Preface

Why Study Physics?

Imagine you have lived your entire life without being able to see the world in color. Imagine you can only see in black and white. Then imagine that someone gives you a way to see color for the first time. Before you experience color vision, however, you could not know what you were missing. You would have only the word of others to imagine how wonderful it could be. Seeing the world without any understanding of physics is like seeing the world without color. It is being blind to much of the beauty, richness, and depth of the physical universe. A good course in physics provides the means to open this universe to you, to see the world with the insight that physics provides. More specifically, knowledge of physics allows you:

To begin to appreciate the diverse phenomena of the world in a new, more unified way, to see a world governed by physical principles, and to understand how these principles serve as a foundation for understanding other sciences such as biology and chemistry.

To be able to apply the principles of physics to the solution of problems and to understand how physical principles have been used to solve enormous technical problems, opening up new vistas of experience of the physical universe undreamed of 50 or 100 years ago—space exploration, lasers, electron microscopes, computer memory chips, magnetic resonance imaging, and so on.

To wonder about the mysteries of the physical universe that remain and the vistas that will unfold within your lifetime.

You are very likely taking physics because it is a required course, and you may rightly regard it as a challenge, a means for realizing your professional goals. But if you can be open to some of the broader educational objectives, you may find your physics course to be a lasting, enriching experience, and you may even find that such an attitude enhances your chance for success.

Goals of the Text

Designed for a 1-year course in college physics or advanced high school physics, using algebra and trigonometry, this text is the product of more than 20 years of experience teaching college physics. For more than 10 years I have worked to develop the best possible physics textbook. The following are some general goals that have guided my work:

1. Use the most direct, concise language possible to convey ideas.
2. Use illustrations and photographs as effectively as possible to aid understanding.
3. Improve the explanation of difficult concepts.
4. Introduce abstract physical concepts wherever possible by appealing to common experiences that illustrate the concepts.
5. Present applications of physical principles—to biology, modern technology, sports and other everyday activities—in a way that clearly distinguishes applications from physical principles.
6. Present derivations in a way most likely to help, not hinder, understanding. Adapt both the style of derivations and placement of derivations to individual topics in

such a way that the relationship of physical concepts is demonstrated in the clearest possible way.

7 Formulate new and interesting examples and problems, many drawn from real-life experiences, to make the course more interesting for both students and instructors.

Features

Organization

The overall organization of this text is very traditional. The following departures from tradition are intended to improve unity and coherence: a separate chapter on universal gravitation placed just after chapters 4 and 5 on Newton's laws and applications; a single chapter treating all mechanical waves, including sound, in an integrated way; an introduction to wave optics that begins with a qualitative overview of the wave properties of light, showing how diffraction and interference are related before each is discussed separately and quantitatively.

To allow the reader to quickly locate specific topics, I have made frequent use of subsection headings within sections of a chapter.

Explanations

The text offers particularly good explanations of many difficult concepts, including instantaneous speed, relative motion, universal gravitation, energy, Archimedes' principle, surface tension and capillarity, entropy, the eye and visual acuity, measurement of time in relativity, and wave-particle duality. A completely original feature is an elementary, quantitative discussion of optical coherence. The treatment of electricity and magnetism is unusually thorough and effective.

Applications

Numerous applications of physics to biology, technology, sports, and everyday life help motivate student interest. Every effort is made to distinguish applications from fundamental physical principles. For example, many applications are presented in examples and problems.

Each half of the book contains one extended biophysical application: in Chapter 11 the physics of fluids is applied to the human circulatory system, and in Chapter 25 optics is applied to the human eye. These unusually detailed biophysical applications are chosen for the richness of the results that follow from simple physical principles.

Illustrations and Photographs

Great care and meticulous attention to detail has been given to the development of full-color art that would realize the enormous potential of pictures to teach physics. The text contains approximately 1100 drawings and over 400 photographs, nearly all of which were planned as the manuscript was written, so that words and pictures work together to convey ideas.

Illustrations accompanying end-of-chapter problems are particularly plentiful in mechanics, where they serve to ease the student toward increasingly abstract thinking. Three-dimensional perspective drawings are used extensively, especially in the chapter on magnetism. In the chapters on optics, unusually careful ray diagrams are provided, for example, to show chromatic aberration and image formation by a microscope.

Illustrations often accompany examples. These illustrations are placed within the body of an example for easy reference. Often an example contains two illustrations, one relating to the formulation of the question, and a second relating to the solution (a free body diagram, for example).

Examples

Over 300 worked examples guide the student first to the solution of elementary problems and then to the solution of conceptually and/or mathematically more complex problems. A general problem-solving strategy is outlined in a special section preceding the problem set in Chapter 1. This strategy is then reinforced in the solution of examples throughout the book.

Particular attention is given to solution of "word problems" in kinematics. In Chapter 2 I introduce the technique of translating questions formulated in words to questions expressed in symbols. For example, the question "If a speed of 70 m/s is needed for a plane to leave the ground, how long a runway is required?" becomes "Find x when $v = 70$ m/s." This kind of translation from words to symbols is surprisingly effective in helping students overcome their difficulty with word problems.

Questions and Problems

The focus of student effort in a physics course is on problem solving. Therefore I have tried to make the over 2000 end-of-chapter questions and problems a strong feature in this text. They serve to build understanding of physical principles and to stimulate student interest in applications of physics to a wide variety of subjects, including biology and sports. Many reviewers have praised the originality and effectiveness of the problems.

The questions encourage students to build their qualitative, conceptual understanding of physics. Answers to odd-numbered questions are provided at the end of the questions section in each chapter.

Problems are rated in difficulty by the number of stars appearing next to them: those with no stars are easiest, one-star problems are more difficult, and two-star problems are most difficult. Answers to odd-numbered problems are provided at the end of the book.

Historical Insights

Historical background is provided in introducing certain topics, for example, universal gravitation, electromagnetic waves, and atomic theory. These are areas in which history provides insight into the meaning of physical concepts by showing how these concepts evolved. A secondary goal is to provide insight into the process of discovery in physics, revealing it as a human activity. *In Perspective* essays give additional historical material.

Essays

Two kinds of essays are provided: 9 *In Perspective* historical essays and 12 *Closer Look* essays that involve physical concepts or applications. Both kinds of essays are intended to stimulate students to think about ideas beyond what is required for the course.

The *In Perspective* essays are mainly short biographies of physicists who have made some of the most important discoveries in physics: Galileo, Newton, Faraday, Einstein, Feynman, Hawking, and Curie. These are more than just a few paragraphs; they offer enough depth to humanize their subjects and sometimes to help understand what motivated their discoveries.

The *Closer Look* essays are discussions of physical principles and applications that encourage the student to think about subjects likely to arouse interest. For example, "Magic in the Sky" describes rare atmospheric optical effects such as the glory and Fata morgana. "Energy to Run" explains, in terms of energy principles, why it is so much easier to ride a bicycle than it is to run at the same speed. "Electrical Effects in the Human Body" provides the biophysical basis for understanding why an electric shock that produces only a small electric current inside the body can nevertheless be lethal. "Biomagnetism" describes how magnetotectic bacteria have evolved in such a way as to take advantage of the earth's magnetic field. "Structure of the Retina and Color Sensitivity" describes the biophysics of the human eye. "General Relativity" shows how simple questions about relative motion led to a profound theory with amazing astronomical implications.

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Introduction

Stonehenge

Why can some insects walk on water? What causes the beautiful colors in a soap bubble or an oil film? Is time travel in a time machine a scientific possibility? If you have ever wondered about such questions, you possess the most basic motivation for the study of physics: curiosity about physical phenomena. The origins of physics began with human curiosity in a prescientific age long ago. Two fundamental problems stimulated that curiosity: the **nature of motion** and the **composition of matter**.

Motion

Observing the stars was important in many early societies, for both practical and mystical reasons. In Egypt astronomers were able to predict the annual flooding of the Nile, which coincided with the first appearance each spring of the star Sirius. Astrology, a system of beliefs begun by the Babylonians and later developed by the Greeks, held that our personalities are affected by the position of the planets relative to the stars at the instant we are born. Ancient astronomers observed and charted the heavens. In England an early civilization produced Stonehenge, an arrangement of huge stones, which may have been used as a primitive observatory 1500 years before the birth of Christ.

Observation ultimately led to the attempt to organize astronomical data. In the second century, the Greek philosopher Ptolemy developed a system for describing the motion of the sun, moon, and planets about a stationary earth. Although earlier Greek astronomers had suggested that the earth moves about the sun, this idea was lost in antiquity, and Ptolemy's model was generally accepted until the middle of the sixteenth century. Then, in 1543, the Polish astronomer and mathematician Nicolaus Copernicus published *De Revolutionibus*, in which he challenged the Ptolemaic description of the universe and proclaimed that all the planets, including the earth, revolve about the sun.

In the early seventeenth century, Galileo Galilei built one of the first telescopes and used it to observe the heavens. He is probably best known for his defense of the Copernican system and his ensuing controversy with the Catholic Church.

Of even greater significance for the development of physics, however, was Galileo's study of the nature of motion. He defined mathematically precise concepts with which to describe motion and performed simple experiments that led him to formulate the law of inertia.

Galileo was aware of the potential of the powerful new ideas he introduced. In *Two New Sciences* he wrote:

> The theorems set forth in this brief discussion, if they come into the hands of other investigators, will continually lead to wonderful new knowledge. It is conceivable that in such a manner a worthy treatment may be gradually extended to all the realms of nature.

Experimental and theoretical studies by many scientists led to a fundamental understanding of motion by 1687, when the book *Philosophiae Naturalis Principia Mathematica* was published in England. This monumental work by Isaac Newton expounded his system for explaining both celestial and terrestrial motion. Today this branch of physics, covered in the first 10 chapters of this book, is called "classical mechanics."

In his own time, the scientific effect* of Newton's ideas was to provide a complete solution to the problem of understanding planetary motion. In historical perspective, however, Newton's work assumes even more importance, in that it is the basis for later physical theories. For example, investigations into the nature of electric and magnetic phenomena are built upon classical mechanics.

Matter

The other ancient problem of physics was the relationship between bulk matter and the microscopic particles of which it is composed. About 400 B.C. the Greek philosopher Democritus speculated that all matter consist of indivisible particles which he called "atoms." What we call atoms today are *not* indivisible. But the possibility of finding the subatomic particles that truly are the basic building blocks of matter remains an intriguing question that has been only partially answered. Physicists continue to search for the fundamental particles. They also seek a unified understanding of the multiplicity of particles that have emerged from that search.

The general trend in our study of physics will be toward an increasingly microscopic view, since many of the questions that arise in a study of macroscopic phenomena have their answer on the atomic or molecular level. For example, we shall study classical mechanics—a macroscopic view—in Chapters 1 to 10 and then apply these concepts on the microscopic level to explain temperature and heat. Our study of electricity and magnetism (Chapters 17 through 22) will involve a description of the electron and proton, the basic charged particles within the atom. Chapters 29 and 30 will complete our gradual transition from a macroscopic description of matter to a particle description with a study of atoms, nuclei, and elementary particles.

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*Newton's work had great influence on other areas of thought. Newtonian mechanics revealed a "clockwork universe," a world of intricate but orderly motion. This picture of the universe as an ordered whole influenced religious, philosophical, and political ideas.

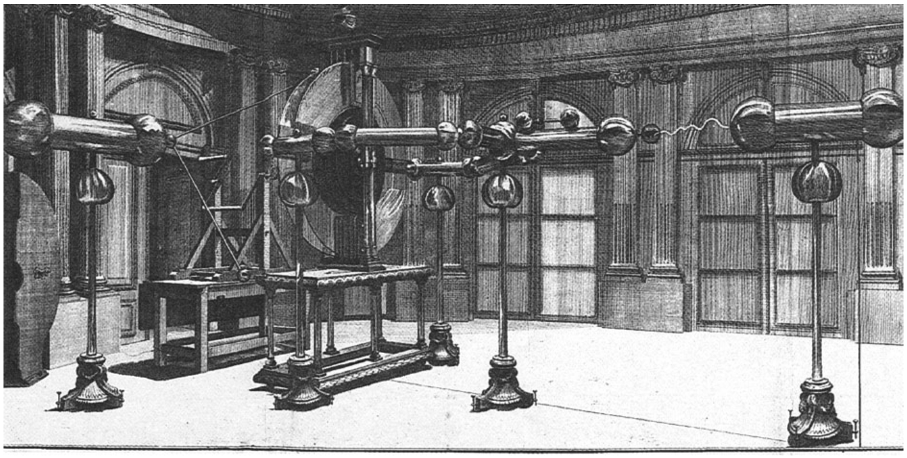
Applications

Although the questions we ask in physics are typically motivated by curiosity rather than by practical consideration, discoveries in physics have often had a dramatic impact on technology. This in turn has had very obvious and pervasive effects on modern society. For example, our entire electronic technology began with fundamental questions about the nature of electricity and magnetism. Early experiments used simple, large-scale equipment. Today we have sophisticated electromagnetic communications systems and small, powerful computers utilizing tiny integrated circuits. These technologies are changing the way we live. The discovery of high-temperature superconductors in 1987 may lead to further change—practical electric cars, 300-mph magnetically levitated trains, smaller and more powerful computers using superconducting components, and controlled fusion as an abundant new source of energy. An educated person in this high-tech age should have some knowledge of the principles of physics underlying the new technologies, if only to make the technologies less mysterious.

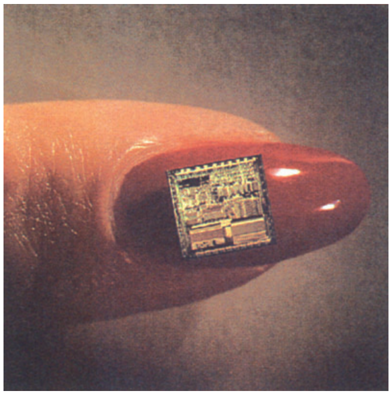
A knowledge of physics is important for professional competence in many fields, since physics serves as a foundation for other sciences. For example, principles of quantum mechanics and atomic physics are used in chemistry to understand many biological processes, including nerve conduction. Thus a knowledge of physics is essential for chemists and biologists and also for physicians, dentists, engineers, geologist, architects, and physical therapists.

Aside from the very practical reasons for knowing some physics, there can be an esthetic value. Our appreciation of the world around us is enhanced when we view phenomena with the eyes of a physicist. Admittedly this is an acquired taste, and not everyone who takes a physics course will agree. But you may find pleasure in seeing physical principles applied to your environment—in understanding, for example, why you are pushed outward in a car as you turn a corner, or why a spinning baseball curves, or why the sky is blue.

Many of the examples and problems in this text describe applications of physics to everyday life. There are also more lengthy descriptions of applications, many involving biological systems. Newton's laws of motion, applied to the flow of fluids, are used to



Eighteenth-century equipment used to study electricity.



A modern integrated circuit containing hundreds of thousands of electrical components.

understand the human circulatory system. Principles of electricity are used to explain household electricity and electric shock. Optical principles are applied both to the human eye and to the microscope. Quantum physics is used to understand lasers. Nuclear physics is applied to carbon dating of ancient archeological specimens.

Essays on various applications of physics appear throughout the text under the heading "A Closer Look." The topics of essays are not commonly part of an introductory course and are included only to stimulate your interest. The text also contains "In Perspective" essays that give brief biographical sketches of physicists who have made some of the most important discoveries in physics.

Mathematics

Mathematics has an important role in the study of physics because the laws of physics are written in the language of mathematics; that is, they are expressions of precise relationships, set in a conceptual framework. As Galileo said nearly 400 years ago,

> Philosophy is written in this grand book, the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and reads the letters in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures… Without these one wanders about in a dark labyrinth.

Thus there are certain mathematical prerequisites for a study of physics, mainly high-school algebra and trigonometry. This text does not require a knowledge of calculus. Appendix A gives a brief review of the math you will need in your study of physics.

Derivations

Some physical laws are more fundamental than others. Derivations in the text show how the more fundamental laws lead to secondary ones, which are then applicable to particular kinds of problems. Although students often find derivations unappealing, they are an important part of physics. A physics book is not an encyclopedia. It certainly does not deal with all the detailed manifestations of physical law that occur in nature. Instead it provides a coherent description of fundamental physical laws and demonstrates the unity of physics—the relationship of physical laws—through derivations.

There is another, very practical reason for supplying derivations in a text, rather than simply describing results. If you thoroughly understand a derivation, you will also understand when the derived equation may be used. Obviously the intelligent use of equations requires that you know where they are applicable. Thus you should at least be aware of the assumptions made in the text when equations are derived.

Study Objectives

You should have two objectives in studying physics: (1) to obtain a **unified understanding of the fundamental principles of physics**, their areas of applicability, and their interrelationships, and (2) to develop the ability to **solve practical problems** using these principles. The two goals are complementary, and it is impossible to achieve one without the other.

When the answer to a problem is provided, it is sometimes possible to "solve" the problem by a trial-and-error process of formula juggling devoid of any real understanding. If you have no idea of why the principle used should apply, obtaining a correct numerical answer will not be of much value. Therefore the time you spend working on specific problems should be preceded by a careful reading of the text and lecture notes, so that you thoroughly understand the concepts.

A first course in physics is usually a great challenge and is often undertaken with considerable fear and anxiety. You may find it difficult to understand some of the concepts and impossible to solve certain problems. This is to be expected. It is definitely possible to learn from your mistakes in physics, and so it is important not to become discouraged. Like learning a new athletic skill or learning to play a musical instrument, learning physics requires practice. If you continue to work hard, your understanding will grow. You will find that you are able to understand many phenomena with a relatively small number of concepts. It can be very satisfying to see that the workings of both nature and technology can be explained in terms of just a few basic laws. It can also be satisfying to use physical laws to predict the outcome of a laboratory experiment and then verify your prediction by making measurements.

In this book I attempt to explain in the clearest possible way some of the mysteries of the physical universe. It is my hope that you will learn from it, and at the end of your physics course you will be able to look back on it as a positive experience.

Math phobic's nightmare