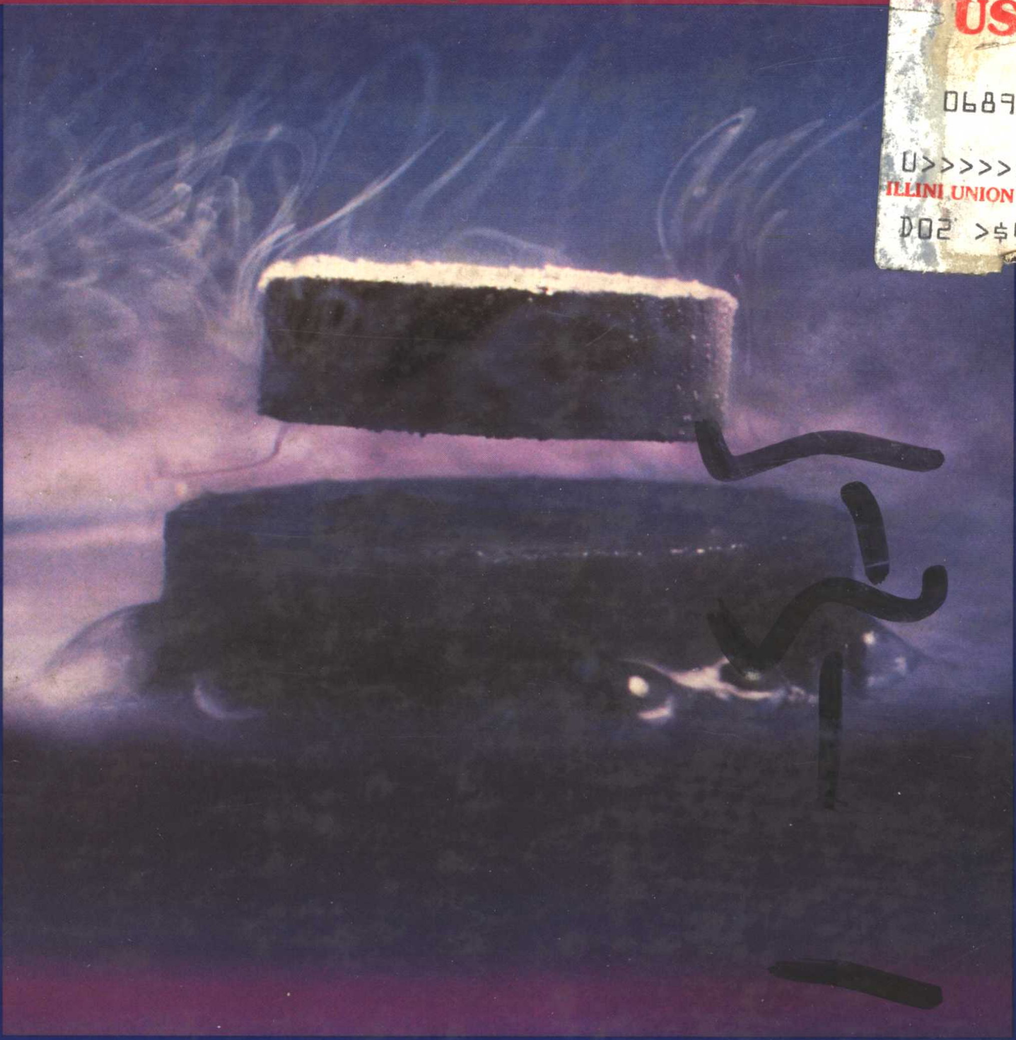
THIRD EDITION



PRINCIPLES OF

PHYSICS

FRANK J. BLATT

Principles of Physics

Third Edition

Frank J. Blatt

University of Vermont

Allyn and Bacon

Boston • London • Sydney • Toronto

Preface

In preparing this third edition of *Principles of Physics,* I have been guided by the many thoughtful suggestions of reviewers and numerous faculty and students who have used the earlier edition. The new edition features a number of important changes in both organization and content. However, the spirit and philosophy of the book remains as before. It is, as were the previous editions, a most suitable text for a one-year introductory course in physics for students in the biological, environmental, and social sciences. The mathematical prerequisites are again only algebra and elementary trigonometry; calculus is not used. Like the previous editions, this third edition presents a comprehensive account of physics, concentrating on fundamental concepts by emphasizing physical reasoning with minimal reliance on mathematical crutches.

The aim 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, a derivation of every important relation without recourse to calculus is practically impossible. Hard as one may try, one is occasionally forced to resort to the phrase "It can be shown . . ." I have made every effort to avoid that *tour de force;* in those few instances (e.g., exponential decay of *RC* and *RL* circuits, and radioactive decay) where a derivation of the time dependence cannot be accomplished without recourse to calculus, I have made a special effort to show that the result is physically plausible and dimensionally correct.

The overall organization of this edition is the same as that of the previous. The following changes have been made. (1) The chapter on kinematics has been divided into two parts: Chapter 2 is restricted to rectilinear motion; kinematics in two and three dimensions is treated in Chapter 3. Consistent with this restructuring, vectors and the discussion of vector addition is deferred to Chapter 3, where these constructs are first required by the physics. (2) The concept of a potential function now appears initially in Chapter 8, "Gravitation" and surfaces again in Chapter 18, "Electrostatics". (3) Interference of waves is introduced in Chapter 17, "Sound". (4) The two chapters devoted to electrostatics in the earlier editions have been combined into a single chapter, as have the two chapters on steady electric currents and DC circuits. The economies of these and other minor alterations allow the inclusion of new material without significantly increasing the overall length of the text.

Since the earlier editions already encompassed a complete and concise presentation of the fundamentals, most, though not all, of the new topics fall into the "optional" category. These include: Section 20.10 on nerve conduction and action potentials; section 15.8 on the physical pendulum; section 29.6 on atomic energy levels in a magnetic field, which contains a brief discussion of electron spin resonance; section 31.3 on nuclear magnetic resonance, which describes, in qualitative terms, NMR imaging, perhaps the most significant medical diagnostic advance since the discovery of X rays; section 31.12 on quantum field theories, which presents an abbreviated and simplified account of recent developments in the arena of unification (electroweak theory and Grand Unified Theories). Other sections have been expanded: For example, section 12.6, "Heat Transport", now includes a discussion of the R-factor of home insulation materials, and section 22.7 on superconductivity summarizes the recent developments in the area of high T_c superconductors and includes a more comprehensive discussion of potential technological applications of superconductivity.

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 equations and obtain the correct numerical answer may delude themselves into believing that they have truly mastered a new concept; conversely, students who understand the subject but have little mathematical dexterity may be discouraged because they fail to get the "right answer." Every reviewer of the previous editions has commented favorably on the inclusion of qualitative multiple choice questions carefully designed to probe a student's grasp of new concepts and their physical significance. The number of these questions has been increased by more than 20 percent over the second edition so that, on the average, there are sixteen such questions at the end of each chapter.

This third edition also contains 25 percent more problems than the second, a total of nearly 1700, giving the instructor a wide and varied selection. Some of the new problems are in the category of simple, "confidence builder" problems. The majority are of medium difficulty, and I have also substantially increased the number and variety of the more challenging problems.

All of the historical material of the earlier editions has been retained, and I have made a few minor additions here also. I have found that anecdotal commentary not only enlivens the text but dramatizes the sometimes tortuous path leading to new and better understanding of nature. It is, I believe, vitally important that students, especially students not majoring in the physical sciences, recognize that physics is very much a human enterprise, exciting but also sometimes quite frustrating.

There is undoubtedly more material in this text than can be covered in most one-year sequences. That is as it should be. A text that must be augmented by auxiliary notes prepared by the instructor, evidently falls short. The topics included in this text encompass those traditionally taught (and listed in the MCAT manual). Many sections and two chapters (Chapter 27, "Relativity," and Chapter 30, "Aggregates of Atoms: Molecules and Solids") have been marked with an asterisk (*). These sections and chapters are optional and, though of considerable interest to most students, could be omitted without loss of continuity; no material needed in subsequent chapters is included in optional sections.

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

Charles Bacon, Ferris State College
Kenneth Clark, University of Washington
Philip Dilavore, Indiana State University
S. James Gates, Jr., University of Maryland
John Ivory, Indiana University–Malaysia Project
Harvey Picker, Trinity College

Nothing exasperates students more than to discover, after hours of frustration, that their results do not agree with the answer at the back of the book because the latter is incorrect. Every effort has been made to ensure that the answers given are, indeed, correct. I have personally worked through every problem in this text. The following have also worked selected problems from various chapters: Professors J. Baughman, D. DeYoung, A. Dickinson, R. G. Graham, B. Halkides, C. G. Hood, K. Kemper, T. Kremser, J. Lamela, J. Leddon, L. MacDonald, F. Subramanian, S. Venkatarman, and M. W. Webb. The section "Answers to Odd-Numbered Multiple Choice Questions and Problems" has been carefully proofread. Yet, as all authors know, an occasional misprint is almost unavoidable. The author and publisher would be grateful to know of any corrections that should be made in later printings.

I have been fortunate to have had the assistance and encouragement of the staff at Allyn and Bacon, in particular my editor, James Smith, and production manager, Judith Fiske. Ms. Carol Beal copyedited the manuscript with meticulous care, and the lengthy process of production, from the galley to the final printing stage, was in the very capable hands of Ms. Barbara Gracia.

Last but not least, I owe a special debt to Ms. Jane Dahl, who has been a constant companion and helpmate throughout the preparation of this third edition. Her unfailing and cheerful professional assistance at every stage is most gratefully acknowledged.

Contents

5 Work, Energy, and Power 81

6 Impulse and Momentum 109

7 Circular Motion 134

8 Gravitation 152

9 Rotational Equilibrium; Dynamics of Extended Bodies 168

10 Mechanical Properties of Matter 201

11 Hydrostatics and Hydrodynamics 222

12 Thermal Properties, Calorimetry, and the Mechanical Equivalent of Heat 260

13 The Ideal Gas Law and Kinetic Theory 291

14 Thermodynamics 314

15 Oscillatory Motion 338

16 Mechanical Waves 364

17 Sound 388

18 Electrostatics: Charges, Electric Fields, and Potentials 415

19 Capacitors 462

20 Steady Electric Currents 480

21 Magnetism 520

22 Electromagnetic Induction 552

23 Time Dependent Currents and Voltages; AC Circuits 576

24 Electromagnetic Waves and the Nature of Light 605

25 Geometrical Optics; Optical Instruments 635

26 Physical Optics 665

* 27 Relativity 704

28 Origins of the Quantum Theory 731

29 Atomic Structure and Atomic Spectra 755

*30 Aggregates of Atoms; Molecules and Solids 782

31 Nuclear Physics and Elementary Particles 802

Appendixes

Index of Tables

Units, Dimensions, and Other Preliminaries

1

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 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 eventually

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 $10^{52}/10^{-30} = 10^{82}$

will 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 50.0 miles per hour (mph). What is the speed of the car in kilometers per hour and in meters per second?

Solution The conversion between miles and kilometers (see inside front cover) is 1 mile = 1.61 km. Denoting the speed of the car by v, we have

$$v = \left(\frac{50.0 \text{ miles}}{1 \text{ h}}\right)\left(\frac{1.61 \text{ km}}{1 \text{ mile}}\right) = 80.5 \text{ km/h}$$

Note that the unit, miles, cancels out in the conversion.

To convert to meters per second, we note that there is one hour per 60 minutes and one minute per 60 seconds, and that there are 1000 meters per kilometer. Thus

$$80.5 \text{ km/h} = \left(\frac{80.5 \text{ km}}{1 \text{ h}}\right)\left(\frac{1 \text{ h}}{60 \text{ min}}\right)\left(\frac{1 \text{ min}}{60 \text{ s}}\right)\left(\frac{1000 \text{ m}}{1 \text{ km}}\right) = 22.4 \text{ m/s}$$

Example 1.2 What is the conversion factor between cubic feet and liters?

Solution One liter (L) is defined as 1000 cm^3. To get the answer, we must therefore first determine the number of cubic centimeters contained in one cubic foot. Since 1 ft = 30.48 cm, it follows that

$$(1 \text{ ft})^3 = (30.48 \text{ cm})^3 = 28{,}320 \text{ cm}^3 = 28.32 \text{ L}$$

One of the attractive and convenient features of the SI is that it is a *decimal* system. Kilometers, micrograms, nanoseconds, megawatts are all derived from basic units by multiplication by integral powers of *ten.* This makes computation much simpler than in the British system, in which the inch, foot, yard, rod, chain, and mile bear no such simple relation to each other. With SI units we can then use "scientific notation" to advantage. Another convenience of SI units is the existence of a standard prefix and symbol for each important power of ten. These are listed in Table 1.2.

1.2 Fundamental Units

Forces, velocities, pressures, energies—indeed all mechanical properties—can be expressed in terms of three basic quantities: mass, length, and time. In the SI, the corresponding units are

Kilogram	Mass
Meter	Length
Second	Time

These are known as *fundamental units.*

For many years the *standard meter* was defined as the distance between two hairline scratches on a bar of platinum-iridium alloy maintained at constant temperature in a vault of the Bureau of Weights and Measures in Sèvres near Paris. Similarly, the *standard kilogram* is a solid platinum-iridium alloy cylinder, also carefully preserved at Sèvres. Since it is not practical for scientists to make regular pilgrimages to Paris, secondary standards of the meter

Table 1.2 *Prefixes and their symbols used to designate decimal multiples and submultiples*

Factor	*Prefix*	*Symbol*	*Factor*	*Prefix*	*Symbol*
10^{18}	exa	E	10^{-1}	deci	d
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10^{1}	deca	da	10^{-18}	atto	a

and kilogram, carefully prepared to replicate the primary ones, are kept at the U.S. Bureau of Standards and similar establishments throughout the world. Today, the standard meter is defined as the distance light travels in a vacuum in 1/299,792,458 second. That is, the speed of light in vacuum is a fixed universal constant whose value is, by definition,

$$c = 299{,}792{,}458 \text{ m/s} \qquad \text{Speed of light in vacuum}$$

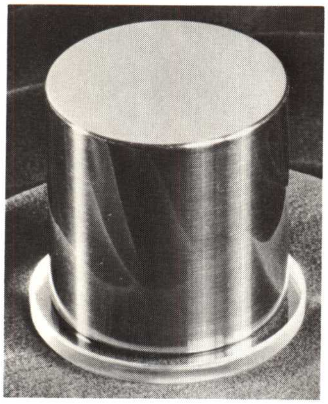


Figure 1.1 The standard kilogram, made of platinum-iridium alloy, at the International Bureau of Weights and Measures in Sèvres, France.

The frequencies of light emitted by properly stimulated atoms are often very sharply defined. Atoms have, as far as we know, remained unchanged since creation and will, we confidently believe, remain unchanged in future centuries. Moreover, atoms are not subject to the hazards of destruction by fire, earthquake, or war and other forms of vandalism. Consequently, these atomic radiations are excellent, truly permanent time standards. Today, the second is defined as 9.192,631,770 times the period (duration) of an oscillation associated with a particular atomic transition of the cesium atom. Cesium clocks are now generally used in all experiments requiring the most precise determination of long time intervals.

Though chronometers and secondary standards of the meter are still very useful for many purposes, it is only the kilogram standard that is really needed today.

1.3 Derived Units and Dimensional Analysis

Quantities that concern scientists are not limited to mass, length, and time. We often describe the behavior of objects in terms of their *velocities;* we need to identify the *forces* that act on bodies; we pay for the *energy* consumed by appliances and are curious about the *power* a motor can deliver; atmospheric *pressure* is a useful indicator of weather conditions. All these apparently disparate properties, measured in the units meters per second (velocity), newton (force), joule (energy), watt (power), and pascal (pressure), are ultimately expressible as products of powers of mass, length, and time. These units are therefore known as *derived units,* to distinguish them from the three fundamental units.

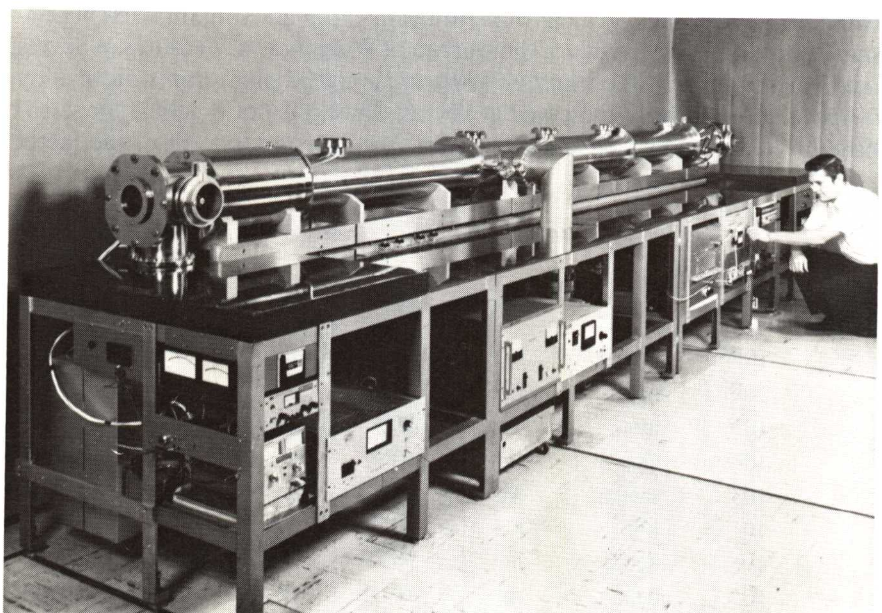


Figure 1.2 Cesium atomic clock of the National Bureau of Standards, Washington, D.C.