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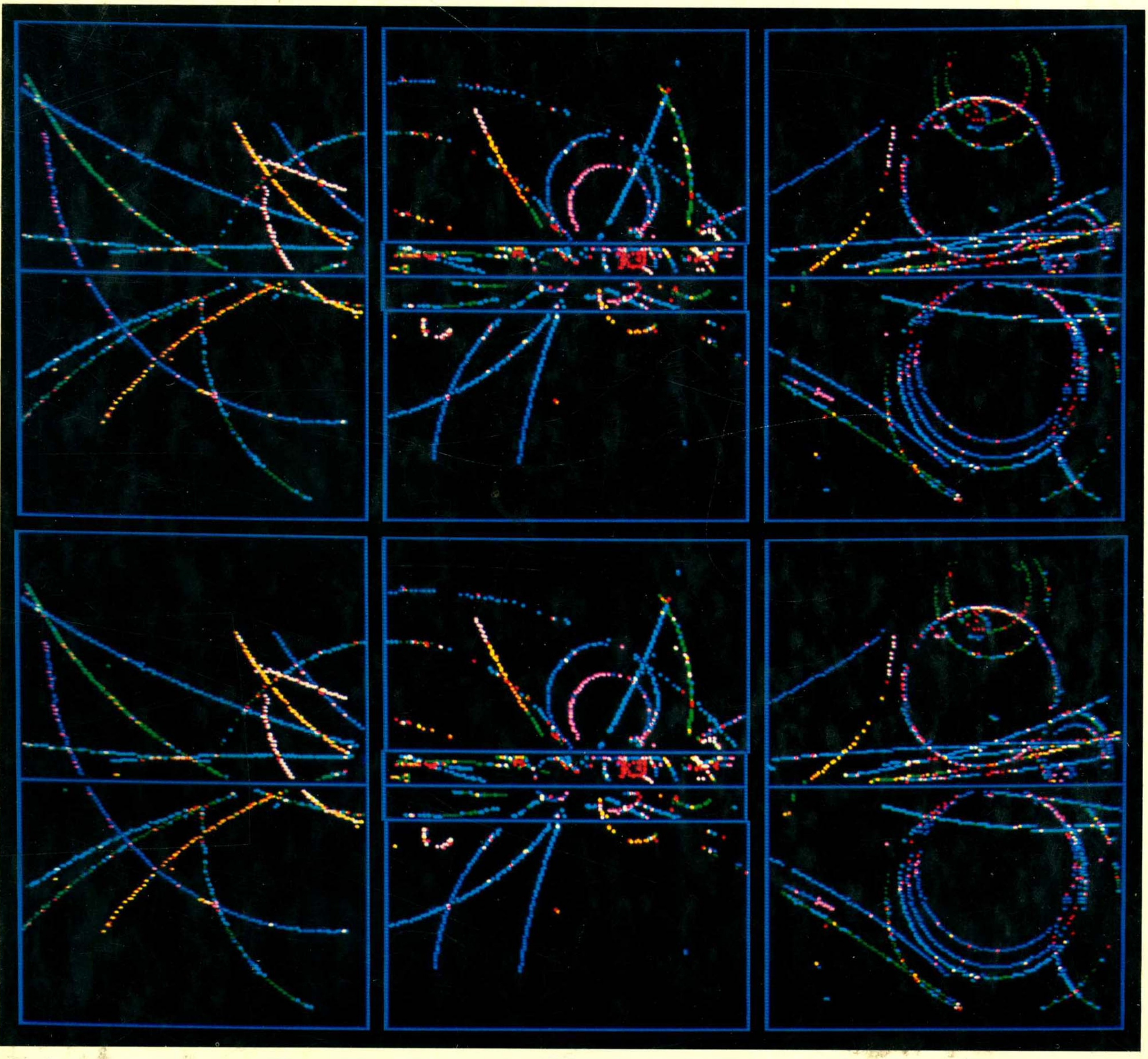
FRANK J. BLATT

PRINCIPLES OF PHYSICS

SECOND EDITION



SECOND EDITION

Principles of Physics

Frank J. Blatt

Michigan State University

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The Front Cover. Detectors at today's powerful accelerators are enormous arrays of intricate electronic devices that record the trajectories of particles produced in high energy collisions. The coordinates are stored in the memory of a large computer and particle tracks are displayed on video screens.

The front cover shows such a computer generated image, one of great historical significance. It revealed the existence of the Z^0, the "Intermediate Vector Boson," whose mass is about 90 proton masses. The Z^0 (and its charged counterpart, the $W^{\pm}$) was postulated some years earlier in a theory that encompasses the electromagnetic and weak interactions in a single framework. This "electroweak" theory is widely regarded as the first step toward the realization of a dream that Einstein pursued throughout his life: a Grand Unified Theory to explain the fundamental origin of all forces—gravitational, weak, electromagnetic, and strong nuclear.

C. Rubbia and S. van der Meer received the 1984 Nobel Prize for the discovery of the W and Z particles in experiments performed at CERN, Geneva.

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CREDITS

CHAPTER 1 FIG. 1.1, p. 4—Courtesy of National Bureau of Standards. FIG. 1.2, p. 4—Trustees of the Science Museum, London.

CHAPTER 2 QUOTES, p. 25—Leon N. Cooper, *An Introduction to the Meaning and Structure of Physics,* Harper & Row, New York, 1968, pp. 2, 10 (Galileo, Dialogue Concerning Two New Sciences, Henry Crew and Alfonso de Salvio, trans., Macmillan, New York, p. 155). FIG. 2.7, p. 25—AIP Niels Bohr Library. QUOTES, p. 26—Cooper, p. 10. FIG. 2.8, p. 26—Sears/Zemansky, *University Physics,* Addison-Wesley, Reading, Mass., 1976. FIG. 2.13, p. 31—*PSSC Physics,* 5th ed., D. C. Heath, Lexington, Mass., 1981. FIG. 2.14, p. 32—Courtesy Dr. Harold Edgerton, MIT.

CHAPTER 3 QUOTE, p. 47—J. Bronowski, *The Ascent of Man,* Little, Brown, Boston, 1973. FIG. 3.10, p. 57—Courtesy of NASA.

CHAPTER 4 FIG. 4.2, p. 75—AP/Wide World Photos. FIG. 4.9, p. 81—Boeing Aircraft Company. FIG. 4.12, p. 83—Bureau of Reclamation, U.S. Department of the Interior. FIG. 4.13, p. 84—Courtesy Dr. Harold Edgerton, MIT.

CHAPTER 5 FIG. 5.1, p. 99—Courtesy Dr. Harold Edgerton, MIT. FIG. 5.2, p. 99—Courtesy Dr. Harold Edgerton, MIT. QUOTES, p. 100—W. F. Magie, *A Source Book in Physics,* Harvard University Press, Cambridge, Mass., 1963, pp. 32, 37. FIG. 5.5, p. 102—AP/Wide World Photos. FIG. 5.6, p. 103—Harold Wes Pratt.

CHAPTER 6 FIG. 6.6, p. 125—Susan Dodington. FIG. 6.11c, p. 130—Photo by Dan Feicht, Cedar Point, Inc. FIG. 6.13a, p. 131—Stock Boston.

CHAPTER 7 QUOTE, p. 138 (top)—Leon N. Cooper, *An Introduction to the Meaning and Structure of Physics,* Harper & Row, New York, 1968, p. 56 (Sir *Isaac Newton's Mathematical Principles of Natural Philosophy and His System of the World,* Andrew Motte, trans., University of California Press, 1962). QUOTE, p. 138 (bottom)—Cooper, p. 57 (Charles C. Gillispie, *The Edge of Objectivity,* Princeton University Press, 1960). FIG. 7.1, p. 139—Culver Pictures. QUOTE, p. 139—J. Bronowski, *The Ascent of Man,* Little, Brown, Boston, 1973, pp. 223, 226, 232. FIG. 7.3, p. 141—The Granger Collection. FIG. 7.4a, p. 143—BBC Hulton Picture Library. FIG. 7.6, p. 144—Courtesy of NASA.

CHAPTER 8 FIG. 8.21, p. 164—National Aeronautics and Space Administration. FIG. 8.23, p. 166—Sperry Division, Sperry Corporation.

CHAPTER 9 FIG. 9.7a, p. 188—Photo Researchers, Inc. FIG. 9.8b, p. 189—Photo Researchers, Inc.

CHAPTER 10 QUOTES, pp. 199-200—W. F. Magie, *A Source Book in Physics,* Harvard University Press, Cambridge, Mass., 1963, p. 75. FIG. 10.1, p. 200—Culver Pictures. FIGS. 10.6a, 10.6b, p. 204—Deutsches Museum, Munich. FIG. 10.12, p. 208—Bettmann Archive. FIG. 10.19, p. 214—Courtesy of the late Professor Frank N. M. Brown Photographic Collection, University of Notre Dame. FIG. 10.29d, p. 222—Bradford Washburn. FIG. 10.32, p. 226—Fundamental Photographs, New York.

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Preface

In preparing this second edition of *Principles of Physics,* I have been guided by the many thoughtful suggestions of numerous reviewers. The new edition features a number of important changes and additions. However, the spirit and philosophy of the book has not changed. It is, as was the first edition, an appropriate text for a one-year introductory course in physics for students in the biological, environmental, earth, and social sciences. The mathematical prerequisites are again only algebra and elementary trigonometry; calculus is not used. Like the first edition, this second edition presents a comprehensive account of physics, concentrating on fundamental concepts by emphasizing careful physical reasoning with minimal reliance on mathematical crutches.

The goal of a first, and often only, course in physics at the college level should be to help students develop physical intuition and to teach them not merely how to solve but, more important, how to approach new problems. To this end, I have stressed the use of symmetry, dimensional analysis, and conservation laws.

As every experienced instructor knows, to derive every important relation without recourse to calculus is practically impossible. Hard as one may try, one is occasionally forced to avail oneself of the phrase "It can be shown. . . ." I have made every effort to avoid that procedure; in those rare instances (e.g., exponential decay of an *RC* or *RL* circuit) where a derivation cannot be accomplished without calculus, I have made a special effort to show that the result is physically plausible and dimensionally correct.

Though problem solving is unquestionably an essential part of the learning process, the ability to carry a problem to its correct numerical solution is by no means the only, sometimes not even the best, measure of understanding. In problem solving mathematical manipulation too often demands a disproportionate effort: Students who can substitute numbers into the proper equation and obtain the correct answer may delude themselves into thinking that they have mastered a new concept; conversely, students who understand the subject but have less mathematical dexterity may be discouraged because they fail to get the "right answer." Every reviewer of the first edition has commented enthusiastically on the qualitative multiple choice questions that are designed to probe a student's understanding of new concepts and their physical significance. I have retained nearly all of these questions and have added a substantial number of new ones to nearly every chapter.

There are even more problems at the end of each chapter than before. Some problems of the first edition have been omitted and many new ones have been added; most, though by no means all, of them are of the simple, "confidence builder" type. As in the earlier edition, problems are grouped according to principal sections to aid the instructor; the level of difficulty of a problem is indicated by a simple code (no mark, simple exercise; one dot, average difficulty; two dots, challenging problem). Answers to the odd-numbered multiple choice questions and problems are listed following the Appendixes.

Several reviewers urged the inclusion of more in-text examples. This new edition incorporates nearly 50 percent more examples than the first; almost every section contains at least one and frequently two or more examples. Many of them are taken from biology, medicine, archeology, astronomy, and the earth sciences. They have been carefully selected with a view to timeliness and fundamental simplicity, and they are discussed in sufficient detail to allow the reader to understand the technique as well as the application of the physical principles involved in each instance.

Other noteworthy changes that distinguish this from the earlier edition are as follows: The chapter on kinematics has been completely rewritten. A section on Kepler's laws has been added to the chapter on gravitation. The chapter on thermodynamics has been reorganized; a section on general heat engines and refrigerators has been added, and the discussion on the relation between statistical mechanics and thermodynamics is an optional section at the end of the chapter. The chapter on simple harmonic motion has been rewritten and the relation of SHM to circular motion clarified. The last chapter has been expanded to include an up-to-date account of elementary particles and the quark model. These changes are, however, only a few of the revisions. The entire text has been scrutinized and made more concise, and a few sections have been shortened where possible without damage to clarity or style.

Practically all of the historical material of the first edition has been retained; in fact, I have made one or two minor additions. Such anecdotal commentary not only enlivens the text but shows dramatically that science does not progress in a logical step-by-step sequence along a straight path. I believe it is vitally important that students, especially students who are not in the physical sciences, recognize that physics is very much a human enterprise, exciting but sometimes quite frustrating.

There is undoubtedly more material in this text than can be covered in most one-year courses. That is as it should be. A text that must be augmented by auxiliary material evidently fails to meet the needs of the instructor. The topics I have included encompass all those traditionally taught (and listed in the MCAT manual). Several sections have been marked with an asterisk (*). These sections are optional and, though of interest to special groups of students, can be omitted without loss of continuity. No material needed in later chapters is included in an optional section.

Two entire chapters have been marked optional. Chapter 28, "Relativity," addresses the widespread interest of students in this topic. Even though the material is devoid of mathematical complexity, instructors should keep in mind that the subject demands a level of sophistication few beginning students have achieved. Chapter 31, "Aggregates of Atoms: Molecules and Solids," contains some material that is often taught in chemistry; the section on solids—in particular, the discussion of semiconductor devices—is again an attempt to satisfy the curiosity of many students. None of the topics of this chapter is essential in a first-year physics course.

I have already alluded to my debt to reviewers; it is fitting that their assistance be recognized here:

Paul Bender, Washington State University
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Walter G. Wesley, Moorhead State University

Nothing exasperates students more than to find, after hours of frustration, that their answers do not agree with those in the back of the book because the latter are wrong. Every effort has been expended to ensure that the answers given are, indeed, correct. I have solved these problems, and my work has been checked by Edith Cassel and Betty Richardson, Cornell University, and Luis F. Garcia, Michigan State University, who prepared the solutions in the *Instructor's Manual.*

I have again been fortunate to have had the expert assistance and support of the staff at Allyn and Bacon, Inc., in particular, Carol Beal, Jane Dahl, Judith Fiske, Gary Folven, Barbara Gracia, and James Smith. The excellent artwork was executed with meticulous care by Scientific Illustrators under the direction of Mr. George Morris.

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1

Units, Dimensions, Vectors, and Other Preliminaries

There shall be standard measures of wine, beer, and corn—the London quarter—throughout the whole of our kingdom, and a standard width of dyed, russet and halberject cloth—two ells within the selvedges; and there shall be standard weights also.

MAGNA CHARTA (1215)

1.1 Units

The observations and experiences that interest scientists span an immense range. Distances extend from the incredibly small dimensions of subnuclear particles to the thousands of light years that separate galaxies of the universe; times encompass those of stellar evolution and the almost infinitesimally short lifetimes of some "elementary particles." Similarly, enormous ranges of masses, electric charges, magnetic fields, pressures, densities, or other variables engage the attention of physicists in their daily work. The ranges of distance, mass, and time of phenomena studied today are listed in Table 1.1.

To describe and characterize these phenomena, scientists must agree on a consistent set of *units* with which measurements are to be compared. Masses, lengths, times, currents, velocities become meaningful only in comparison with ones familiar to us. The unit is simply the standard yardstick with which a particular event is contrasted.

Unfortunately, in the historical development of science different systems of units were used in different parts of the world, and in the same country by different professions. To confuse matters further, the fact that certain physical quantities like electric current and magnetic field are not independent but fundamentally related was not recognized when they were first studied. As a

Table 1.1 Ranges of length, time, and mass in the universe

Length (in meters)	
10^{-17}	Present experimental limit in determining nuclear structure
10^{-15}	Diameter of proton
10^{-10}	Diameter of atom
10^{-8}	Length of ribosome
10^{-6}	Wavelength of visible light; length of bacterium
1	Height of man
10^{7}	Radius of earth (6371 km)
10^{11}	Radius of earth's orbit (149×10^6 km)
10^{16}	One light year
10^{22}	Distance to nearest galaxy (M31 in Andromeda)
10^{26}	Radius of universe
	Range of $10^{26}/10^{-17} = 10^{43}$
Time (in seconds)	
10^{-23}	Time for light to cross a proton
10^{-15}	Period of light wave
10^{-8}	Time for emission of photon from excited atom
10^{-2} } 10^{9}	Human time scale: range between reaction time to visual or other stimulus and average life span
10^{7}	One year (3.16×10^7 s)
10^{16}	Solar system completes one turn about galactic center
10^{17}	Age of earth
10^{18}	Age of the universe
	Range of $10^{18}/10^{-23} = 10^{41}$
Mass (in kilograms)	
10^{-30}	Mass of electron
10^{-27}	Mass of proton
10^{-21}	Mass of ribosome
10^{-15}	Mass of bacterium
10^{2}	Mass of man
10^{25}	Mass of earth (5.98×10^{24} kg)
10^{30}	Mass of sun (1.99×10^{30} kg)
10^{41}	Mass of our galaxy
10^{52}	Mass of universe
	Range of $10^{52}/10^{-30} = 10^{82}$

result, several diverse units have been in common use. These are now being replaced, under international agreement, by units of the *Système International,* or SI units. In this system, the *meter, kilogram,* and *second* are the fundamental units of *length, mass,* and *time,* respectively.

Students in the United States are more conversant with the pound, foot, and quart of the British system than with the newton, meter, and liter. However, the SI units are now widely used throughout the world, and will soon be in use in this country as well. The study of physics is a good initiation to the "metric" system; moreover, use of that system makes the physics itself more lucid and the computations more tractable. We shall therefore rarely mention the British units, and then only to compare them with their metric equivalents.

Although we shall stay with the SI, it is important to know how to convert from one unit to another. Conversion factors are listed inside the front cover. Two examples will illustrate the method.

Example 1.1 A car is driving at a speed of 50 miles per hour (mph). What is the speed of the car in kilometers per hour and in meters per second?