HUGH D. YOUNG

FUNDAMENTALS OF WAVES, OPTICS, AND MODERN PHYSICS

SECOND EDITION

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Editor's Introduction

This volume in the Introductory Program of the McGraw-Hill Series in Fundamentals of Physics is devoted primarily to the physics of the twentieth century, including relativity, the successes and failures of classical optics, and the fundamentals of quantum mechanics as applied to atomic and molecular structure, nuclear physics, the solid state, and high-energy physics. Although it can be used independently, this textbook was particularly planned to be used in conjunction with the two companion volumes in this series, *Fundamentals of Mechanics and Heat* by Hugh D. Young and *Fundamentals of Electricity and Magnetism* by Arthur F. Kip. The homogeneity of level and viewpoint of these three books makes them an ideal "package" for a high-level calculus-based introductory physics sequence which includes a substantial component of modern physics. However, the present volume may also be used following any of several other popular texts which include mechanics, heat and thermodynamics, and electromagnetism.

Preface to the Second Edition

The objectives and basic outline of the book, as described in the original Preface, remain unaltered, but several substantial changes have been made to enhance its usefulness. Here are the most significant changes:

1 The two opening chapters provide a self-contained introduction to the special theory of relativity, including simple but complete derivations of the Lorentz transformations and the relativistic energy and momentum expressions.

2 The treatment of mechanical waves has been expanded somewhat, and now includes consideration of energy and normal modes.

3 The material on physical optics has been reorganized and expanded into two chapters; among the additions are a section on circular polarization, material on diffraction from a circular aperture, and a section on holography.

4 The chapter on statistical mechanics now includes an introduction to the elementary kinetic theory of an ideal gas, including a derivation of the equation of state and a discussion of specific heats.

5 The treatment of quantum mechanics and its applications to atomic systems has been simplified somewhat, but no important results from the first edition have been deleted.

6 The chapter on fundamental particles has been updated and expanded, especially the material on classifying particles and interactions and the role of symmetry and conservation principles.

7 Several topics not included in the first edition have been added; there is a new section on lasers and masers, one on nuclear decay rates, and one on the biological effects of radiation.

8 Nearly 200 new problems have been added, bringing the total to over 500 and providing greater variety and broader coverage than in the first edition.

The book may be used in its entirety for a one-semester, four- or five-credit-hour course, following introductory courses in mechanics, thermodynamics, and electromagnetism. For a three-credit-hour course some instructors may wish to shorten it somewhat by the omission of certain topics. Any or all of Chapters 7 and 12 through 16, and numerous sections within the other chapters, may be omitted without interrupting the continuity. Thus courses with a variety of length and emphasis can be constructed. The position of the relativity chapters is somewhat arbitrary; this material can be postponed until after Chapter 7 if desired.

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Finally and most important, the author acknowledges again his great debt to his wife Alice and his children Gretchen and Rebecca for their unending patience, confidence, and moral support throughout the writing and revising of this text.

HUGH D. YOUNG

Preface to the First Edition

The principal objective of this book is to present in elementary form some of the most important physical theory that has been developed during the current century. Contemporary concepts of atomic and nuclear physics and the structure of matter are presented against a background of classical mechanics, electrodynamics, and optics, and at each stage in the presentation the empirical basis and physical motivation of new developments are exhibited clearly. Analytical techniques such as calculus and vector analysis are used freely wherever they are needed, and a strong attempt is made to exhibit the spirit of scientific inquiry and the empirical basis of natural science.

Specifically, this book is intended for the conclusion of a series of courses with a total length of one to two years, starting in the freshman or sophomore college year, and with a concurrent course in calculus. For the beginning of the sequence, the other volumes in the McGraw-Hill Series in Fundamentals of Physics are particularly suitable because of their uniformity of level and viewpoint, but there are several other suitable combinations.

As the table of Contents shows, the subject of optics is regarded as a natural and useful bridge between classical mechanics and electrodynamics and contemporary quantum theory. The classical theory of optics is a natural outgrowth of classical electrodynamics; in turn, optical phenomena have provided much of the important motivation for the development of quantum mechanics and its many applications, especially to an understanding of the macroscopic behavior of matter on the basis of its microscopic structure, one of the unifying themes of this book.

The table of Contents indicates the scope of the book, but we also wish to point out the following features:

1 The book assumes that the student has taken a thorough course in classical mechanics, electromagnetism, and elementary thermodynamics, including

Maxwell's equations in integral form. However, applications of these equations are spelled out in considerable detail, since for most students they will be new and somewhat unfamiliar. Calculus and vector algebra, including line and surface integrals, are used freely where needed, but no knowledge of the vector differential operations (grad, div, and curl) is assumed. As is customary, vector quantities are denoted by boldface symbols; in addition, boldface **+**, **−**, **Σ**, and **=** signs are used in vector equations to denote vector operations and equality.

2 The book attempts to exhibit the inductive and empirical nature of physics along with its deductive aspects. Care has been taken to distinguish clearly between principles that are generalizations from experience and those that are derived and to indicate the experimental basis of the former. The relative status of each principle in the whole logical structure is thus made clear. The author has made every effort to avoid the two extremes of a dry recitation of experimental results or of a tightly knit body of theory without reference to empirical observations.

3 Throughout the book the importance of *models* is stressed. We rarely deal directly with physical reality but rather with simplified models designed to retain the essential features of a physical situation and eliminate the unessential ones, to facilitate analysis. The student is constantly reminded of the process of constructing models as idealizations of reality as well as of the limitations of analytical results imposed by the limitations of validity of the models.

4 The texture of the book is not entirely even; some sections are more difficult reading than others. This variation is deliberate; some topics are intrinsically more subtle or demanding than others, and in addition not all students have equal abilities. Almost always the most difficult sections are arranged in such a way that they can be omitted without undue interruption of continuity. In addition, several important topics which are likely to cause difficulty, such as the concept of waves, wave pulses, and group velocity, are introduced several different times with a "spiral" approach, in order to help the student attain successively higher levels of sophistication in these important but sometimes elusive concepts. In the latter chapters of the book, some topics which are conceptually most subtle are softened somewhat by including less than the usual amount of analytical detail.

5 The mks system of units is used exclusively. There seems little doubt that it will eventually be used universally in scientific work. In addition, the author feels strongly that the burden of mastering several systems of units simultaneously should not be added to that of mastering new physical concepts.

6 A large collection of over 300 problems is included. A few of them are simple substitution exercises, designed to illustrate definitions, but most require some thought and insight on the part of the student. Many of the problems are literal or algebraic rather than numerical; some are too difficult for all except the best students, and there is plenty of material for "honors" sections. Many problems ask only for an order of magnitude or for a discussion; the author feels strongly that such questions are often at least as instructive as more specific problems having a definite numerical answer. For some problems the student will need to look up additional information in the *Handbook of Chemistry and Physics* or a similar reference; familiarity with such standard reference works is highly recommended.

Although this book is intended primarily as a high-level introductory text, it may also be used for an intermediate-level course following a first general physics course given without calculus. A thorough and detailed exposition of principles and a plentiful supply of challenging problems make it useful for such intermediate courses.

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PROSPECTUS

"To both the intellect and the emotions the study of physics is exciting, satisfying, and even beautiful, and it is the author's intention to convey these qualities to the student." This remark appears at the beginning of the first volume of the Fundamentals of Physics Series, but it is even more appropriate for the present volume. The subject matter of this book includes some of the most exciting areas of physics, concentrating particularly on the physics that has developed in the twentieth century, some of it even during the lifetime of the reader. These recent years have witnessed many revolutionary changes in our conception of the physical world in which we live and remarkable progress in our understanding of it.

The special theory of relativity is a natural starting point for our study of twentieth-century physics. The concepts of this theory, including the relative nature of space and time and of matter and energy, and the role of the observer in measurements, provide a unifying thread that runs through all of contemporary physics and plays an essential rôle in our present-day understanding of the nature and structure of the physical world.

From relativity we proceed into optics; this is a logical direction for the continuation of our study, for a variety of reasons. Some branches of optics, especially those concerned with wave phenomena, are a natural outgrowth of classical electrodynamics and provide a beautiful illustration of the great power of Maxwell's electromagnetic field equations in unifying various branches of physical science. Conversely, however, the shortcomings and insufficiencies of this so-called classical branch of optics, especially with problems involving the interaction of matter and radiation, provided the original motivation for the development of quantum mechanics, one of the central themes in this book.

Since the language of waves and wave phenomena occupies a central *position in both classical optics and contemporary quantum mechanics, we first undertake a general discussion of waves, using as a prototype problem the propagation of waves in a simple mechanical system. The wave concept, together with Maxwell's electromagnetic field equations, provides the basis for an understanding of a wide variety of optical phenomena such as interference, diffraction, and polarization. We then discuss these, along with the simpler but more specialized subject of geometrical optics.*

With Chap. 8 we begin an investigation of the inadequacies of classical optics, and in the process of analyzing them we develop the basic ideas of quantum mechanics, which form the core subject matter for the remainder of the book. A number of phenomena are introduced, concerning the structure of atoms and the interaction of radiation with matter, which cannot be understood on the basis of classical newtonian mechanics (even with relativistic modifications) and classical electromagnetism as formulated in Maxwell's equations. We discuss in some detail the basic modifications in the formal structure of these disciplines which are needed for the foundation of quantum mechanics.

The next several chapters are devoted to applications of quantum mechanics to various systems whose understanding is central to a thorough analysis of the structure and properties of matter. Beginning with the simplest atom, hydrogen, we progress to more complicated atoms, molecules, matter in the solid state, and finally the structure of nuclei and of fundamental particles.

The careful reader will notice several central themes running throughout this book. Among them are the use of idealized models to simplify complex situations, the general concepts of waves and of wave propagation, the relationship of the microscopic structure of matter to its macroscopic properties, and such fundamental concepts as mass, energy, momentum, force, and the associated conservation principles. In these common themes is found much of the great power and beauty of physical science.

The author has tried throughout to exhibit his personal conviction that physics is beautiful, exciting, and satisfying. It is his hope that the reader will enjoy understanding new principles and grasping their power and usefulness and will feel the satisfaction and personal achievement that come from struggling with and solving challenging problems.

Relativity 1

The special theory of relativity is one of the indispensable cornerstones of the entire structure of twentieth-century physics. It is based on the principle that all inertial frames of reference are completely equivalent with respect to the formulation of physical laws. This requirement can be satisfied for both the laws of mechanics and those of electromagnetism only when certain modifications are made in the familiar relationships between distances and time intervals measured in two different coordinate systems which are moving relative to each other. The modified *kinematic* relations which result also necessitate a reformulation and generalization of the laws of *dynamics*. The resulting principles have greater generality than those based on Newton's laws; newtonian mechanics emerges as a special case of the more general formation, retaining its validity in situations where all speeds are much smaller than the speed of light.

1-1 INVARIANCE OF PHYSICAL LAWS

The concept of *inertial frame of reference* plays an essential role in newtonian mechanics. By definition, a coordinate system in which Newton's laws of motion are found to be valid is called an inertial frame of reference. For many purposes the earth may be taken as an inertial frame, although its rotation and orbital motion make it not precisely an inertial frame. A rotating merry-go-round or an accelerating truck is *not* an inertial frame; when the motion of a body is described using coordinates based on such a system, Newton's laws are *not* obeyed.

Once an inertial frame has been found, any other frame moving relative to it with constant velocity is *also* inertial, because the acceleration of a body is the same when measured in the two frames. Newton's laws of motion are