyond being hunters and gatherers of formulae to solve problems—they must become, like physicists, creative problem solvers. In this book we have tried to help students develop the logical reasoning and analytical skills that enable a physicist to practice his or her art.

Citizens in a modern technological society need to be scientifically literate. That only a small, elite group of bright students survives introductory physics and goes on to become aerodynamic engineers or physics professors is no longer acceptable. We hope to make physics accessible to all those who choose to take a physics course. We make it accessible not by watering it down, but by giving students the tools they need to grab hold of the subject and make it their own. Physics is fascinating and fun—at least we think so—and we have tried to convey some of our own enthusiasm for the subject. Examples such as the motion of a "hot-dog" skier (Example 3.5, Exercise 3.2) show the power of physics as a tool for understanding the world and, at the same time, spark students' interest.

Intended for a course that requires calculus as a prerequisite or co-requisite, this text uses calculus throughout, in derivations, examples, and problems. In the first few chapters calculus is used sparingly, mostly in optional sections, so that those students who are just starting calculus will not be overwhelmed. Later in the book, more familiarity is assumed. An interlude following Chapter 7 discusses the use of integration in physics and presents a five-step plan for setting up integrals. Basic knowledge of algebra, geometry, and trigonometry is assumed. Appendix I includes some basic relations from these disciplines as a reminder and reference for students.

This book can be used by students with widely varying levels of ability. Each chapter stresses the basic concepts first. By including or excluding the *Digging Deeper boxes,* the optional *Math Topic boxes, Optional sections* (marked with an ✲), and the *Advanced and Challenge Problems,* the instructor can tailor the text to her or his own students. *Instructor marginal notes (in blue)* indicate which optional topics are used later in the book, and also explain the reason for some of our choices of topic and organization. We have also given references for some of our sources.

Organization

The order of topics in the book is largely traditional, but is organized to allow a large range of sequencing options. For example, introducing angular momentum of a particle in Part II offers the option of foregoing rigid body dynamics in favor of a faster move to the twentieth century. The chapter on oscillatory motion could be used any time after the discussion of energy (Chapter 8). We have included optics in the section on wave motion, to stress the unity of such wave phenomena as interference. However, Chapters 16–18 on optics could easily be covered after E&M if desired. Part V on thermodynamics is self contained and could be studied any time after basic mechanics. The first three sections of Chapter 34 (relativity) could be covered after Chapter 3, and Section 34.4 could be introduced after Chapter 8. The chapters on modern physics tend to be more qualitative, because of the level of mathematical sophistication required for a detailed treatment. They are designed to serve as the culmination of a two- or three-semester survey or as an impedance-matching introduction to a standard course on modern physics. These chapters emphasize the conservation principles developed in Part II.

[1] Lucretius based his book on earlier work by the Greek philosopher Democritus.

Throughout the book we stress *two major themes: conceptual understanding and a consistent approach to problem solving.* The material in the book is divided into eight parts, each introducing a unified body of concepts: Newtonian Mechanics; Conservation Laws; Continuous Systems; Oscillations and Waves; Thermodynamics; Electromagnetic Fields; Electrodynamics; and Twentieth Century Physics. This division helps the students organize their knowledge. The introduction to each part explains the theme to be covered and provides some historical perspective. We begin each chapter with a discussion of the opening photograph, frequently raising a question that we answer within the chapter. Just as each chapter begins with a physical situation to introduce the concepts of the chapter, each topic within the chapter is introduced with a conceptual discussion before the mathematics is presented. In this way we emphasize that working with the concepts is the first essential step in solving a problem. Then the mathematics is used to complete the solution. Similarly, we place a great deal of emphasis on using diagrams to help conceptualize problems and plan their solution. We encourage students to use diagrams as graphical tools to aid their understanding and to help make the transition from a verbal presentation to a mathematical model. Unlike many texts, we not only tell students to use diagrams, we *always* do it ourselves.

PROBLEM SOLVING

Two *Interludes* in the early parts of the text help lay the groundwork for a systematic approach to problem solving. In the first interlude, following Chapter 3, we lay out *our basic four-part problem-solving strategy.* The major stages of each problem solution— **MODEL** , **SETUP** , **SOLVE** , and **ANALYZE** — are identified and discussed at this point. These steps are used and labelled in every example throughout the book. Seeing the method at work in each example better enables students to apply a similar approach in their own solutions.

The second Interlude, following Chapter 7, shows students how to set up problem solutions using *integration.* The method involves five steps. The first four steps are a procedure for describing a physical process or system in terms of differential elements and transforming a sum over such elements to a standard mathematical form. Only at the final step does the actual evaluation of an integral occur. This final step is the one that students learn in their calculus classes. In each example requiring integration we use this method, with the steps clearly labelled.

Throughout the book we present *Solution Plans.* These are problem-solving strategies that show the logical steps necessary in certain specific classes of problems. Each plan is explicitly laid out in flow-diagram form. The method for analyzing dynamical systems with Newton's laws (Chapter 5, p. 167) provides a good example of a Solution Plan. A table in the appendix lists all the plans for easy reference. These Solution Plans will help the students develop the skills they need to solve problems in physics, and help them to go beyond that hunter-gatherer, "find the right equation and stuff in," stage. As students become more proficient they will be able to adapt these problem-solving strategies to their personal style.

The Solution Plans can also be valuable teaching tools, allowing you to identify precisely where students have difficulties. For example, using the plan in Chapter 5, we found that an astonishingly large number of students are convinced that they can't analyze a system with strings unless they know the value of the tension before carrying out the algebra. Once these difficulties have been identified, it is much easier to confront them and, ultimately, eliminate them.

The careful use of *vectors* is stressed throughout. In particular we introduce vectors as the primary descriptive tool in kinematics, using geometrical addition (Sections 1.4–1.6), and then solve one-dimensional problems as a special case of one-component vectors (Section 2.3). Not only does this approach stress the importance of vectors from the beginning, but it makes the meaning of signs in one-dimensional motion obvious. (An instructor's marginal note on page 52 explains how this material can be presented in other sequences.) In addition to boldface type, we have used the *"arrow-over" notation* so that equations in the book will look the same as the equations you write on the blackboard, or the students write in their notes. We have avoided the use of "magic" minus signs (as in the spring force) that are not explicitly tied to a coordinate choice or stated sign convention.

Beginning students often focus on finding "the answer" without first framing any expectation of what the magnitude, units or other characteristics of the answer might be. As scientists, instructors know the importance of estimation as a problem-solving strategy. It can be difficult to integrate this strategy into teaching, however, especially if students don't see it used regularly in their text. We introduce students to these valuable skills by using *back-of-the-envelope calculations* to estimate results, or to decide what is or is not important in a given situation. These methods are also used to estimate the reasonableness of an answer or to figure out the basic physics behind a complicated event like a thunderstorm. The envelope symbol ( ) alerts the students whenever we use these techniques in examples or discussions. Some problems show this symbol to indicate that the students should use these techniques in their solution, and that an exact answer is not expected.

EXAMPLES, QUESTIONS, AND PROBLEMS

Each chapter starts by emphasizing the basic concept, then developing it through a carefully graded series of *Examples.* All Examples consistently use the four-part problem-solving strategy presented in the first Interlude, and show the appropriate free-body diagram or other illustration at each step. While we have attempted to keep the introductory examples straightforward, and to assure that they demonstrate a steady gradual increase in difficulty throughout a chapter or part, twenty *Study Problems,* spread throughout the book, emphasize the use of the problem-solving method in detail with interesting and sometimes intricate problems. The inclusion of these problems should help to alleviate the complaint that the "examples didn't prepare me to do the problems."

The text offers many opportunities for students to test their knowledge and their ability to use the material. Within each chapter, *Exercises* allow students to practice with ideas they have just learned. Abbreviated solutions—not just answers—are given at the end of each chapter, so students can get real feedback after they work an exercise.

The end-of-chapter material includes a carefully structured array of problems for student review or assignment by an instructor. *Review Questions* emphasize conceptual understanding and can be answered by a quote or paraphrase of material from the chapter; *Basic Skill Drill* is a set of problems that test student's knowledge of fundamental mathematical relations and the meaning of terms introduced in the chapter; an extensive set of *Questions and Problems* include practical applications and conceptual questions as well as the usual "textbook exercises." Symbols preceding each problem identify the level of difficulty, and also indicate the conceptual problems. Many of the problems are sorted by chapter sections, but numerous *Additional Problems* are included that may require use of material from several sections, or even from previous chapters. *Computer problems* give the students an opportunity to hone their computer skills—an increasingly important component of education. Most of these problems can be solved using a spreadsheet program, or one of the simple programs on the supplementary computer disk available with the text. Students with more advanced computer skills will have an opportunity to incorporate these skills into their physics problem solving. *Challenge problems* introduce the more capable students to interesting and stimulating exercises that require advanced problem-solving skills. *Part Problems,* found at the end of each of the eight parts of the text, give students an opportunity to synthesize their understanding and to see how each topic builds on and enhances what went before.

OTHER HELPFUL FEATURES

Math Toolboxes appear throughout the text. Each one presents a set of techniques that are necessary tools for doing physics. They are located in the text where the techniques are first needed. For examples, see the Math Toolbox on the properties of the scalar product (p. 229) or the one called *How to Solve a Differential Equation* on p. 1005.

Digging Deeper boxes and *Math Topic* boxes present ideas that are not essential but that provoke interest, give greater depth to a point in the text, or simply point out a delightful consequence of the physical principles. See for example *More on Cyclotrons* (p. 928), *Use of Calculus in Circular Motion* (p. 98), and *How Do Fish Survive the Winter?* (p. 686).

Essays, some by guest authors, address interesting sidelights or more advanced topics. We happily remember the student who suddenly remarked "I get it!" after reading the bicycle essay. By applying Newton's laws to a subject he enjoyed, he finally made sense of it all.

Definitions and equations are color-coded to help students recognize their level of importance. Despite the emphasis throughout the text on problem-solving as a reasoning process, some things must be memorized to be used efficiently. Anything in a gold box is fundamental and should be memorized!!! Level 2 equations, in tan boxes, are important and will often be useful in solving problems. Level 3 equations, unboxed and unnumbered, are intermediate or less important results that need not be memorized. Occasionally we need to refer to intermediate results in order to guide students through a problem solution or derivation. Such results are given lower case Roman numerals. Any reference to these equations is local (within a page or so of the original statement).

Marginal notes (in black) alert the students to common errors, point out important features and special cases, give additional references, refer to previously discussed, related issues, and add clarifying commentary.

Instructor's Marginal Notes (in blue) appear throughout the *Instructor's Annotated Edition*. In this special version of the text, these marginal notes signal the location of related material, explain why a particular approach is used, cite references to the physics literature, provide suggestions and comments on possible changes in the sequence of topics and so forth. Many of the *Instructor's Marginal Notes* in the text are the result of "dialogues" that are carried on between reviewers of the manuscript and ourselves through many drafts of the text. In the *Instructor's Annotated Edition*, the Contents (on page *xi*) includes instructor's notes that comment on various organizational and content features of the text.

Our book has *more art* than other texts presenting the same material. We don't just tell students that good problem solving starts by making a drawing as conceptual link from the physical situation to the correct mathematical model, we consistently follow this practice. To help reinforce the importance of using and understanding graphical models, *color is consistently used in all illustrations* throughout the book. Acceleration is always blue, for example. See the color key that appears on page ii in the front of the book.

ACCURACY

The authors and publisher recognize that errors in quantitative material can undermine the effectiveness of a text. A great deal of attention and effort has been invested to assure that all of the quantitative material in the text (and the solutions manuals) is correct and accurate. Accuracy checking went on throughout preparation of the manuscript, as well as during production of the physical book. During the years that manuscript was being written and developed, many people were involved in assuring accuracy.

- Dozens of physics professors reviewed numerous drafts of the manuscript. All were asked to review the examples, exercises and problems. Many reviewers focused specifically on this quantitative material, at the publisher's request.
- The authors solved every end-of-chapter problem and checked each to be sure that it did not make unstated assumptions or rely upon unstated information.
- Jon Celesia of San Francisco State University carefully reviewed the final manuscript, checking for unstated assumptions, unclear explanations, and any possible inaccuracies.

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- The authors proofread every syllable and symbol through two (in some cases three) stages of proof.

An important group of people has been helpful in working end-of-chapter problems to check both problems and solutions for accuracy and clarity. Special thanks go to Chris Kelly, Shuleen Martin, Russ Patrick, Peter Salzman, and Ladye Wilkinson. We appreciate the herculean efforts of Jeremy Hayhurst and his team at Chrysalis Productions, who turned a mountain of manuscript into the two Solutions Manuals. Lauren Fogel, at West, also deserves our thanks for her steadfast work on coordinating the entire Solutions Manual project, and keeping the authors going when we thought no more was possible. And thanks for the brownies, Lauren!

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To Andy Crowley, who started with us on this project many years ago: we thank you for your faith in us, and wish you well in your present ventures.

Finally, we owe an enormous debt of thanks to our families, who have endured the enormous piles of paper that have littered our homes for years and who have tolerated our long hours and grouchiness for lack of sleep. We would especially like to thank Jennifer Lampton who gracefully consented to be the guinea-pig on whom we tested our ideas and explanations to see if they made sense. To those friends we haven't seen for ages, perhaps we'll see you soon, and we thank you, too, for your patience.

In Conclusion

In writing this book we have been guided by our students. We have listened to their complaints, watched how they work and noted where they have difficulties. We have also been cognizant of recent research on physics education, which, for the most part, supports our own observations. Thus, this book is written for the student. No book can make physics easy for everyone, but we can show students an approach that works. Our problem-solving strategy has been tested and approved by hundreds of our students, and it has increased their exam scores dramatically. We are confident it can work for your students as well.

. . . just for the fun of doing Physics.

MARIA GOEPPERT-MEYER

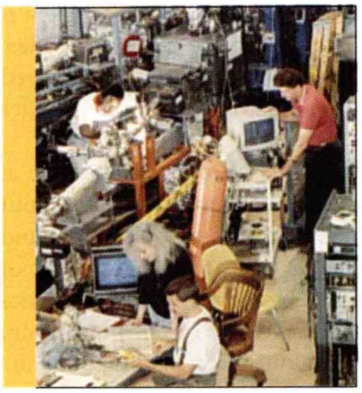
To see the world for a moment as something rich and strange is the private reward of many a discovery.

EDWARD M. PURCELL

. . . If there turn out to be any practical applications, that's fine and dandy. But we think it's important that the human race understands where sunlight comes from.

WILLIAM FOWLER

PROLOGUE



WHY DO PHYSICS?

Reasons for doing physics are nearly as diverse as the people who do it. For the professional, the challenge of teasing secrets from nature is a calling, an exciting occupation, and often a source of profound personal satisfaction. Physicists often view their discoveries as major additions to human culture, not unlike great symphonies or epic poems. Physics is, at the same time, a very practical science—basic to the design of your alarm clock, the computer that handles your bank account, and whatever transportation system gets you to work and school. Most students take a physics course because of this practical aspect.

Every citizen in a modern society needs to have some scientific understanding. The scientific way of thinking about our world has become an integral part of modern culture, interwoven with theories of politics and justice and with the economic structure of our society. Most scientists believe that a scientific worldview liberates the mind and that technological progress will continue to be beneficial. Critics of science argue that it diminishes traditional, humanistic ways of thinking without offering a valid, alternative view, and that technology has left us with problems of pollution, atomic bombs, global warming, to name a few. As both an individual and a citizen, you will need to judge these issues for yourself, and this physics course offers an introduction to the necessary scientific reasoning.

Whatever your reason for studying physics, you will acquire powerful skills that you can use professionally as well as in developing your personal philosophy. Perhaps you will also come to share some of the physicist's deep fascination with the beauty and logic of the universe *and* to enjoy solving its puzzles. Welcome to the enterprise!

SO, WHAT IS PHYSICS?

The name is derived from an ancient Greek word meaning *the nature of things that move of themselves.* Through physics, we strive to discover the fundamental structure of the universe and the rules by which it operates. This structure turns out to be both *simple* and *complex!* It is *simple* because only a small number of rules are needed to explain the world around us. It is *complex* because of the large numbers of objects that interact. We have a good set of rules for the behavior of everyday objects and can understand those rules in terms of atoms and only two kinds of interaction. For atoms we have yet deeper *levels of description* that involve three kinds of interaction. We're pretty sure we haven't reached bottom yet!

Occasionally someone (who should know better) declares to the world that we now know it all . . . then someone else will discover nuclear energy, or semiconductors, or lasers! Physics is a dynamic subject, and physicists continually test the limits of current ideas, probe for exciting new phenomena, attempt to explain puzzling phenomena when they are discovered, and strive to create new ideas that provide deeper or more wide-ranging explanations. The fun of science is in this dynamic quest.

New scientific ideas, as Einstein put it, are "free creations of the human mind," as fresh and unpredictable as any other creative endeavor. But any theoretical picture must be consistent with the actual behavior of the world. So, scientific ideas experience evolutionary pressure as intense as do biological species in a jungle—with similar results: some stable, well-adapted, broad-ranging ideas thrive, while certain variant ideas test the limits of survival. Most of the variants become extinct, but occasionally one proves highly adaptive, takes over the whole environment, and establishes a new level of description. Physics research is the process of creativity, skepticism, and competition that drives this evolution.

Good ideas, unlike dinosaurs, don't always become fossils when a new one takes over their habitat. Most often, a long-lived old idea remains the easiest to learn and use where it is valid, even though it is recognized as a *special case* of the newer and more penetrating idea. For example, a mechanical engineer works almost entirely with mechanical principles obeyed by everyday objects; a metallurgist uses atomic physics to develop stronger metals. Neither would probably ever work with subatomic physics or the theory of relativity.

So, what *is* physics? It is at least three things: a set of ideas describing the universe at various levels of detail; a set of methods for using these ideas to understand the world about us; and a dynamic, evolutionary process for testing, extending, and refining those ideas and methods. The study of physics calls on us to employ a peculiar way of thinking—that of viewing familiar events as the sum of many parts, each governed by the principles of physics and interacting with one another. The term *natural philosophy,* used until recently in Britain, describes physics well: it is a method that has evolved for thinking successfully about the natural world.

What Are the Aims of this Text?

Fortunately, you don't need to master the whole of physics to achieve your purposes in this introductory course. Our main aim here is to help you learn how to become a *natural philosopher*—to understand the structure of physics and to be able to apply it to the world. Like most introductory physics texts, we shall work primarily with classical physics. These ideas, developed largely before 1900, describe most systems on the everyday scale of existence and still find broad application. Though everyday events are familiar and we can study them at a level consistent with your mathematical experience, don't make the error of thinking them trivial. It took 2000 years to get *everyday* physics right, and you will find it a challenge to figure out just how the basic rules work. Once you've met the challenge though, you'll have a method for using physics, for further study of science, or for deciding whether a political candidate takes sound positions on technical issues.

At the beginning of the twentieth century, physicists discovered that phenomena involving strong gravity, objects moving near the speed of light, small numbers of atoms, or low temperature are not well described by classical ideas. The last part of the text introduces you to the modern ideas that have resolved these difficulties and provides a framework for appreciating discoveries at the current frontiers of physics.

We know you will find your study of physics challenging. We hope you will also find it fascinating and rewarding. Good luck!

Suggestions for Using the Text

We have divided the text into eight parts. The chapters in each part form a conceptual unit that will prove useful in organizing your knowledge. We suggest that you read each chapter before attending a lecture on the material. You will understand the lecture better and also be able to ask your instructor about anything that was not clear. Be sure to work the exercises.

Complete solutions are given at the end of the chapter. Peek for hints, but don't just copy them; that doesn't do you much good. The chapter summaries review the major ideas.

The lists of concepts and goals indicate the ideas and methods you should understand after reading the chapter. A wise way to use them is to scan the list as you begin reading so that you know which terms to look for. When you have finished the chapter, go back and be sure you know what each item is about. Then you are ready to tackle the problem set.

The problem set is divided into two parts: *Basic Skills* and *Questions and Problems.* The *Basic Skills* section includes review questions and a basic skill drill. The review questions bring out the main points of the chapter and should be answered with a short quote or paraphrase. The skill drill tests your knowledge of the most fundamental concepts in the chapter. We suggest that you answer all the questions in *Basic Skills,* whether or not your instructor assigns them.

We have provided questions and problems for each chapter section, as well as additional problems for the whole chapter. They are rated according to the following scheme:

CONCEPTUAL ❖
These questions involve primarily verbal and/or graphical discussion. These questions are not necessarily easy!

BASIC ♦
These problems are mostly calculations (more than 10% of the total effort), but ones that involve only a single physical principle from the current chapter.

INTERMEDIATE ♦♦
These problems (except those in the *Additional Problems* category) rely on ideas from the current chapter or ideas encountered so frequently before that they are now taken for granted.

ADVANCED ♦♦♦
Advanced problems may involve subtleties that go beyond the examples and exercises, require more difficult mathematics, take more than one page to complete, or involve ideas from previous chapters. These problems usually involve more than one physical principle.

COMPUTER PROBLEMS are intended to be used with a simple computer program or spreadsheet. Some may be solved graphically, or with a calculator and patience.

CHALLENGE PROBLEMS, at the end of each problem set, require an intricate or subtle argument and/or an expert level of computational skill.

The *Additional Problems* may involve concepts from one or more sections of the chapter, or even from different chapters. The text is divided into eight parts, and you will find a problem set at the end of each part. These problem sets involve material such as might be asked on comprehensive examinations.

THE UNIVERSE: AN OVERVIEW

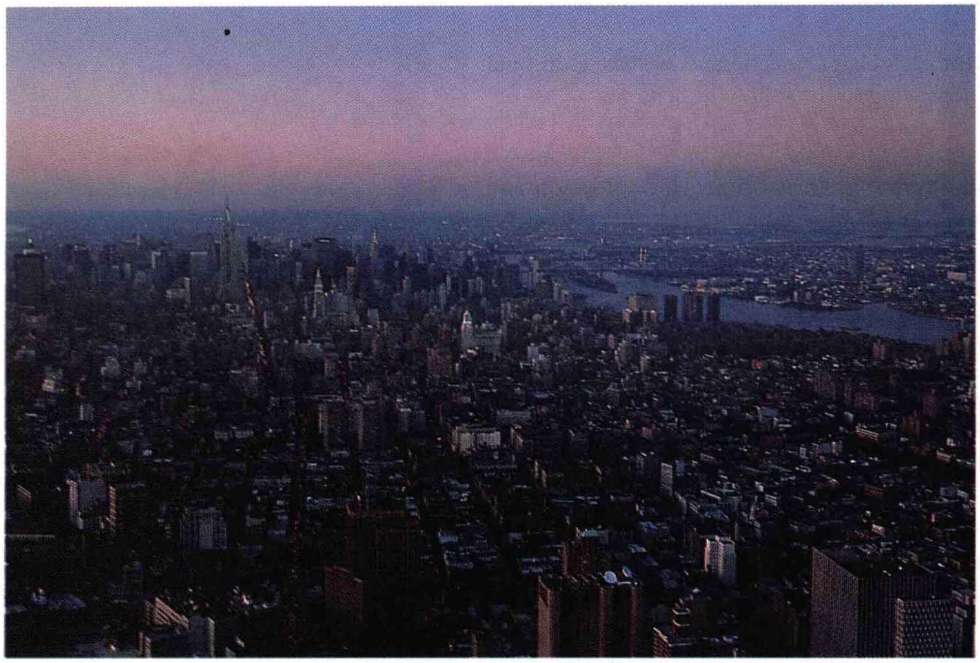
Small children quickly learn that the world is made up of definite objects with identifiable properties: soft blankets, hard floors, hot water, cold ice. They also learn that certain behaviors are predictable: push your cup off the table and it falls to the floor! As adults, we notice that changes occur because the objects interact with each other. To model this world, we need to classify the kinds of objects that exist and the ways in which they interact. Physicists do this systematically, distilling intuitive experience into a precise and succinct set of ideas, then probing far beyond common experience with carefully designed experiments.

In daily life, we interact with a wide variety of objects more or less similar in size to our own bodies. A description on this scale is completely adequate for a study of mechanics and yields precise methods for problems as diverse as the design of machines or the maneuvering of spacecraft. However, on the everyday scale we find no explanation of why such a huge variety of objects exists or of the reasons for their interactions. Better understanding comes

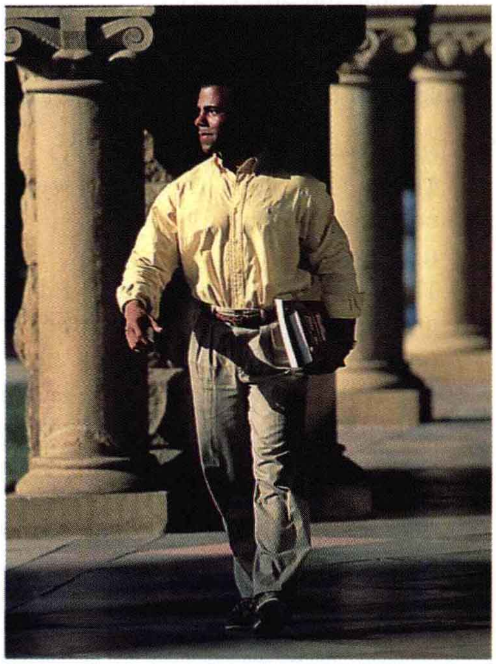
SEE APPENDIX IA FOR A DISCUSSION OF SCIENTIFIC NOTATION.

from looking at different size scales—different magnifications. For both very large and very small systems, we find a simpler, if weirder, description, although the everyday description, which we shall study first, remains an important and useful approximation. Physicists can now shed light on phenomena with size scales ranging from 10^{-37} meter to 10^{26} meters and can discuss events that occurred as early as 10^{-45} second after a beginning some 10^{10} years ago or that will occur as late as some 10^{100} years in the future. Touring the universe on different length scales will allow us to sample the ideas physicists now use.

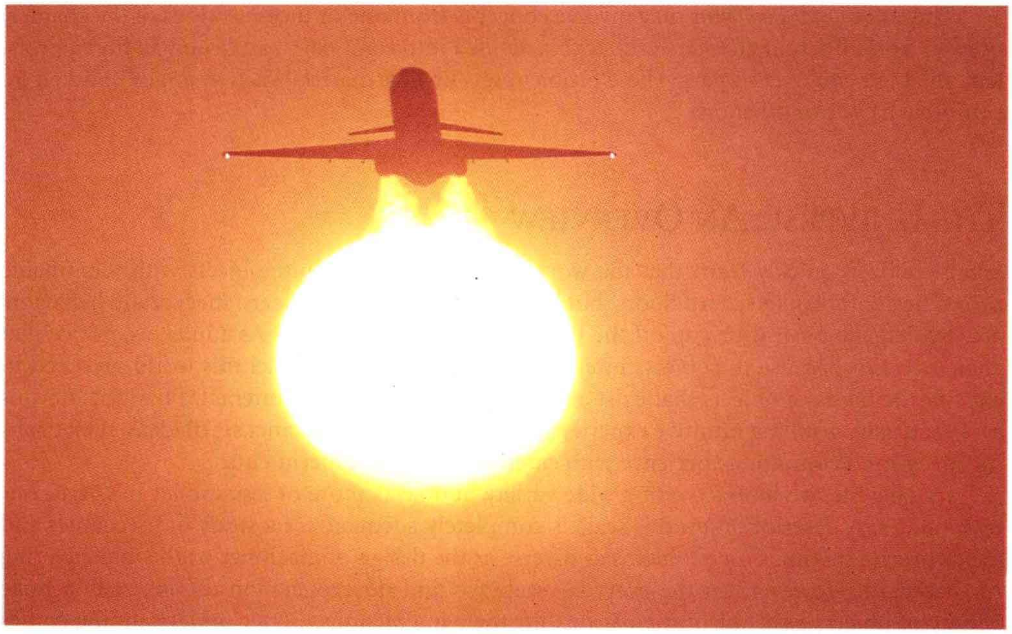
The Everyday Scale



■ **New York City.** *We are very familiar with size scales ranging from 1 millimeter to about 10 kilometers—that is, from roughly the size of a grain of sand to the size of a city.*

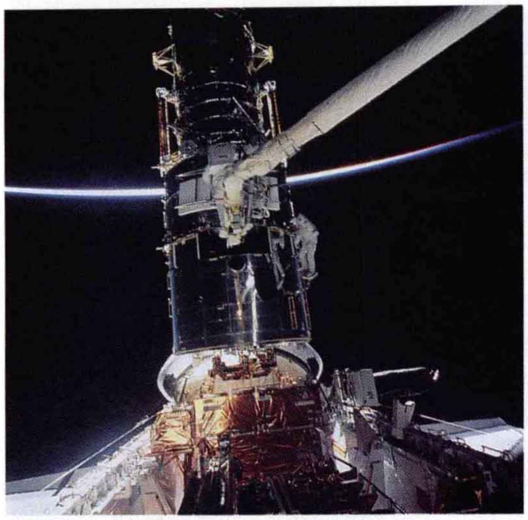


■ *We are familiar with the sensation of force. Your muscles ache after carrying your physics books around all day. In Part I we'll begin to study the forces we experience in our daily lives.*

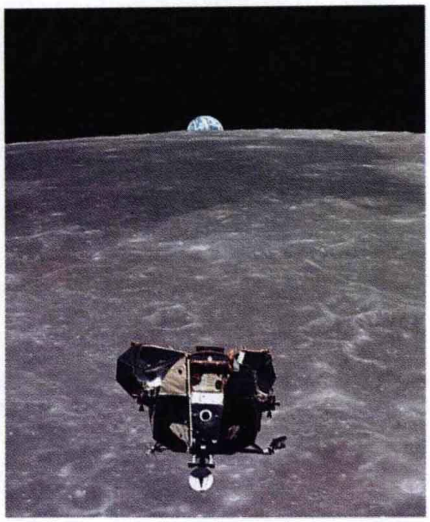


■ *A jet aircraft is a good example of modern technology. To build one, you must understand mechanics (Part I), to understand how it flies is an exercise in fluid mechanics (Part III), its engine is a thermodynamic machine (Part V), and plotting its course is an exercise in kinematics (Part I). This picture also shows interesting optical effects due to refraction of sunlight through the jet engine exhaust (Part IV).*

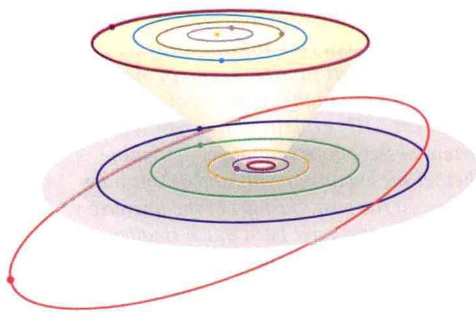
The Solar System



■ At a size scale of 10^7 meters, things begin to look different. The Earth's surface now appears curved. Gravitational attraction by the Earth is the dominant interaction, accelerating the space shuttle in its orbit around the Earth. The Hubble telescope (Part IV), being refurbished on this shuttle mission, offers us a view of the universe we live in.



■ On a scale of 10^9 meters, the Earth's spherical shape is obvious. This view is from Earth's closest natural companion, the Moon, a rocky body similar to Earth but without atmosphere or native life-forms. Both the Earth and the Moon exert gravitational forces on each other and on the spacecraft used to reach the Moon.

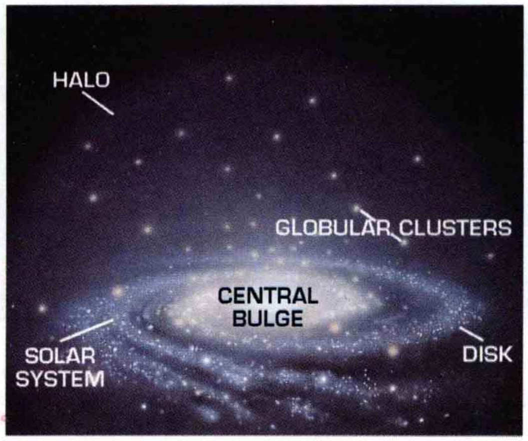


■ At a scale of 10^{12} meters, the Earth has faded into insignificance, and there is no evidence of the magnificent detail we are so familiar with on Earth. The Sun's gravitational pull holds planets, comets, and sundry other debris in orbits that form the solar system. Isaac Newton's study of the solar system led him to discover that every object exerts a gravitational attraction on every other object (Part I).

The Universe of Stars

Outside the solar system, there is no trace of human existence. On very large scales, the interactions between objects are simplified, and a single force—the gravitational force—dominates.

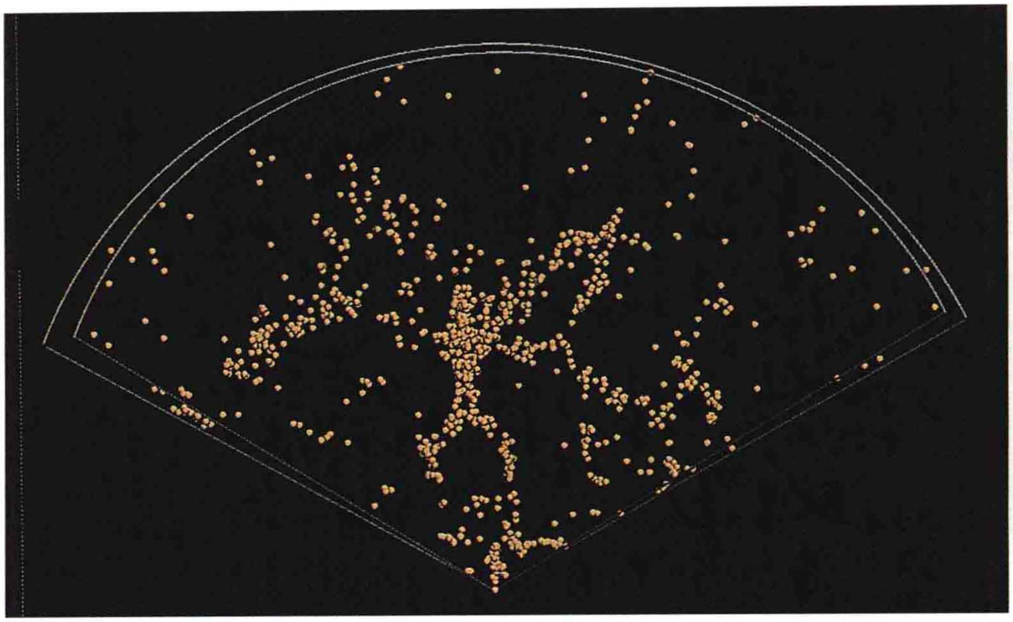
■ The distance to the nearest star is some 30 000 times the size of the solar system. A cube around the Sun with sides of 10^{18} meters contains about 10 000 stars so distant from one another that their individual gravitational attractions have negligible influence on the motions of the other stars.



■ We belong to a galaxy of roughly a thousand billion stars called the Milky Way, a system that is about 10^{21} meters in size. All the stars in a galaxy (plus about ten times as much material that we don't see visually) together exert enough gravitational force to hold individual stars in orbit around the center of the galaxy.

■ On a scale of 10^{24} meters, galaxies cluster together, moving under their mutual gravitational attraction.

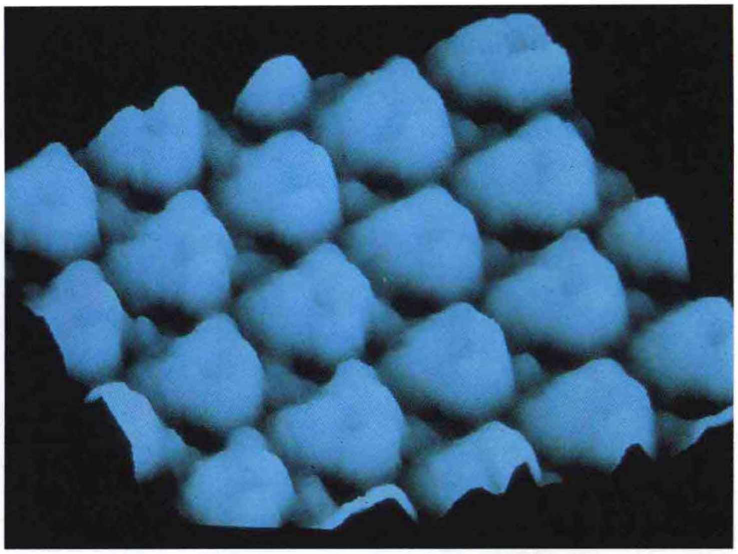
■ *Here we see a plot of galaxy positions within a slice of the universe. The distribution is clumpy, but on size scales larger than about 10^{27} meters, the structure seems to average out. This uniform universe is expanding; all the galaxies are rushing away from each other. Albert Einstein's concept of gravity as variations in the geometry of space and time (Part VIII) explains this expansion, but current observations cannot yet determine whether the expansion will stop or continue forever. In the past, the part of the universe we can see must have been much smaller. Cosmological theories suggest that, between 10 and 20 billion years ago, all the stars and galaxies we can see were squeezed into a volume the size of a single atomic nucleus.*



The World as Atoms

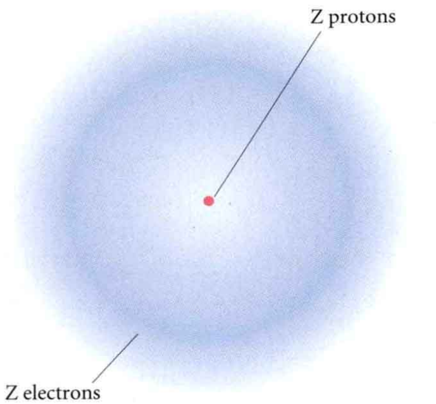
As with the large scales of astronomy, our description of the world changes radically when we look at very small size scales. Again, we find odd and wonderful things and a small number of fundamental interactions.

■ *Single cells of living creatures are several micrometers (10^{-6} meter) in size. Although we cannot see them with our own eyes, we can still comprehend their behavior with concepts from the everyday world.*

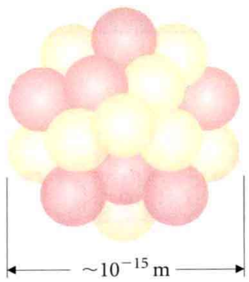


■ *At a scale of 10^{-9} meter, we observe the atomic nature of matter. Fluid forces result from collisions between rapidly moving atoms of gas or liquid. Forces between solid bodies in contact result from the forces between individual atoms in the surfaces of the bodies. The atoms consist of electrons, with negative electric charge, surrounding small, positively charged nuclei. Interatomic forces are electromagnetic forces between these charged pieces of the atoms. All of the kinds of force we experience on the everyday scale are either gravitational or result from electromagnetic interactions between atoms (Part VI). This photo shows benzene molecules.*

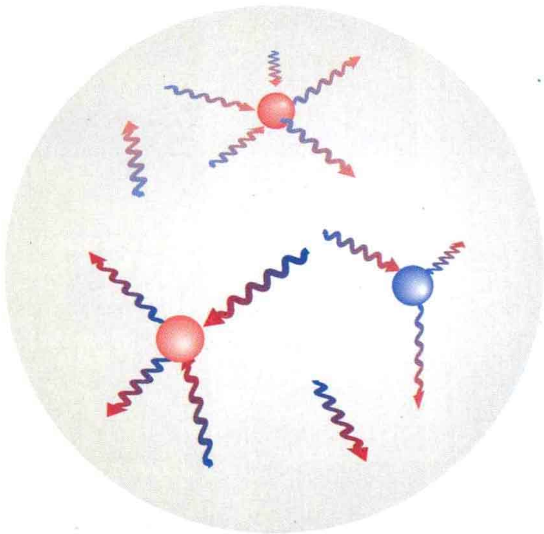
The Subatomic World



■ *Nearly all the mass of an atom is concentrated in the nucleus, pointlike compared with the size of the atom, 10^{-10} meter. The volume of the atom is filled by much less massive electrons, which form a cloud around the nucleus. (Part VIII)*

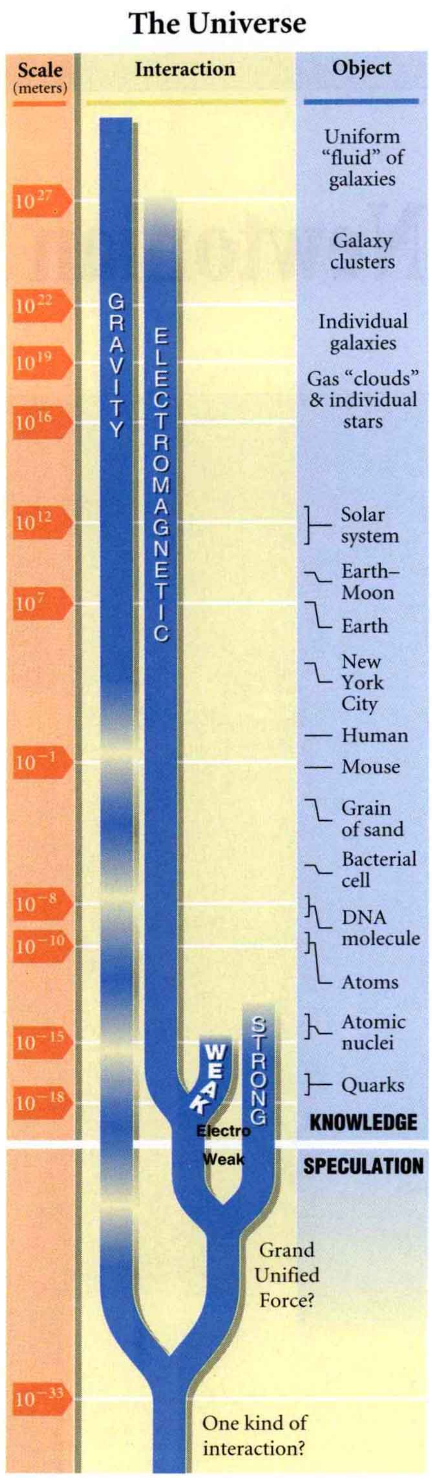


■ *On a scale of 10^{-15} meter, we become aware of the electrically neutral neutrons and positively charged protons that comprise the nucleus. The protons repel each other electrically and are held together by the strong nuclear force. A second nuclear force, the weak nuclear force, causes some nuclei to change form.*



■ *Nuclear particles themselves have structure. A proton consists of three particles called quarks, which exert strong nuclear forces on each other by exchanging particles called gluons, and exert electromagnetic forces by exchanging photons. The quarks also exert weak forces through the exchange of particles. In the 1970s, these particles were shown to be cousins of the photons. In this sense, there is but one "electroweak" kind of force, rather than separate electromagnetic and weak nuclear forces. Theorists are now trying to show that the electroweak and strong nuclear forces are just different aspects of one force. Yet more intriguing is the possibility that gravity and this unified force may be aspects of a single interaction. An experimental test of these ideas is far beyond current techniques. Because only these most fundamental particles could exist at the beginning of the universe, the way they behave may be responsible for the way the universe is today. In this way, the smallest and largest scales are intimately connected.*

Summary Chart



■ *The most important forms of material substance are listed for each size scale. For the fundamental types of force, solid lines denote scales at which the force is of major importance. Fuzzy lines indicate scales at which a particular kind of force is present but relatively unimportant.*