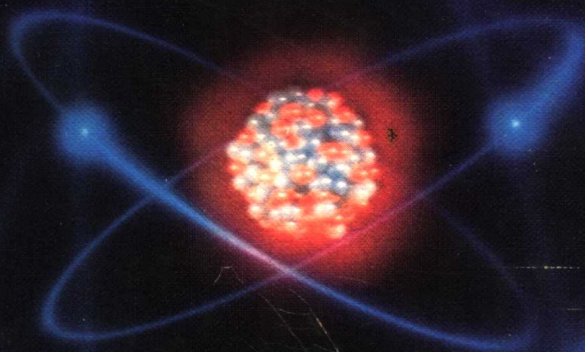


# PHYSICS IN THE MODERN WORLD



Jerry B. Marion

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Jerry B. Marion

*University of Maryland  
College Park*



Academic Press New York / San Francisco / London

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ACADEMIC PRESS, INC.  
111 Fifth Avenue, New York, New York 10003

*United Kingdom Edition published by*  
ACADEMIC PRESS, INC. (LONDON) LTD.  
24/28 Oval Road, London NW1

Library of Congress Cataloging in Publication Data

Marion, Jerry B.  
Physics in the modern world.

Bibliography: p.

Includes index.

I. Physics. I. Title.

QC23.M36 530 75-13104

ISBN 0-12-472277-6

PRINTED IN THE UNITED STATES OF AMERICA

In addition to the acknowledgments expressed in credit lines accompanying photographs in the text, permission to reproduce illustrations on the following pages from the sources listed is gratefully acknowledged: 29, C. F. Powell, P. H. Fowler, and D. H. Perkins (eds.), *The Study of Elementary Particles by the Photographic Method* (Pergamon Press, Oxford, 1959); 48, 53, 275, 283, 285, 307, 310, *PSSC Physics* (Heath, Lexington, Massachusetts); 123, (1) NASA, E. C. Goddard, (2) Novosti from Sovfoto; 187, J. N. Pitts and R. L. Metcalf, *Advances in Environmental Sciences*, Vol. 1 (Wiley, New York, 1969); 247, The University of Maryland, Richard Farkas; 324, J. B. Marion, *Physics and the Physical Universe* (Wiley, New York, 1971); 326, Educational Development Center; 366, British Crown Copyright, Science Museum, London; 387, 403, ERDA, Lotte Jacobi; 415, Harbrace; 444, Lent to Science Museum, London by Sir Lawrence Bragg, F.R.S.

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# PREFACE

This is a text for a one-year introductory course in physics for students who are specializing in other disciplines. In these chapters you will find a survey of topics in physics with emphasis on those aspects of current interest. No mathematics beyond basic trigonometry is required to follow the discussions.

Today we live in a world that is dominated by technology. Moreover, the impact of technology on society, already enormous, will almost certainly continue to increase. In order to cope with the problems of a highly technical world, it is necessary to appreciate some of the basic scientific ideas that are the foundation stones upon which our modern technology is built. Lacking this understanding, we would find it increasingly difficult to contribute effectively to the complex decisions that affect our everyday lives. It is the purpose of this book to put forward these fundamental ideas as clearly as possible and to draw attention to the way that basic physical principles are applied in our technological world.

In *Physics in the Modern World* you will see that physical principles bring a pattern of simplicity and continuity to the diverse natural and technological world around us. To show the many ways that physical ideas are manifest in everyday situations, numerous short essays on various kinds of applications have been included. In these special sections the reader will learn about the operation of rockets and cameras, and about the principles at work in space travel and X-ray photography. Discussions of automobile air bags, drag racing, artificial gravity, pollution control, appliance economics, musical instruments, radar, and other modern phenomena and devices emphasize the way that physical principles are applied in today's world. Historical sketches of individual scientists detail their important contributions to our present knowledge and technology. Physics is not an abstract subject. Physical principles form the basis of the world in

which we live, and they constitute a vital part of the knowledge we must have to understand and appreciate that world.

An important part of learning about physics is becoming familiar with some of the quantitative aspects of the subject by solving simple problems. However, the main thrust of this book is not concerned with problem-solving techniques. Instead, the emphasis here is on the basic concepts and principles. To be sure, these ideas are reinforced through examples and exercises. But it is much more important to understand the physical basis of an event or situation than to be able to substitute numbers into some formula.

A serious effort has been made to present each topic in the clearest possible terms. The explanations are developed carefully and in depth, frequently including a detailed example. Accordingly, this book is more than a source of questions for the instructor to answer. It is a book that the student can *read*.

To enhance the value of this text as a learning tool, a supplementary student guide is available. In this guide the student will find a short summary of the important ideas in each chapter, some additional worked examples, suggestions for outside reading, and a list of questions and problems (with answers) to test his comprehension of the material.

I hope that you, the reader, will enjoy this book as much as I have enjoyed writing it!

JERRY B. MARION

*College Park, Maryland*

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# 1

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## INTRODUCTION TO PHYSICAL IDEAS

From his home on the Earth, Man can look through a telescope into the vast reaches of space. Or he can look through a microscope into the miniature world of cells and molecules. The scale of things that Man has been able to observe and study truly staggers the imagination. Roughly speaking, the Universe is as many times larger than the Earth as the Earth is larger than an atom. Thus, Man stands in a middle position, privileged to view the immensely large Universe populated with an incalculable number of stars and galaxies as well as the microscopic domain of incredibly tiny atoms and molecules.

Man has reached out from his position between the large and the small of the Universe and he has uncovered at least some of the rules by which Nature governs the *microscopic* (or small-scale) world of atoms and the *macroscopic* (or large-scale) realm of everyday objects, the Earth, planets, and stars. In this book we will examine some of these discoveries, and we will see how they are used to describe the world around us.

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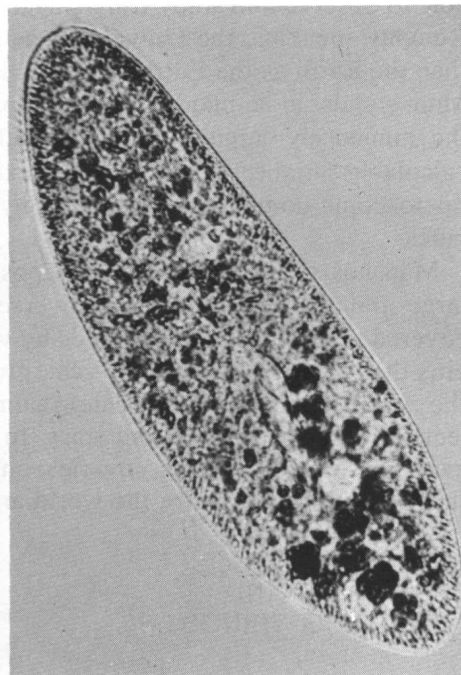
### DESCRIBING AND MEASURING THINGS

#### The Basic Concepts

Progress is made in understanding our physical surroundings through *observation* and *measurement* coupled with *logic* and *reason*. In order to describe our observations and to record our measurements, we must

agree on the language and the terms that we will use. Our intuitive ideas concerning physical concepts will serve as the starting points for most of our discussions of the world around us. One of the important aspects of measurements of any type is the existence of a set of *standards*. Unless we all agree on the meaning of terms such as *one quart* or *one acre* or *one hour*, it will be impossible to give a precise interpretation to any measurement. The necessity for standards of various kinds has given rise to an enormous number of measuring units. Many of these measuring units have very specialized applications—for example, the *tablespoon* in cooking or the *rod* in surveying or the *carat* in gemmology. Fortunately, in scientific matters a restricted set of measuring units is used.

The fundamental units of measure in science are those of *length*, *time*, and *mass*. These are familiar concepts, but because they are so basic to the description of physical events and phenomena, we will briefly discuss each of these units in turn.



HALE OBSERVATORIES

The large and the small of the Universe. At the left is a telescopic photograph of the great galaxy in the constellation Andromeda and at the right is a microscopic photograph of a *paramecium*, a one-celled animal. The diameter of Andromeda is approximately 1 000 000 000 000 000 000 000 m ( $10^{21}$  m) whereas the size of the *paramecium* is approximately 0.000 1 m ( $10^{-4}$  m).

## Length

Most Americans are accustomed to measuring distance in terms of inches, feet, yards, and miles, which are length units in the so-called *British* system of units. These length units are derived from a variety of sources, dating back hundreds or thousands of years to periods when there were only the crudest of standards for the measurement of length. Today, the scientific community universally uses the *metric system* of measure. Indeed, even for everyday matters, most of the world (with the primary exception of the United States) uses metric measure. In order to preserve our position in world trade, the United States will eventually change over from its archaic system to metric units. But it will probably be many years until we will have foregone completely our present system.

The standard of length in the metric system is the *meter* (m). Compared to the length units in the British system, the meter has the following values:

$$1 \text{ m} = 39.37 \text{ in.} = 3.281 \text{ ft} = 1.094 \text{ yd}$$

That is, a *meter* is about 10 percent longer than a *yard*.

Until 1961 the meter was defined as the distance between two finely drawn lines on a certain metal bar housed in the International Bureau of Weights and Measures, near Paris. Copies of this bar were distributed to national standards laboratories throughout the world. However, in 1961 an international agreement was made to define the meter in terms of the wavelength of the orange light emitted by krypton atoms. Thus, we now have an *atomic* standard for length. Because all atoms of krypton are exactly alike,\* a length standard can be established in any laboratory where it is required, and it is guaranteed that all such krypton standards will be absolutely identical. Not only does the adoption of an atomic standard for length eliminate the necessity of relying on the inconvenient standard meter bar, but now it is possible to report lengths in terms of the atomic standard to a precision of 1 part in 100 000 000, almost a hundred times better than was previously possible.

The metric system has the advantage (not shared by the British system) that the various units of a physical quantity are related by factors of 10, thus considerably

\* More accurately, we should say that all atoms of the isotope krypton-86 are exactly alike; we will learn about *isotopes* in the next chapter.



UPI

It will require many years for the United States to change to the metric system, but evidence that the conversion is underway is beginning to appear.

TABLE 1-1 METRIC UNITS OF LENGTH

10 mm = 1 cm
100 cm = 1 m
1000 m = 1 km

simplifying any conversions that are necessary. For example,

$1\text{ m} = 100\text{ centimeters (cm), or }10^2\text{ cm}$   
 $1\text{ cm} = 0.01\text{ m, or }10^{-2}\text{ m}$   
 $1\text{ m} = 0.001\text{ kilometer (km), or }10^{-3}\text{ km}$   
 $1\text{ km} = 1000\text{ m, or }10^3\text{ m}$

The metric units of length are summarized in Table 1-1.

TABLE 1-2 LENGTH CONVERSION FACTORS

2.54 cm = 1 in.
39.37 in. = 1 m
1.609 km = 1 mi

Conversion of Units

Occasionally, we will need to convert from the British system to the metric system or vice versa. For length conversions we use the correspondences shown in Table 1-2. Suppose that we wish to express 18 inches in terms of centimeters. Now, 1 inch (in.) is exactly equal to 2.54 cm. Therefore, we can form a *ratio* that is equal to unity:

$$\frac{2.54\text{ cm}}{1\text{ in.}} = 1$$

We can multiply (or divide) any quantity by unity without affecting its value. If we use the above ratio for unity, and multiply it by 18 in., we find

$$(18\text{ in.}) \times \left(\frac{2.54\text{ cm}}{1\text{ in.}}\right) = 45.72\text{ cm}$$

TABLE 1-3 COMMONLY USED PREFIXES

SYMBOL	PREFIX	POWER OF 10	EXAMPLE
$\mu$	micro-	$10^{-6}$	$10^{-6}\text{ second} = 1\text{ }\mu\text{s}$
m	milli-	$10^{-3}$	$10^{-3}\text{ meter} = 1\text{ mm}$
c	centi-	$10^{-2}$	$10^{-2}\text{ meter} = 1\text{ cm}$
k	kilo-	$10^3$	$10^3\text{ watts} = 1\text{ kW}$
M	mega-	$10^6$	$10^6\text{ volts} = 1\text{ MV}$

Powers of Ten—How We Use Them

One of the problems that we encounter when dealing with physical quantities is how to express very large and very small numbers in a convenient way. For example, to write that the distance from the Earth to the Sun is 150 000 000 000 meters or that the mass of a hydrogen atom is 0.000 000 000 000 000 000 000 001 673 kilograms is obviously quite awkward (and subject to errors unless the zeroes are counted carefully!). To overcome this difficulty in writing very large or very small numbers, we use a compact notation employing *powers of ten*. For example, notice that

$$10 \times 10 = 100 = 10^2$$
$$10 \times 10 \times 10 = 1000 = 10^3$$
$$10 \times 10 \times 10 \times 10 = 10\,000 = 10^4$$

That is, the number of times that 10 is multiplied together appears in the result as the superscript of 10 (called the *exponent* of 10 or the *power* to which 10 is raised).

Any number can be expressed in powers-of-ten notation. For example,

$$147\ 000\ 000 = 1.47 \times 100\ 000\ 000 = 1.47 \times 10^8$$

Notice that in going from 147 000 000 to  $1.47 \times 10^8$ , we move the decimal *eight* places to the left; therefore, the exponent of 10 that appears in the result is 8. Similarly, in going from  $1.47 \times 10^8$  to 147 000 000, we move the decimal eight places to the *right*.

Products of powers of 10 are expressed as

$$10^2 \times 10^3 = (10 \times 10) \times (10 \times 10 \times 10) = 10^5 = 10^{(2+3)}$$

That is, in general, the product of  $10^n$  and  $10^m$  is  $10^{(n+m)}$ :

$$10^n \times 10^m = 10^{(n+m)}$$

If the power of 10 appears in the denominator, the exponent is given a negative sign:

$$\frac{1}{10} = 0.1 = 10^{-1}$$

$$\frac{1}{100} = 0.01 = 10^{-2}$$

$$\frac{1}{1000} = 0.001 = 10^{-3}$$

In general,

$$\frac{1}{10^m} = 10^{-m}$$

Any decimal number can be expressed as a negative power of 10:

$$0.037 = \frac{37}{1000} = \frac{3.7}{100} = 3.7 \times 10^{-2}$$

Notice that in going from 0.037 to  $3.7 \times 10^{-2}$ , we move the decimal *two* places to the right; therefore, the exponent of 10 that appears in the result is  $-2$ . Similarly, in going from  $3.7 \times 10^{-2}$  to 0.037, we move the decimal two places to the *left*.

Calculations involving large or small numbers are made considerably easier by using the powers-of-ten notation:

$$400\ 000 \times 0.02 = (4 \times 10^5) \times (2 \times 10^{-2}) = (4 \times 2) \times 10^{(5-2)} = 8 \times 10^3$$

$$\frac{640\ 000}{4\ 000\ 000\ 000} = \frac{6.4 \times 10^5}{4 \times 10^9} = \frac{6.4}{4} \times 10^{(5-9)} = 1.6 \times 10^{-4}$$

Sometimes we use a prefix to a unit to express the appropriate unit. For example, *centi-* means  $\frac{1}{100}$ ; therefore, *centimeter* means  $\frac{1}{100}$  of a meter. The commonly used prefixes are listed in Table 1-3.

---

TABLE 1-4 THE RANGE OF DISTANCES IN THE UNIVERSE (ALL VALUES ARE APPROXIMATE.)

Radius of the Universe	100 000 000 000 000 000 000 000 000 m = $10^{26}$ m
Nearest galaxy	10 000 000 000 000 000 000 000 m = $10^{22}$ m
Nearest star	10 000 000 000 000 000 m = $10^{16}$ m
Earth-Sun	100 000 000 000 m = $10^{11}$ m
New York-Chicago	1 000 000 m = $10^6$ m
Length of a football field	100 m = $10^2$ m
Height of a child	1 m = $10^0$ m
Width of a finger	0.01 m = $10^{-2}$ m
Grain of salt	0.000 01 m = $10^{-5}$ m
Radius of an atom	0.000 000 000 1 m = $10^{-10}$ m
Nuclear radius	0.000 000 000 000 01 m = $10^{-14}$ m

Notice that *in.* occurs both in the numerator and the denominator of the left-hand side and therefore cancels, leaving the result expressed in cm. We can always use this technique to convert from one system of units to another.

The range of lengths and distances that we encounter in the Universe is truly enormous. Table 1-4 lists some representative values. Notice that the size of the Universe is about  $10^{40}$  times the size of a nucleus! Some useful distances are given in Table 1-5.

Time

We all have a firm intuitive idea of the meaning of *length*. And although we have a similar feeling for *time*, it is more difficult to give expression to this concept in words. One possible definition: “*Time* is that which takes place between two events.”

In order to *measure* time, we must have a series of regularly spaced *events*, such as the ticks of a clock. Ancient peoples used the apparent motion of the Sun as a crude clock. The interval between sunrise and sunset was reckoned to be *one day*. The Egyptians further divided the day and the night into 12 hours each, using shadow clocks (sun dials) to keep track of the daylight hours. But in this system the hours are not of equal duration because the length of the day changes with the seasons. Early attempts to reproduce constant fractions of a day included measuring the level of water in a large vat as water was allowed to trickle out through a small hole at the bottom.

Sun dials and water clocks eventually gave way to mechanical clocks. About 1300 A.D., the *escapement*

TABLE 1-5 SOME USEFUL DISTANCES

1 light year, L.Y. (the distance light will travel in 1 year)	$9.46 \times 10^{15}$ m
Earth-Sun distance (called 1 <i>astronomical unit</i> , A.U.)	$1.50 \times 10^{11}$ m
Radius of Sun	$6.96 \times 10^8$ m
Earth-Moon distance	$3.84 \times 10^8$ m
Radius of Earth	$6.38 \times 10^6$ m
Radius of Moon	$1.74 \times 10^6$ m
Wavelength of yellow light	$6.0 \times 10^{-7}$ m
1 angstrom, Å	$10^{-10}$ m
Radius of hydrogen atom	$5.29 \times 10^{-11}$ m
Radius of proton	$1.2 \times 10^{-15}$ m

TABLE 1-6 TIME UNITS

1 second = 9 192 631 770 vibrations of cesium atom
1 minute = 60 s
1 hour = 3600 s
1 day = 86 400 s
1 year = $3.156 \times 10^7$ s



clock was invented in which a toothed wheel, driven by a set of weights or a spring, engages a ratchet to regulate its turning. This device is basic to the operation of all mechanical clocks, even the modern variety. By the early 18th century, the great English clockmaker John Harrison had produced a clock for navigational purposes that maintained an accuracy of 15 seconds during a 5-month sea voyage—this was the first true *chronometer*, or precision clock.

The next important advance in timekeeping occurred in this century with the introduction of rapidly vibrating systems, such as tuning forks or quartz crystals, to regulate the motion of clock mechanisms. Miniaturized tuning-fork and quartz-crystal devices have recently been developed for use in wristwatches (see the photograph). Tuning-fork regulation can achieve an accuracy of about 1 second per day. Crystal-controlled clocks are capable of an accuracy of 1 part in 100 000 000 ( $10^8$ ), which corresponds to 1 second in 3 years.

Even a precision as high as that possible with crystal control is not sufficient for many scientific purposes. Within the last few years methods that depend on *atomic* vibrations have been developed for controlling clocks. In fact, since 1967 the international standard of time has been based on the vibrations of cesium atoms. Thus, we now have atomic standards for two of the fundamental units of measure: the meter and the second. The various time units that we use are listed in Table 1-6 and the range of time intervals in the Universe is shown in Table 1-7.



BULOVA WATCH COMPANY, INC.

A quartz-crystal regulated wristwatch. The digital readout is by means of light emitting diodes.

TABLE 1-7 RANGE OF TIME INTERVALS IN THE UNIVERSE  
(ALL TIMES ARE APPROXIMATE.)

Age of the Universe	1 000 000 000 000 000 000 s = $10^{18}$ s
Age of the Earth	100 000 000 000 000 000 s = $10^{17}$ s
Age of the Pyramids	100 000 000 000 s = $10^{11}$ s
Lifetime of a man	1 000 000 000 s = $10^9$ s
4 months	10 000 000 s = $10^7$ s
Light travels from Sun to Earth	1000 s = $10^3$ s
Interval between heartbeats	1 s = $10^0$ s
Period of a sound wave (typical)	0.001 s = $10^{-3}$ s
Period of a radio wave (typical)	0.000 001 s = $10^{-6}$ s
Light travels 1 foot	0.000 000 001 s = $10^{-9}$ s
Period of atomic vibration (typical)	0.000 000 000 000 001 s = $10^{-15}$ s
Period of nuclear vibration (typical)	0.000 000 000 000 000 001 s = $10^{-21}$ s