UNIVERSITY PHYSICS — PART I

SIXTH EDITION

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PREFACE

University Physics is intended to provide a broad introduction to physics at the beginning college level for students of science and engineering who are taking an introductory calculus course concurrently. Primary emphasis is placed on physical principles and the development of problem-solving ability rather than on historical background or specialized applications. The complete text may be taught in an intensive two- or three-semester course, and the book is also adaptable to a wide variety of shorter courses. Numerous worked-out examples and an extensive collection of problems are included with each chapter. *University Physics* is available as a single volume or as two separate parts. Part I includes mechanics, heat, and sound, and Part II includes electricity and magnetism, optics, and atomic and nuclear physics.

In this new edition, the basic philosophy and outline and the balance between depth of treatment and breadth of subject-matter coverage are unchanged from previous editions. We have tried to preserve those features and characteristics that users of previous editions have found desirable, while incorporating a number of changes, some quite extensive, that should substantially enhance the book's pedagogical usefulness. Here are some of the most important changes:

1. A new single-column two-color format has been adopted, and all the figures have been redrawn for two-color treatment. The second color is used not for cosmetic effect but to add clarity to figures through color-coding of vectors, materials, and other significant features.

   Color is also used to identify important equations and to set off examples. Thus the second color should make a very substantial improvement in the book's usefulness as a learning tool for students.
2. A list of thought-provoking questions, many of them related to everyday experience, has been included with each chapter, about 700 questions in all. These should help students to attain a deeper understanding of principles and to relate these principles to their everyday lives and should also serve as effective springboards for class discussion.

3. The problem collections have been carefully reviewed and expanded, especially with the aims of filling gaps in problem coverage, providing additional straightforward "confidence-builder" problems, and furnishing applications of elementary calculus to physical problems. The book now includes about 1600 problems, an increase of 140 from the previous edition. Worked-out examples in the text have also been reviewed, and about 100 new examples have been included. The authors have resisted the temptation to key problems to specific sections of the text. Learning to select the principles appropriate for a specific problem is, after all, part of learning to solve problems. In addition, many problems require material from more than one section.

4. Unit vectors are introduced in the opening chapter and are used to a limited extent where appropriate. Their use in later chapters of the text is optional, however; instructors who wish to omit unit vectors completely can do so without loss of continuity.

5. There are several minor changes in the outline. The chapter on rigid-body equilibrium has been placed following dynamics of a particle and just before rotational motion. However, users who want to go into this material immediately following equilibrium of a point may still do so. The thermodynamics material has been split into two chapters, one each for the first and second laws. The introductory material on optics has been somewhat condensed and consolidated into a single chapter. The relativity chapter has been moved to the end of the book to accompany the other chapters on twentieth-century physics, which have been considerably expanded. The number of chapters is now 47, but the overall length of the book is about the same as that of the previous edition.

6. Many sections have been extensively rewritten to improve clarity and continuity. New introductory material has been prepared for nearly every chapter; this will provide the student with a sense of perspective and ease his or her entry into the chapter. The first chapter is completely new; it now includes discussion of units, unit conversions, and significant figures, as well as an introduction to vector addition in the context of displacement vectors, preceding the more abstract addition of forces. Products of vectors are also introduced here. All of the material in the areas of magnetic fields and forces has been rewritten with the aim of making it less formal (and less formidable) than in the previous edition.

7. The treatment of modern physics topics has been considerably expanded. There is a completely new chapter on quantum mechanics. The discussion of nuclear fission and fusion has been expanded, as has the treatment of fundamental particles and the associated conservation and symmetry principles. Several topics have been added, including lasers, integrated circuits, superheavy nuclei, quarks, and several others.

8. Some material that is outdated or of peripheral importance has been de-emphasized; a few examples are the Wheatstone bridge, the potentiometer, thermoelectricity, and some aspects of magnetic materials.

The text is adaptable to a wide variety of course outlines. The entire text can be used for an intensive course two or three semesters in length. For a less intensive course, many instructors will want to omit certain chapters or sections to tailor the book to their individual needs. The format of this edition facilitates this kind of flexibility. For example, any or all of the chapters on relativity, hydrostatics, hydrodynamics, acoustics, magnetic properties of matter, electromagnetic waves, optical instruments, and several others can be omitted without loss of continuity. In addition, some sections that are unusually challenging or out of the mainstream have been identified with an asterisk preceding the section title. These too may be omitted without loss of continuity.

Conversely, however, many topics that were regarded a few years ago as of peripheral importance and were purged from introductory courses have now come to the fore again in the life sciences, earth and space sciences, and environmental problems. An instructor who wishes to stress these kinds of applications will find this text a useful source for discussion of the appropriate principles.

In any case, it should be emphasized that instructors should not feel constrained to work straight through the book from cover to cover. Many chapters are, of course, inherently sequential in nature, but within this general limitation instructors are encouraged to select from among the contents those chapters that fit their needs, omitting material that is not relevant for the objectives of a particular course.

Again we wish to thank our many colleagues and students who have contributed suggestions for this new edition. In particular, Professors William M. Cloud (Eastern Illinois University), James R. Gaines (Ohio State University), and A. Lewis Ford (Texas A. and M. University) have read the entire manuscript, and their critical and constructive comments are greatly appreciated. In addition, Professors Malcolm D. Cole and Charles McFarland (University of Missouri at Rolla) have read portions of the manuscript and have provided many valuable suggestions. One of the authors (H.D.Y.) offers special thanks to his students and colleagues at Carnegie-Mellon University for their many helpful comments. He acknowledges a special debt of gratitude to Professors Robert Eisenstein, Robert Kraemer, and Frederick Messing of Carnegie-Mellon for many stimulating discussions about the book and about physics pedagogy generally, and to Professor Kraemer for major contributions to the sections on high-energy physics. The kindness and helpfulness of these people will not soon be forgotten.

As usual, we welcome communications from readers concerning our book, and especially concerning any errors or deficiencies that may remain in this edition.

New York
Pittsburgh
November 1981

M.Z.
H.D.Y.

AVAILABLE SUPPLEMENTS

The following supplementary materials are available for use by students:

Study Guide	James R. Gaines and William F. Palmer (Ohio State University, Columbus)
Solutions Guide	A. Lewis Ford (Texas A&M University, College Station)

The following supplement is available to instructors:

Answers to Even-Numbered Problems	(The answers to the odd-numbered problems are in the back of the book.)

MECHANICS, HEAT, AND SOUND

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PART II

UNITS, PHYSICAL QUANTITIES, AND VECTORS 1

1-1 Introduction

Physics is an *empirical* study. Everything we know about the physical world and about the principles that govern its behavior has been learned through *observations* of the phenomena of nature. The ultimate test of any physical theory is its agreement with observations and measurements of physical phenomena.

Thus physics is inherently a science of *measurement*. Lord Kelvin (1824–1907), one of the pioneers in investigating energy relations in heat and thermal phenomena, stated this principle eloquently:

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of *science,* whatever the matter may be.

Any number or set of numbers used for a quantitative description of a physical phenomenon is called a *physical quantity*. To *define* a physical quantity we must either specify a procedure for *measuring* the quantity, or specify a way to *calculate* the quantity from other quantities that can be measured. For example, we can define *distance* and *time* by describing procedures for measuring them, and then define the *speed* of a moving body as the distance traveled divided by the time of travel.

A definition in terms of a procedure for measuring the defined quantity is called an *operational definition*. Certain fundamental quantities can be defined *only* with operational definitions. The fundamental quantities of mechanics are usually taken to be mass, length, and time. For other areas of physics other fundamental quantities, including temperature, electric charge, and luminous intensity, will be introduced later.

1-2 Standards and units

In measuring a quantity, we always compare it with some established reference standard. To say that a rope is 30 meters long is to say that it is 30 times as long as an object whose length has been *defined* to be one meter. Such a standard is called a *unit* of the quantity; thus the *meter* is a unit of distance, and the *second* is a unit of time.

For precision in making measurements, it is essential to have precise and reproduceable definitions of the units of measurement. When the metric system was established in 1791 by the Paris Academy of Sciences, the meter was originally defined as one ten-millionth of the distance from the equator to the North Pole, and the second as the time for a pendulum one meter long to swing from one side to the other. In later years these definitions have been modified and greatly refined.

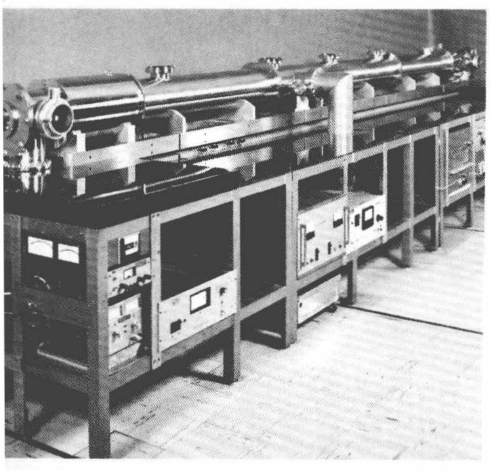
Since 1889 the definitions of the basic units have been established by an international organization called the General Conference on Weights and Measures, to which all the major countries of the world send representatives. The system of units defined by this organization, based on the metric system, has been known officially since 1960 as the *International System,* abbreviated SI because of the French equivalent, *Système International.*

Two essential characteristics of a unit standard are *permanence* and *reproduceability.* Thus in 1889, a meter bar of platinum-iridium alloy was chosen as the *standard of length;* this alloy is particularly stable chemically. However, the use of such a bar as a world standard is cumbersome; replicas must be made and compared with the world standard periodically. On October 14, 1960, the General Conference changed the standard of length to an *atomic constant,* namely, *the wavelength of the orange-red light emitted by the individual atoms of krypton-86* in a tube filled with krypton gas in which an electrical discharge is maintained. One meter is defined to be 1,650,763.73 times the wavelength of this light. Such a standard is more precise and more readily reproduced in various locations than is one based on a specific material object.

The standard of *mass* is the mass of a cylinder of platinum-iridium alloy, designated as *one kilogram,* kept at the International Bureau of Weights and Measures at Sèvres, near Paris. An atomic standard of mass has not yet been adopted because it is not yet possible to measure masses on an atomic scale with as great precision as on a macroscopic scale.

Until 1960 the standard of *time* was based on the mean solar day, the time interval between successive arrivals of the sun at its highest point, averaged over a year. In 1967 an atomic standard was adopted. The two lowest energy states of the cesium atom have slightly different energies, depending on whether the spin of the outermost electron is parallel or antiparallel to the nuclear spin. Electromagnetic radiation (microwaves) of precisely the proper frequency causes transitions from one of these states to the other. One second is now defined as the time required for 9,192,631,770 cycles of this radiation. Figure 1-1 shows a cesium frequency standard, which may be used as a clock.

1-1 NBS-6 is the latest of six generations of primary atomic frequency standards developed by the National Bureau of Standards (NBS). Consisting of a 6-meter cesium beam tube, NBS-6 achieves an accuracy of better than one part in 10^{13}, and when operated as a clock, can keep time to within 3 millionths of a second per year. (Courtesy National Bureau of Standards.)



Once the fundamental units are defined, it is easy to introduce larger and smaller units for the same physical quantities. In the metric (SI) system these additional units are always related to the fundamental ones by multiples of 10 or $\frac{1}{10}$. Thus one kilometer (1 km) is 1000 meters, one centimeter (1 cm) is $\frac{1}{100}$ meter, and so on. The multiplicative factors are most conveniently expressed in exponential notation; thus $1000 = 10^3$, $\frac{1}{1000} = 10^{-3}$, and so on. The names of the additional units are always derived by adding a prefix to the name of the fundamental unit. For example, the prefix "kilo-", abbreviated k, always means a unit larger by a factor of 1000; thus

$$1 \text{ kilometer} = 1 \text{ km} = 10^3 \text{ meters} = 10^3 \text{ m},$$
$$1 \text{ kilogram} = 1 \text{ kg} = 10^3 \text{ grams} = 10^3 \text{ g},$$
$$1 \text{ kilowatt} = 1 \text{ kW} = 10^3 \text{ watts} = 10^3 \text{ W}.$$

Table 1-1 lists the standard SI prefixes with their meanings and abbreviations. We note that most of these are multiples of 10^3.

Table 1-1 Prefixes for powers of ten

Power of ten	10^{-18}	10^{-15}	10^{-12}	10^{-9}	10^{-6}	10^{-3}	10^{-2}	10^3	10^6	10^9	10^{12}	10^{15}	10^{18}
Prefix	atto-	femto-	pico-	nano-	micro-	milli-	centi-	kilo-	mega-	giga-	tera-	peta-	exa-
Abbreviation	a	f	p	n	μ	m	c	k	M	G	T	P	E

In pronunciation of unit names with prefixes, there is *always* an accent on the *first* syllable; some examples are *kil*-o-gram, *kil*-o-meter, *cen*-ti-meter, and *mic*-ro-meter. Accenting "kilometer" on the *second* syllable is not correct!

Following are several examples of the use of multiples of 10 and their prefixes, and some additional time units.

$$1 \text{ nanometer} = 1 \text{ nm} = 10^{-9} \text{ m} \quad \text{(used by optical designers)},$$
$$1 \text{ micrometer} = 1\ \mu\text{m} = 10^{-6} \text{ m} \quad \text{(used commonly in biology)},$$
$$\left.\begin{aligned} 1 \text{ millimeter} &= 1 \text{ mm} = 10^{-3} \text{ m and} \\ 1 \text{ centimeter} &= 1 \text{ cm} = 10^{-2} \text{ m} \end{aligned}\right\} \text{(used most often)},$$
$$1 \text{ kilometer} = 1 \text{ km} = 10^3 \text{ m} \quad \text{(a common European unit of distance)}.$$
$$1 \text{ microgram} = 1\ \mu\text{g} = 10^{-9} \text{ kg},$$
$$1 \text{ milligram} = 1 \text{ mg} = 10^{-6} \text{ kg},$$
$$1 \text{ gram} = 1 \text{ g} = 10^{-3} \text{ kg}.$$

$$1 \text{ nanosecond} = 1 \text{ ns} = 10^{-9} \text{ s},$$
$$1 \text{ microsecond} = 1\ \mu\text{s} = 10^{-6} \text{ s},$$
$$1 \text{ millisecond} = 1 \text{ ms} = 10^{-3} \text{ s}.$$

$$1 \text{ minute} = 1 \text{ min} = 60 \text{ s},$$
$$1 \text{ hour} = 1 \text{ hr} = 3600 \text{ s},$$
$$1 \text{ day} = 1 \text{ day} = 86{,}400 \text{ s}.$$

Finally, we mention the British system of units, used only in the United States and the British Commonwealth and rapidly being replaced by SI in the latter. The British units are now officially *defined* in terms of SI units, as follows:

$$\text{Length: } 1 \text{ inch} = 2.54 \text{ cm} \quad \text{(exactly)}$$
$$\text{Mass: } 1 \text{ pound-mass} = 0.45359237 \text{ kg} \quad \text{(exactly)}.$$

The fundamental British unit of time is the second, with the same definition as in the SI. In the British system, the *pound* is a unit of *force,* and is a force equal to the weight of one pound-mass, under specified conditions. In this book the pound-mass is not used, and the pound is *always* a unit of force.

In physics, British units are used only in mechanics and thermodynamics; there is *no* British system of electrical units. For illustrative purposes, a few problems in each chapter in the first half of this book use British units, but the last half of the book uses only SI units.

1-3 Unit consistency and conversions

Relations among physical quantities are often expressed by equations in which the quantities are represented by algebraic symbols. An algebraic symbol always denotes both a *number* and a *unit.* For example, s might represent a distance of 10 m, t a time of 5 s, and v a speed of 2 m/s or $2\ \mathrm{m \cdot s^{-1}}$. (In this book negative exponents will usually be used with units to avoid use of the fraction bar.)

An equation must always be *dimensionally consistent;* this means that two terms may be added or equated only if they have the same units. For example, if a body moving with constant speed v travels a distance s in a time t, these quantities are related by the equation.

$$s = vt. \tag{1-1}$$

If s is measured in meters, then the product vt must also have units of meters. Using the above numbers as an example, we may write

$$10\ \mathrm{m} = (2\ \mathrm{m \cdot s^{-1}})(5\ \mathrm{s}).$$

The unit ($\mathrm{s^{-1}}$) or (1/s) cancels the unit (s) on the right side; thus the right side *does* have units of meters (m), as it must. This illustrates the fact that in calculations, units are treated just like algebraic symbols with respect to multiplication, division, and cancellation.

In all calculations needed for problems, units should *always* be written with all numbers and treated as in the above example. This provides a very useful check on calculations; if at some stage in a calculation an expression is found to have inconsistent units, an error has been made somewhere. In all worked-out numerical examples throughout this book, units will be carried through the calculations, and the student is strongly urged to follow this practice in solving problems.

The algebraic properties of units provide a convenient procedure for converting a quantity from one unit to another. Equality is sometimes used to represent the same physical quantity expressed in two different units. For example, to say that 1 min = 60 s does not mean that the number 1 is equal to the number 60, but rather that 1 min represents the same physical time interval as 60 s. Thus one may multiply by 1 min and then divide by 60 s, or multiply by the quantity (1 min/60 s), without changing the physical meaning. To find the number of seconds in 3 min, we write

$$3\ \mathrm{min} = (3\ \cancel{\mathrm{min}})\left(\frac{60\ \mathrm{s}}{1\ \cancel{\mathrm{min}}}\right) = 180\ \mathrm{s}.$$

Similarly, converting $50\ \mathrm{km \cdot h^{-1}}$ (50 kilometers per hour) into meters per